ECE 451

Automated Microwave Measurements Laboratory

Experiment 3 - Network Analyzer Error Corrections: The 1-term, 2-term, and 3-term Error Model

1 Introduction

When we make a microwave measurement, we have to construct a test setup in order to properly connect our device under test (DUT). This test setup might include cables, adapters, fixtures, probes, etc. A reality of this paradigm is that the measurement equipment we use will affect the measurement of the DUT. This effect on the measurement is unavoidable and will cause an error in the measurement. Fortunately, if this error is known, it can be corrected. The process of determining this error is called error correction or, more commonly, calibration. Calibration consists of measuring a number of calibration standards, whose microwave properties are known very precisely over the entire frequency range of the measurement. Based on the resulting data from the measurement of these standards, we can construct a model of the characteristics of the microwave hardware in the measurement, called an error model or error adapter. The network analyzer uses this error model to correct measurements of the DUT to remove the systematic measurement errors. This allows us to view our DUT measurements as though an ideal network analyzer were connected through the error adapter to a location where the calibration standards are connected (test port). Calibration becomes the task of determining the variables in an error adapter and then factoring them out to obtain error-corrected measurements of our DUTs.

In this experiment, we are going to make uncorrected measurements of calibration standards and our DUTs using the Copper Mountain S5048 VNA. We will use the calibration standard measurements to identify the coefficients in the several error models we have developed. Finally, we will perform the error corrections on our DUT measurements manually using ADS.

Useful links

1. Fundamentals of Network Analysis
2. Chapter 3 of the *Handbook of Microwave Component Measurements with Advanced VNA Techniques* by Joel Dunsmore

2 Background

In general, the measured reflection coefficient of a network analyzer is not linearly related to the test port reflection coefficient due to the realities of the measurement system. There are error terms (collectively called the error adapter) that modify the desired measurement, Γ_L, so that the actual measurement that we take, Γ_m, is a distortion of the desired measurement. The purpose of calibration is to remove the effects of these errors. Doing so moves the reference plane of the measurement from the measurement plane to the test port.

Figure 1 shows this situation. The ratio detector is inside the network analyzer.

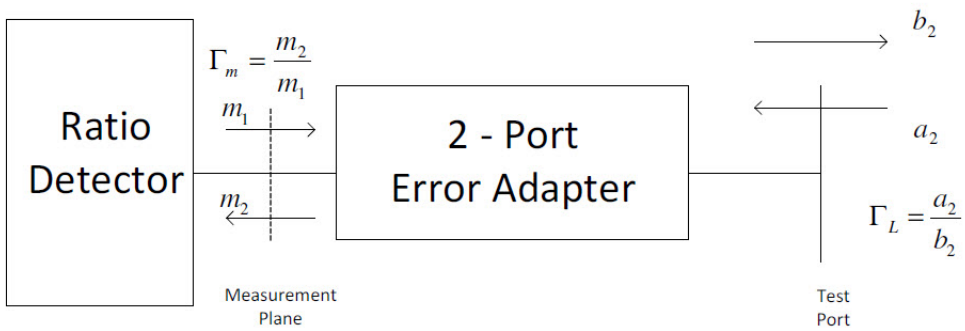

Figure 1: Measurement apparatus including the error adapter

The use of flow graphs offers a much more useful way to depict the error adapter, as shown in Figure 2. This figure depicts the 3-term error adapter for a 1-port measurement.

