How to Calibrate Through Balun Transformers to Accurately Measure Balanced Systems

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***Abstract*—Balun transformers are used in front of network analyzers to measure the balanced- and common-mode characteristics of transmission lines and electronic networks. The nonideal nature of real baluns will cause measurements made with this technique to be in error. This paper shows that by following a calibration procedure similar to the conventional network analyzer calibration of Kruppa and Sodomsky, where known standards are measured, and these measurements are used to correct measurements of unknown devices, one can compensate for the nonideal nature of the measurement baluns. In this procedure, a conventional two-port network analyzer is connected to the balun transformer and, without disconnecting the network analyzer, inaccuracies in the balun can be calibrated out. Balanced mode, common mode, and mode conversion parameters can be accurately measured. This paper applies the previously published method of Silvonen for conventional network analyzer calibration to correct the measurement errors when using balun transformers.**

***Index Terms*—Balanced mode, balun, calibration, common mode, network analyzer.**

I. Introduction

As DIGITAL clock rates increase and data path widths increase, differential signaling is used more and more. With differential signaling, the current drawn by the I/O drivers is constant, leading to good noise performance in a mixed analog and digital environment. This allows lower signaling levels and higher speeds. Differential I/O uses balanced transmission lines, often coplanar lines on a circuit board and a twisted pair in cabling.

Although vector network analyzers are the instrument of choice for measuring reflection coefficients, return loss, and insertion loss at high frequencies, these instruments are designed for use in coaxial systems. To evaluate balanced transmission lines, balanced receivers, and transmitters, some way of converting the coaxially oriented test equipment to a balanced/common-mode type of measurement must be provided. Balun transformers are used for this purpose. This paper describes a method to calibrate the network analyzer through the balun transformer so that the nonideal response of the transformer can be compensated for.

The situation we consider in this paper is shown in Fig. 1. A network analyzer is used to measure some kind of balanced system. A balance measuring device (usually a balun transformer) is used to enable the network analyzer, which is a coaxial single-ended measuring system, to work with the balanced device-under-test (DUT). The balanced-mode reflection coefficient and the common-mode reflection coefficient of the DUT are presented to the network analyzer at the coaxial ports of the balance measuring device. The "unbalance" of the DUT is represented by a coupling between the balanced- and common-mode ports of the balance measuring device.

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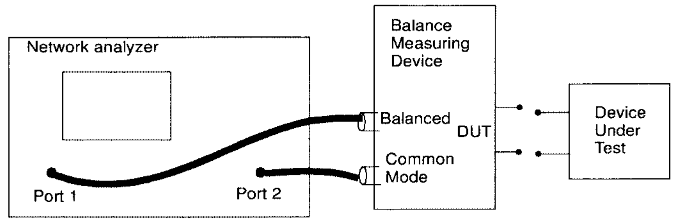

Fig. 1. Measurement scenario addressed in this paper.

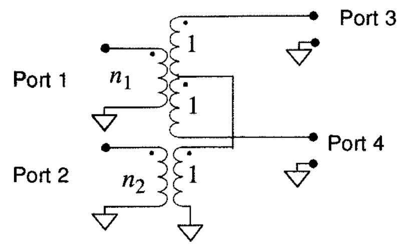

Fig. 2. Balun transformer, shown as a four-port network.

A. Ideal Balun Transformers

Consider the balanced to unbalanced transformer, commonly called the balun. There are several ways to make these devices. One particular balun schematic is shown in Fig. 2.

The balun transformer can be placed around a network and provide ports for the balanced and common connections. A balun transformer can be thought of as a four-port device. Two of its ports are normally connected to the network analyzer during measurements. Port 1 in Fig. 2 is the balanced measuring port and port 2 is the common-mode port. The other two ports of the four port, ports 3 and 4, connect to the DUT.

Circuit analysis of Fig. 2 reveals that the scattering matrix of a balun is given in (1), shown at the bottom of the following page.

