OBJECTIVES

The purpose of this lab is to introduce the concepts of calibration and error correction for microwave s-parameter measurements. As a part of this project, you will compare different calibration methods to measuring a device-under-test (DUT) and learn about an important calibration technique known as “TRL.”

INTRODUCTION (POZAR, 4.4)

By now you have become familiar with the power of the network analyzer as a microwave measurement and diagnostic tool. Network analyzers are devices that measure the s-parameters of unknown networks. The s-parameters of a microwave network are the “scattering coefficients” of the circuit and relate the incident waves at the network terminals to the scattered waves at those terminals. At microwave frequencies, it is more natural to describe circuits in terms of these scattering coefficients than impedance or admittance parameters. Network analyzers come in two basic types. The first, known as the “four-port” network analyzer, uses a phase sensitive ratio meter or “vector voltmeter” as part of the measurement system. The National Instruments PXIe-6532 used in our class is an example of this type of network analyzer. The second type is known as a “six-port” analyzer and uses only microwave power detectors to make the measurement. The six-port analyzer uses simpler hardware but requires more complicated data processing.

To understand the operation of a network analyzer, we will first look at a simple four-port analyzer used to measure only reflection coefficients (known as a “reflectometer”). The basic reflectometer setup is shown in Figure 1 and consists of two identical directional couplers. Directional couplers are four-port circuits that split incident waves into two parts. You designed and fabricated a directional coupler known as a “branchline” coupler a few weeks ago. One coupler samples the forward-going wave and the other samples the reverse-going wave. If the two couplers are identical, perfectly matched to the normalizing impedance, and have perfect directivity†, then the vector voltmeter will indicate the reflection coefficient, \( \Gamma \), times a known complex constant. Real directional couplers, unfortunately, give rise to measurement errors. In early network analyzers, these directional couplers were constructed with impressive precision, but the accuracy of these machines is still quite poor when compared to today’s standards.

CALIBRATION AND ERROR CORRECTION

With the introduction of onboard microprocessors, the need to construct high-precision

†The directivity of a four-port directional coupler is defined as the power ratio \( P_3 / P_4 \) where port 3 is the “coupled output” and port 4 is the isolated port. A perfect directional coupler has infinite directivity.
A four-port reflectometer that uses two identical directional couplers. The vector voltmeter indicates the complex ratio $b_4/b_3$.

Broadband directional couplers vanished. Errors resulting from imperfections in the couplers (and other components in the instrument) are *systematic* errors and can be calibrated out by measuring known impedance standards. The onboard processor can then correct for the errors in the measured data as the measurement is being made. The residual error remaining after calibration is that due only to electronic noise (which typically is quite small) and the repeatability in making the circuit connections, which is usually very good with precision SMA connectors. The reflectometer shown in Figure 1 can be represented with the “error” model shown in Figure 2. The systematic errors are modeled as a two-port “error” network between the load and the reference plane at which the scattered waves are actually measured. The “measured” reflection coefficient, $\Gamma'$, is related to the load’s “true” reflection coefficient, $\Gamma_0$ by,

$$
\Gamma' = e_{11} + \frac{e_{21}e_{12}\Gamma_0}{1 - e_{22}\Gamma_0} = E_D + \frac{E_R\Gamma_0}{1 - E_S\Gamma_0}
$$

where the $\{e_{ij}\}$ are the scattering parameters of the error network and we have defined three “error coefficients,” $E_D \equiv e_{11}$, $E_S \equiv e_{22}$, and $E_R \equiv e_{21}e_{12}$. To determine the parameters of the error network, the reflection coefficients of *three* precisely known loads are measured. These known loads are called “calibration standards” and their measurement allows us to write three equations relating the three unknown quantities, $E_D$, $E_S$, and $E_R$. The process of measuring these known loads is called “measurement calibration” and the process of mathematically removing the systematic errors in the measurement known as “error correction.” In principle, any *three* unique loads are sufficient to calibrate a reflectometer. However, if measurement error causes any two of the calibration standards to overlap (that is, to present the *same* reflection coefficient to the network analyzer), then it will not be possible to solve for the three terms in our error model. For this reason, we prefer the calibration standards to be well-separated on the Smith Chart and typically an open circuit, short circuit, and matched load are chosen.
The measurement of two-port networks is a bit more complicated because transmission as well as reflection must be measured. Figure 3(a) shows the basic measurement configuration for two-port devices. When the vector voltmeter switch is in one position, reflection is measured. When the switch is in the other position, transmission is measured. To measure all four scattering parameters, the device under test must be flipped end-to-end. Fortunately, the network analyzer in the lab has two of these circuits, along with internal switches, so that all $s$-parameters can be measured without physically flipping the device.

**Figure 2.** (a) Error model for a microwave reflectometer. All systematic errors are represented by a two-port “error network” with scattering parameters $\{e_{ij}\}$. (b) Signal flow graph for the one-port reflectometer. Three known standards are required to calibrate the system.