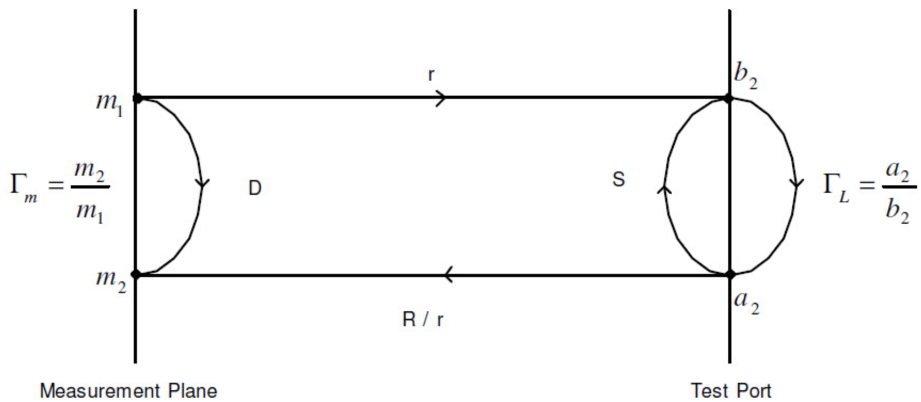

Figure 2: Flowgraph for 3-term Error Adapter

The quantities in error adapter represented by upper case letter are:
R: Reflection Tracking [we only measure the product r*(R/r)]
D: Measurement System Directivity
S: Measurement System Source Match
And will be termed measurement descriptors.

Using Mason's Rule, we can determine the measured reflection coefficient in terms of the test port reflection coefficient and the measurement system descriptor to be:

$$\Gamma_m = \frac{m_2}{m_1} = D + \frac{R \times \Gamma_L}{1 - S \times \Gamma_L} = \frac{D + (R - S \times D)\Gamma_L}{1 - S \times \Gamma_L} \text{ with } \Gamma_L = \frac{a_2}{b_2}$$

If R, S and D were known Γ_L may be found in terms of Γ_m and the measurement system descriptors as

$$\Gamma_L = \frac{\Gamma_m - D}{R + S(\Gamma_m - D)}$$

Ideally, for a well designed and constructed measurement system, $|R| \sim 1$ and $|D|, |S| \ll 1$. In calibration procedures, we measure several standards for which Γ_L is known. We use the known Γ_m values and the corresponding Γ_m values that we measure from them to construct a system of equations from which we can solve for all of the unknowns in our error adapter.

3 Pre-lab

Go to Appendicies for some notes for a start.

1. Derive the two-term including directivity error (D) correction formula.
2. Derive the two-term including source match error (S) correction formula.

   Note: For all of these derivations, you should identify your standards {match, short, open} but DO NOT assume anything about their values: leave the values of their reflection coefficients in general variable form. (For example, Γ_m^{match}, Γ_L^{match}, Γ_m^{short}, Γ_L^{short}, Γ_m^{open}, Γ_L^{open}.)You will need to solve for D, S, and R (as appropriate for each error model) in terms of these variables, then provide an expression for Γ_L in terms of Γ_m and whichever of D, S, and R that are appropriate.
3. Derive the three-term error correction formula. For this derivation, you can use the theoretical values for $\Gamma_L^{match} = 0$, $\Gamma_L^{short} = -1$, $\Gamma_m^{open} = 1$ to make the algebra manageable. **Include the appropriate signal flow graphs in all of your derivations. Hint:** The one-term and both two-term error models are simplifications of the 3-term error model. You can use this insight to verify your work.

4 Equipment

- Advanced Design System (ADS)
- S-A-A-2 NanoVNA
- Student board: DUT 4 & DUT 5

5 Procedure

1. Turn on the VNA and open NanoVNA-QT (PC software). Set the frequency range to be from 1.5GHz to 3GHz with 201 points. Click *Calibration* ⇒ *Load* and load *sol.cal* (`http://emlab.uiuc.edu/ece451/sol.cal`) in.
2. In the procedure below, we will be connecting a long trace to NanoVNA as shown in Figure 3. It will distort our measurements of student unknown significantly so the effects of the calibration should be especially clear.