A well-known result in network theory is that a matched lossless four-port is determined by only two parameters [5]. A similar thought process can show that a balanced lossless four-port

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is also parameterized by only two parameters. Thus, (1) can be considered representative of all lossless balanced balance measuring devices, even if they do not have the schematic of Fig. 2.

Most of the time, the common-mode port of a balun is actually a direct connection to the center tap of the transformer. In this case, $n_2 = 1$. When baluns are designed to interface a 50-Ω network analyzer to a 100-Ω balanced line, then $n_2 = \sqrt{2}$. An ideal transformer with these turn ratios would have a scattering matrix of (2) as follows:

$$S_{\text{idealBalun}} = \begin{bmatrix} 0 & 0 & \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} \\ 0 & \frac{-1}{3} & \frac{2}{3} & \frac{2}{3} \\ \frac{\sqrt{2}}{2} & \frac{2}{3} & \frac{1}{6} & \frac{1}{6} \\ -\frac{\sqrt{2}}{2} & \frac{2}{3} & \frac{1}{6} & \frac{1}{6} \end{bmatrix} \approx \begin{bmatrix} 0 & 0 & 0.7071 & -0.7071 \\ 0 & -0.3333 & 0.6667 & 0.6667 \\ 0.7071 & 0.6667 & 0.1667 & 0.1667 \\ -0.7071 & 0.6667 & 0.1667 & 0.1667 \end{bmatrix}. \quad (2)$$

This kind of balun is very commonly used. Note that the value of n_2 affects the measurement of the common-mode parameters and the balanced- to common-mode conversion gain. There is some confusion in the literature over the precise definition of these parameters. For example, the mixed-mode parameters of Bockelman and Eisenstadt [3] agree with balun measurements when a balun has $n_2 = \sqrt{2}$, while the method of Yanagawa *et al.* [4] agrees with measurements when a balun has $n_2 = 1$.

An example scattering matrix of a typical high-quality balun in its mid-frequency range (at 10.1 MHz) is given in (3), shown at the bottom of this page.

This scattering matrix was computed from measurements described in Section II. These parameters will vary with frequency. Comparing these numbers with those of (2), one can see that an actual balun is not ideal. This paper provides a method of correction for the nonideal nature of the actual balun. The technique is an application of [2].

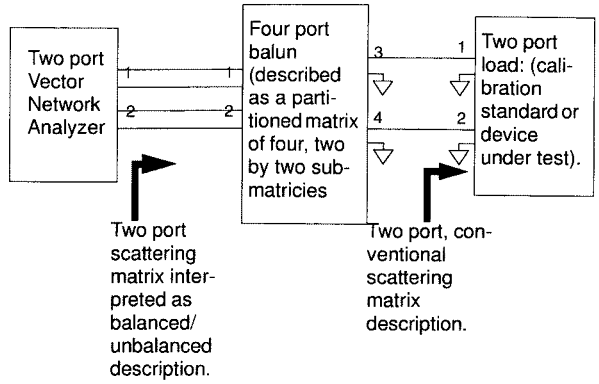


Fig. 3. Indicating the matrix descriptions used for the circuits in this paper.

II. Overview of the Calibration Procedure

The first step in the calibration procedure is to perform the built-in full two-port calibration of the network analyzer to the end of the coaxial cables used to connect to the balun. At the reference plane of the end of the coax cables, the network analyzer can then be considered ideal.

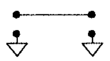
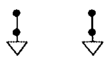
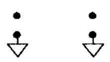
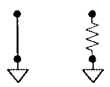
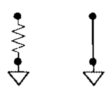
The calibration of the balun response is performed by connecting the two ports of the network analyzer to the two coaxial ports of the balun, and measuring the two-port parameters from the network analyzer five times, each time with a different load on the balun output. The calibration and measurement setup is shown in Figs. 2 and 3.