**Figure 3.** (a) Measurement setup for two-port $s$-parameter measurement. An internal switch allows both reflection and transmission measurements to be made. (b) Error model for the two-port $s$-parameter measurement system. $\{s_{ij}\}$ are the $s$-parameters of the device under test and $\{E_j\}$ are the error parameters of the measurement circuit.
The error model for the two-port measurement is a little more involved than that for the reflectometer. Figure 3(b) shows a flow graph model for the errors in the two-port measurement configuration. We see that there are a total of six unknown coefficients in the error model. Three of these ($E_D$, $E_S$, and $E_R$) are the same as for the reflectometer. In addition, three new error terms have been added. $E_L$ is a “load mismatch” term that accounts for any mismatch between the transmission return port and the network analyzer. $E_T$ is the “gain” of the transmission return path. Finally, $E_X$ models the isolation between the two ports of the analyzer. Because our network analyzer has two of these circuits, there are a total of twelve unknown error terms that must be measured during calibration. In a typical two-port calibration, we measure the reflection of an open, short, and match at each port (6 measurements), the transmission and reflection when the two ports are connected (4 measurements), and the isolation between the ports with each port connected to a matched termination (2 measurements). These measurements allow us to mathematically correct for the error terms and determine the $s$-parameters of the two-port device.

### TRL Calibration Standards

The calibration method described in the previous section works very well for coaxial measurements where high-quality terminations such as shorts and 50 Ω loads are available (and usually quite expensive!). However, when measuring microstrip or other non-coaxial circuits, it is necessary to use a test fixture that makes the transition from coaxial line to the appropriate transmission medium. A major problem encountered when making network measurements of this type is the need to separate out the effects of the test fixture from the device or circuit being measured. This, in principle, can be done by considering the fixture to be part of the network analyzer and calibrating out its effect. Unfortunately, precise impedance standards for non-coaxial media (e.g. microstrip) are difficult to realize and usually not available.

In 1979, Glenn Engen at the National Bureau of Standards (now known as NIST) introduced a new network analyzer calibration method known as “TRL”\(^1\);\(^2\). TRL stands for “Through-Reflect-Line” and uses transmission lines as the calibration standards rather than discrete terminations. This method has several advantages, particularly for non-coaxial measurements:

- Transmission lines are among the simplest components to realize in most non-coaxial transmission media.
- The characteristic impedance of transmission lines can be accurately determined from physical dimensions and material parameters.
- The calibration is done in the same environment as the actual measurement.

Figure 4 shows a block diagram of a simplified 2-port measurement system. Eight of the twelve error terms are represented by two-port error adapters shown in the figure. These error terms are characterized by the basic TRL calibration. The relationship between these new error coefficients and the traditional error terms $\{E_j\}$ are given in Figure 4.

The basic TRL calibration process consists of the following three steps:
1. **THROUGH** — port 1 is connected to port 2, either directly or by a short section of transmission line. The transmission and reflection are measured from each port resulting in four measurements.

2. **REFLECT** — identical one-port, high reflection coefficient loads are connected to each port. The actual value of the reflection coefficient need not be known, but the phase must be known to within \( \pm 90^\circ \). Typically an open or short circuit is used. This results in two measurements.

3. **LINE** — A short section of transmission line is inserted between ports 1 and 2. This line must have a different length than that used for the THROUGH measurement. Again the transmission and reflection are measured from each port resulting in four measurements.

At this point, a total of ten measurements have been made by the network analyzer. However, the basic error model in Figure 4 has only eight unknown error terms. Because there are two more measurements than unknowns, two constants defining the calibration standards can also be determined. In the standard TRL calibration procedure, the complex reflection coefficient of the REFLECT standard and the complex propagation constant of the LINE are determined. This is significant because we do not need to completely specify our calibration standards beforehand — they can be determined as part of the calibration procedure! The only remaining unknown is the characteristic impedance of the transmission lines which can be calculated from physical dimensions.

To complete the calibration and determine the final four error terms in the twelve-term error model, the isolation between the ports is measured. This is done by disconnecting the ports and measuring the residual leakage between the ports (two measurements). Typically this is very small and often can be neglected. Finally, the basic TRL calibration scheme assumes that the two test-set circuits (one of which is shown in Figure 3(a)) are identical. that is, it is assumed that the source and load match terms \( E_S \) and \( E_L \) are the same. Unfortunately, this is not usually the case since the switch may present a different terminating impedance when it is changed between ports 1 and 2. Sophisticated network analyzers account for this difference by measuring the ratio of the incident signals \( a_1 \) and \( a_2 \) during the THROUGH

![Figure 4. Block diagram for a two-port error corrected measurement system.](image)
The TRL calibration method described above allows all twelve error terms in a two-port measurement system to be determined. As a bonus, two of the calibration standards are characterized during the measurement. Over the years, variations on the TRL calibration method have been developed including the “LRL,” which stands for ”Line-Reflect-Line.” The LRL calibration method is essentially identical to the TRL calibration method, with the only difference being that a non-zero length line standard replaces the zero-length through standard. In this lab project, we will be using the onboard LRL calibration algorithm of the NI PXIe-6532 network analyzer to eliminate the effect of the microstrip test fixture from our scattering parameter measurements.