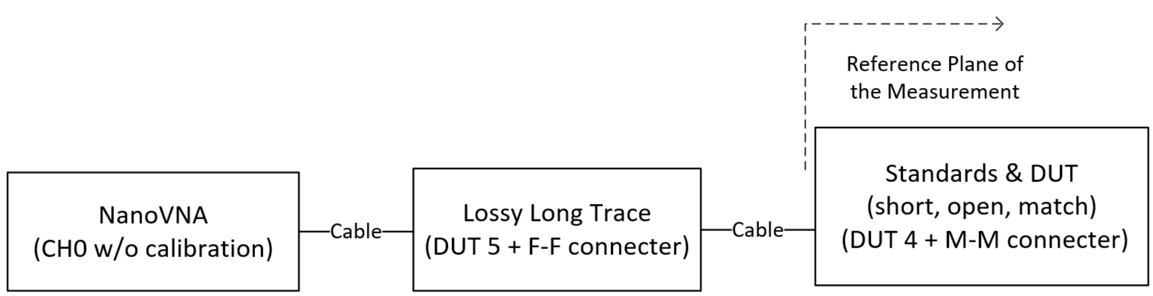

Figure 3: Block Diagram for this experiment

3. The following devices are to be measured and their data is to be saved to Touchstone[1] .s1p file: (sample file names are given.)
   (a) A short ("short")
   (b) An open ("open")
   (c) A 50 ohm termination ("trm50")
   (d) Student unknown: student board DUT 4 ("dut")
4. Open ADS, create a new workspace, and import all of these datasets in, giving them the same names as you saved them in above. See the Notes on Using ADS at the end of the procedure for some advice on dealing with multiple datasets.

[1] `http://cp.literature.agilent.com/litweb/pdf/genesys200801/sim/linear_sim/sparams/touchstone_file_format.htm`

5. Use ADS to calculate the error correction terms that you have derived in the theory questions for all four error adapters. **While error terms may have the same name in different error adapters, they must be calculated independently for each error model** (for example, R for one-term is not equal in value to R from three-term).
   (a) R for one-term.
   (b) R and S for two-term including source match.
   (c) R and D for two-term including directivity.
   (d) R, S, and D for three-term.
6. Calculate Γ_L from Γ_m for each of the four error adapters for your student unknown. You will be plotting these Γ_L values in the next two steps.
7. For your student unknown, obtain **|S11| in dB**, **S11 Phase**, and **Smith Chart plots** as a function of frequency for the following (a total of 12 plots):
   (a) One-term using a short for corrections (3 plots).
   (b) Two-term including source match using a short and an open for corrections (3 plots).
   (c) Two-term including directivity using a short, and a 50 ohm termination for corrections (3 plots).
   (d) Three-term using a short, an open and a 50 ohm termination for corrections (3 plots).
8. Create the following **Smith Chart plots** of your student unknown:
   (a) One-term using a short for corrections.
   (b) Two-term including source match using a short and an open for corrections.
   (c) Two-term including directivity using a short, and a 50 ohm termination for corrections.
   (d) Three-term using a short, an open and a 50 ohm termination for corrections.

   Given that the student unknown is actually a VSWR = 4 load, calculate its theoretical reflection coefficient Γ_{VSWR} and add equation $VSWR = circle(0, \Gamma_{VSWR}, 500)$ to the data display window. Overlay $VSWR$ with all of your smith charts. You may need to change its trace type to scatter and symbol type to dot for better resolution. Comment on which error-correction gives you the most fitted result.
9. Plot the Magnitude (magnitude, not in dB) and Phase of the three error terms—D, R and S that you calculated for the three-term error model. Comment on their effects versus frequency.

6 Conclusion

1. Which standards do you use with each two-term error model? Elaborate your choice?
2. Figure 4 shows Smith charts each showing known standards. Which group of standards can be used to calibrate a network analyzer?
   (a) Theoretically?
   (b) Practically? (Which one of these groups might actually exist in real life?)

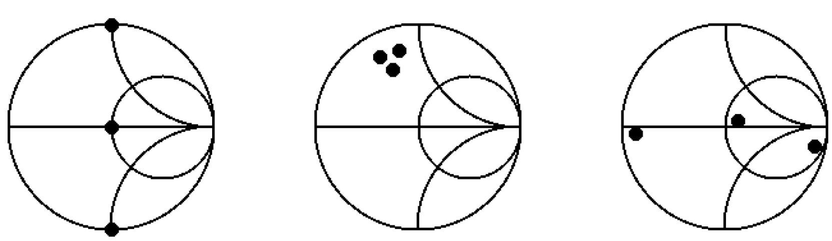

Figure 4: Smith charts each showing known standards

3. Real-life standards obviously have frequency dependence, and thus cannot be just “dots” on the Smith chart. When is this not a problem? When is it a problem? How might we compensate for this frequency dependence in our error correction?

4. Discuss the physical significance of R, S, and D, use the measured values to illustrate your reasoning.

Appendix 1 - Error Models and Their Signal Flow Graphs

One Term Model

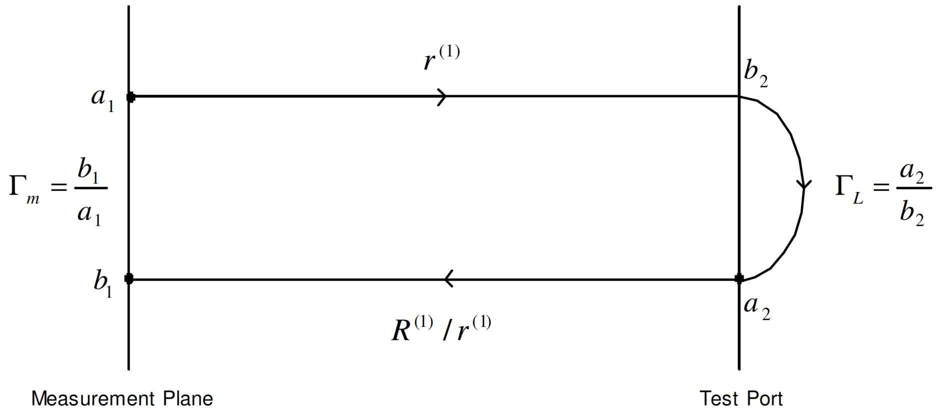

Figure 5: Flowgraph for one-term model of reflectometer

The measurement in terms of the load for the one-term model is $\Gamma_m(\Gamma_L) = R^{(1)}\Gamma_L$.

Using a short for calibration $\Gamma_m(-1) = R^{(1)}(-1)$ or $R^{(1)} = -\Gamma_m(-1)$ so that $\Gamma_m(\Gamma_L) = \frac{\Gamma_m(\Gamma_L)}{\Gamma_m(-1)}$.