To use the LRL calibration method for s-parameter error correction, we first need to set up the network analyzer for this and define the standards we will be using. Figure 5 shows images of the microstrip measurement fixture we have been using in the class, along with microstrip LRL standards we will use for this project. We will consider Line 1 to be a zero-length through. Line 2 is designed to have an electrical length $90^\circ$ longer than the through standard at 2 GHz. Figure 5(b) shows the reflect standard at each port, which is an open-circuit presented to each port. We can also use these open-circuits to set the reference planes for our s-parameter measurements. Thus, when the error-correction is applied, the network analyzer should provide the scattering parameters of a device-under-test placed between the two reference planes (lower circuit of figure 5(b)). Note that since the microstrip fixture is present during all the calibration measurements, its effect on the measurements will be ”corrected” or removed (provided the coaxial-to-microstrip pin connections are repeatable and yield the same response for each of the measurements).

![Figure 5](image_url)

**Figure 5.** Photographs of the microstrip test fixture with a set of LRL calibration standards. (a) The two line standards and (b) the reflect standards. Once the system is calibrated, the scattering parameter of a device mounted across the gap can be measured at the reference planes indicated.
**Procedure**

1. Solder a 100 Ω chip resistor across the gap in the “DUT” microstrip circuit provided. This resistor will be our DUT that will allow us to compare two-port measurements that have been corrected using different calibration approaches.

2. Set the frequency range for measurement of the network analyzer from 800 MHz to 2.1 GHz.

3. Perform the usual “SOLT” (Short-Open-Load-Through) two-port calibration that we have been using during the semester by connecting the appropriate standards at the ends of the measurement cables. Once you have done this, connect a microstrip test fixture between the two measurement ports.

4. Measure and record the two-port s-parameters of the 100 Ω chip resistor with (a) the calibration turned OFF, and (b) with the calibration you just performed turned ON. In case (a) you are observing uncalibrated data that includes the systematic effects of the measurement instrument, cables and fixture. In case (b), the effects of the measurement instrument and cables have been removed, but the effect of the measurement fixture is present in your measurement.

5. For this part of the lab, we will set up and apply an LRL calibration. Click on the Calibration menu (the Wrench icon) at the top of the screen to open the calibration menu (figure 6). From here, select Calibrate → Manual Cal → 2 Port Cal → Modify Cal Setup → Cal Method → LRL/LRM. This last choice will open a dialog box in which you can specify the standards you will use for the LRL calibration.

![Figure 6. Drop-down menus for setting up the LRL calibration.](image-url)
For the LRL calibration, set the lengths of **Line 1** to 0 mm for standard 1 and **Line 2** to 37.5 mm for standard 2. This is the length corresponding to a 90° phase-shift (quarter wavelength) at 2 GHz (in free space). For standard 3 (the reflect), choose “Open-like component.” Finally, select **Middle of Line 1** for the Reference Plane Location. This will set the reference plane in the middle of our DUT, which will result in a small phase error, but is not significant in this project as the DUT we are using is a lumped element.

6. Once you have set up the LRL calibration, it can be used to calibrate the network analyzer for measurements. Perform an LRL calibration using the microstrip Line and Reflect standards provided (shown in figure 5). Once this is done, remeasure the 100 Ω resistor using the LRL calibration turned ON. In this case, the calibration should remove the effects of the measurement instrument, cables, fixture, and microstrip lines up to the DUT reference plane. Record the data obtained from this measurement.

**Results**

In your lab report, present and discuss the $s$-parameter data obtained from the 100 Ω resistor measured using the three different “corrections” (no correction, SOLT calibration and LRL calibration). You should examine both the magnitude and phase responses. Your report should include the following:

1. What $s$ matrix do you expect for an ideal 100 Ω resistor embedded in series within a 50 Ω microstrip line?

2. From your measurement without calibration, comment on the effect and importance of calibration in microwave $s$-parameter measurements.

3. Using your measured data to justify your conclusions, comment on the effect the microstrip test fixture has on $s$-parameter measurements. How does the measured data corrected by the SOLT calibration compare to what is expected from the 100 Ω resistor? Does the fixture introduce a phase error? How much? Can you estimate the quality of the coaxial-to-microstrip transition based on your measurements? Your comments should be **quantitative**.

4. How closely does the LRL-corrected measurement agree with the anticipated $s$-parameters from the 100 Ω resistor. Again, your comments should be **quantitative**.

5. Comment on how useful this project has been in aiding your understanding of microwave measurements. Can you suggest improvements to the project?

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