Two Term Models

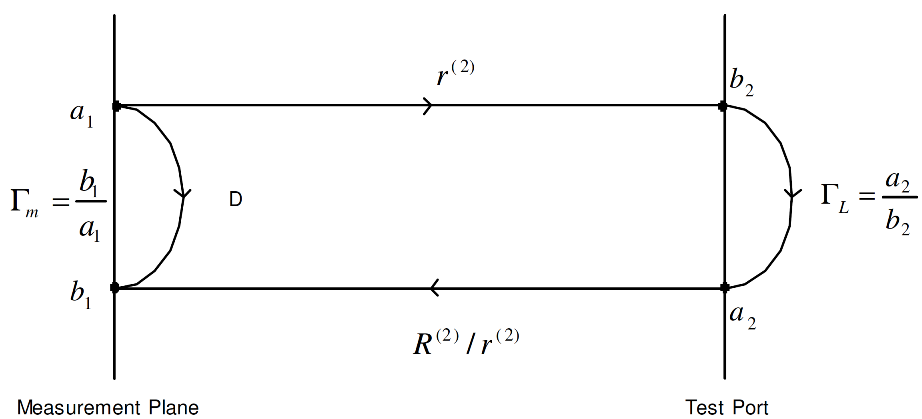

Figure 6: Flowgraph for two-term error model including directivity

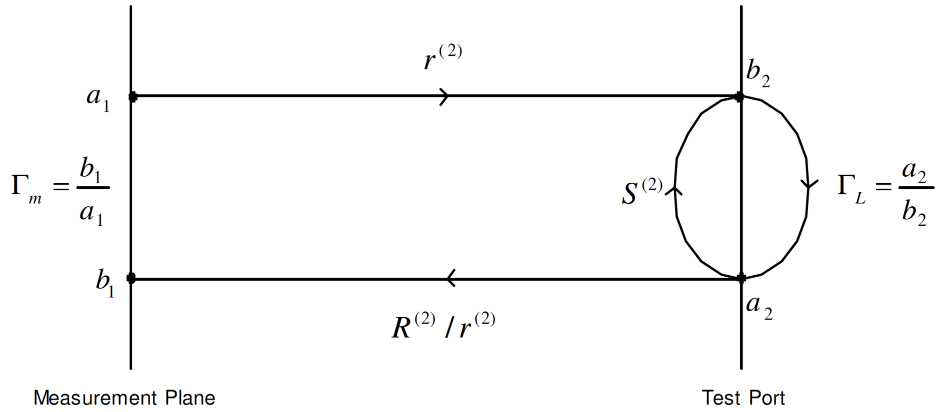

Figure 7: Flowgraph for two-term error model including source match

Three Term Model

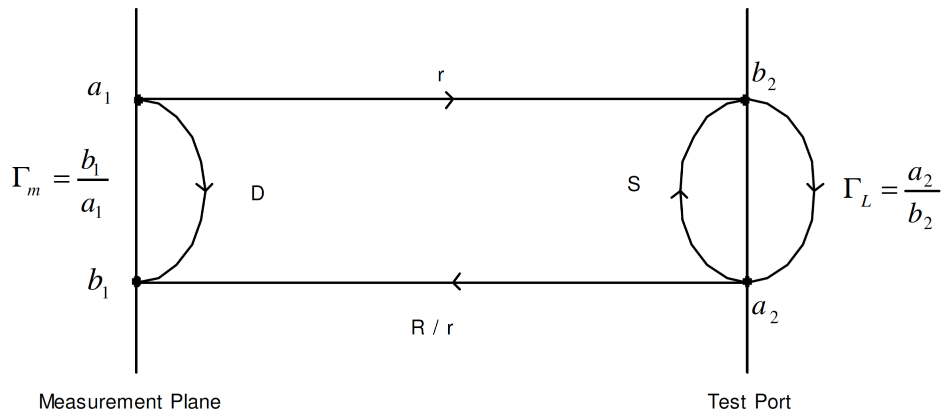

Figure 8: Flowgraph for three-term error model for reflectometry measurement

Appendix 2 - Theory and Conclusion Notes

The reflectometer error adapter may be represented as three complex numbers in an "error box". The nodes a and b in Figure 9 represent the reference and test channels, respectively, and are measured using two detectors

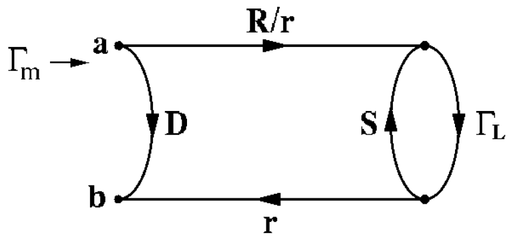

Figure 9: Flowgraph for three-term error model

Significance of R, S, and D

D: "measurement system directivity"

S: "measurement system source match"

R: "measurement system reflection"

In many applications, the error box models a section of cable or some kind of connector/adapter. Therefore, typical values for these parameters are $|D|$,$|S| \ll 3$ and $|R| \approx 1$.

Notice that we could also model the error box using S-parameters, let

$$D = S_{11},\ S = S_{22},\ \frac{R}{r} = S_{21},\ r = S_{12}$$

.

but the error correction equation,

$$\Gamma_m = \frac{b}{a} = D + \frac{R\Gamma_L}{1 - S\Gamma_L}$$

contains no r, and this quantity cannot be found using the three standards. Similarly, we could only determine S_{11} , S_{22} , $S_{12}S_{21}$ of the error box by measuring the three standards.

In general, solving for the terms in the error box is nonlinear, as seen below. However, a change of variables yields a linear system which is practically implemented in hardware:

$$\Gamma_m = D + \frac{R\Gamma_L}{1 - S\Gamma_L} = \frac{x_1 + x_2\Gamma_L}{1 - x_3\Gamma_L}.$$

Given known standards $a_i = \Gamma_L^{(i)}$, and measured values $c_i = \Gamma_m^{(i)}$, the unknowns are expressed as

$$\begin{array}{ccc} x_1 & = & D \\ x_2 & = & R - SD \\ x_3 & = & S \end{array} \Rightarrow \begin{bmatrix} 1 & a_1 & a_1c_1 \\ 1 & a_2 & a_2c_2 \\ 1 & a_3 & a_3c_3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix} \Rightarrow \begin{array}{ccc} D & = & x_1 \\ R & = & x_2 + x_1x_3 \\ S & = & x_3 \end{array}.$$

(see page 132 of Dunsmore.)