The known loads used to characterize the baluns must be different from each other so that all the characteristics of the balun can be extracted from the measurements. However, the loads must be simple so that they are easily constructed and the experimenter can have confidence that the loads are known. To find the balun s-parameters, a system of equations must be solved. If the standard loads are not varied enough, the equations will not have a unique solution. By investigating various combinations of shorts, opens, and known resistors for the standards, it can be shown experimentally that five loads are needed to solve the equations uniquely. Various combinations work and some

$$S\text{mat} = \begin{bmatrix} \frac{(n_1^2-2)}{(2+n_1^2)} & 0 & \frac{2n_1^2}{(2+n_1^2)} & \frac{-2n_1}{(2+n_1^2)} \\ 0 & \frac{(n_2^2-2)}{(2+n_2^2)} & \frac{2n_2^2}{(2+n_2^2)} & \frac{2n_2^2}{(2+n_2^2)} \\ \frac{2n_1}{(2+n_1^2)} & \frac{2n_2^2}{(2+n_2^2)} & \frac{(4-n_1^2n_2^2)}{(2+n_1^2)(2+n_2^2)} & \frac{(2n_1^2-2n_2^2)}{(2+n_1^2)(2+n_2^2)} \\ \frac{-2n_1}{(2+n_1^2)} & \frac{2n_2^2}{(2+n_2^2)} & \frac{(2n_1^2-2n_2^2)}{(2+n_1^2)(2+n_2^2)} & \frac{(4-n_1^2n_2^2)}{(2+n_1^2)(2+n_2^2)} \end{bmatrix} \quad (1)$$

$$S_{\text{actualBalun}} = \begin{bmatrix} -0.0753+j0265 & -0.0002 & 0.6502-j0.0446 & -0.6502+j0.0446 \\ -0.0002 & -0.1532+j0.018 & 0.5608-j0.0103 & 0.5608-j0.001\,03 \\ 0.6502-j0.0446 & 0.5608-j0.0103 & 0.1733+j0.0162 & 0.2268-j0.0103 \\ -0.6502+j0.0446 & 0.5608-j0.0103 & 0.2268-j0.0103 & 0.1734+j0.0165 \end{bmatrix} \quad (3)$$

TABLE I
CALIBRATION STANDARDS FOR BALUN CALIBRATION

Schematic	S-matrix	Seen through balun of equation2.	Description
	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	Short between the balanced wires
	$\begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}$	$\begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}$	The two balanced wires shorted to common
	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	All connections open
	$\begin{bmatrix} -1 & 0 \\ 0 & 0 \end{bmatrix}$	$\frac{1}{7}\begin{bmatrix} 3 & 2\sqrt{2} \\ 2\sqrt{2} & 5 \end{bmatrix}$	Right wire loaded with fifty ohms to common, left shorted.
	$\begin{bmatrix} 0 & 0 \\ 0 & -1 \end{bmatrix}$	$\frac{1}{7}\begin{bmatrix} -3 & 2\sqrt{2} \\ 2\sqrt{2} & -5 \end{bmatrix}$	Left wire loaded with fifty ohms to common, right shorted.

do not work [2]. In this paper, the author presents the five loads shown in Table I as a simple easily constructed set of standards that allow the equations to be solved.

Each time a load is placed on the balun, the four complex numbers of the input two-port s-parameters are measured and recorded. After five measurements, a total of 20 numbers have been obtained. The calibration scheme, especially the reduction scheme used to calculate the 16 numbers that constitute the scattering matrix of the actual balun from 20 measured values, is described in the following section. The parameters of the actual balun are found through the calibration process. The response of the actual balun is then mathematically removed from the measurement, and the response of an ideal balun is substituted.

III. Details of the Procedure

After the measurements, the procedure of [2] is followed. This procedure is summarized here. The calibration loads are assumed to be known exactly. The four-port balun is described by a 4 × 4 chain-scattering matrix with 16 entries. The chain-scattering matrix is partitioned into four 2 × 2 submatrices. These 2 × 2 matrices are denoted by T_1, T_2, T_3, and T_4. The chain-s matrix is defined in terms of the balun s-matrix in the following way:

$$\text{Chain} = \begin{bmatrix} T_1 & T_2 \\ T_3 & T_4 \end{bmatrix} = \begin{bmatrix} E_2 - E_1 E_3^{-1} E_4 & E_1 E_3^{-1} \\ -E_3^{-1} E_4 & E_3^{-1} \end{bmatrix} \qquad (4)$$

where the balun s matrix is similarly partitioned, and the 2 × 2 submatrices of the s matrix are denoted by E_1, E_2, E_3, and E_4. The balun s matrix can be derived from the chain-s matrix using the inverse of (4) as follows:

$$S\text{mat} = \begin{bmatrix} E_1 & E_2 \\ E_3 & E_4 \end{bmatrix} = \begin{bmatrix} T_2 T_4^{-1} & T_1 - T_2 T_4^{-1} T_3 \\ T_4^{-1} & -T_4^{-1} T_3 \end{bmatrix}. \qquad (5)$$

Equations for the measurement of a load through a device described by the chain-s parameters are then

$$S_{\text{meas}}(T_3 S_{\text{load}} + T_4) - (T_1 S_{\text{load}} + T_2) = 0. \qquad (6)$$

When (6) is multiplied out, the terms multiplying each of the 16 entries of the chain-s matrix can be gathered in a matrix of known numbers. Each measurement of a two-port load results in four equations in 16 unknowns of the form

$$\begin{matrix} & \longleftarrow 16 \longrightarrow \\ \uparrow & \\ 4 & [\text{Coefficients}] \\ \downarrow & \end{matrix} \begin{bmatrix} t_1 \\ t_2 \\ \cdots \\ t_{16} \end{bmatrix} = 0. \qquad (7)$$

In (7), the coefficients are expressions that contain the entries of S_{meas} and S_{load}. The unknown vector consists of the 16 entries of the chain-s matrix, here denoted as t_1–t_{16}. When (7) is solved, the chain-s matrix is known and, thus, the scattering matrix of the actual balun can be found.

The solution of (7) lies in the null space of the coefficient matrix. After one measurement, four equations are known, after two measurements, eight equations are known, and so on. Theoretically, measurement with four different loads would provide 16 equations in 16 unknowns, and the null space of the coefficient matrix (in this case, a 16 ×16 matrix) would be one dimensional. Therefore, the solution vector $[t_1 \quad t_2 \quad \cdots \quad t_{16}]^t$ would be known up to an arbitrary complex scaling factor. The scaling factor is not absolutely needed to correct the balun measurements from a two-port [2], but is necessary if a system with more than two ports is to be measured (using multiple baluns) or to make a model for the actual balun. In order to find this scale factor, additional information must be used.

Consider the effect of this arbitrary scaling factor on the scattering matrix converted from the chain scattering matrix. As can be seen from (5), the upper left- and lower right-hand-side submatrices of the scattering matrix are not affected by the scalar. However, the upper right-hand-side submatrix is multiplied by the scalar, and the lower left-hand-side submatrix is divided by the scalar. If the scattering matrix represents a reciprocal device, the upper right-hand-side submatrix must be the transpose of the lower left-hand-side submatrix. Let the scale factor, multiplied by the appropriately sized identity matrix for the balun four-port, be $K = k([1_{2\times 2}])$. Setting the upper right-hand-side submatrix $(KT_1 - (KT_2 - (KT_4)^{-1})KT_3)$, equal to the transpose of the lower left-hand-side submatrix $((KT_4)^{-1})^t$, and solving for the scale factor yields (8) as follows:

$$K^2 = k^2\,[1_{2\times 2}] = \left(T_4^{-1}\right)^t \left(T_1 - T_2 T_4^{-1} T_3\right). \qquad (8)$$

Since baluns are reciprocal devices, (8) is applicable to this problem. There are two solutions to (8). The effect of choosing a positive or negative k in (8) is to change the sign of the balun upper right-hand-side s-matrix entries. Thus, choosing one or the other k merely switches the connections to the DUT ports of the balun. It is important to choose the k that keeps the connection consistent as the equations are solved at each frequency.

Although measurements of four two-ports are theoretically sufficient to find the solution to (7), simulations show that five or more are actually needed [2].

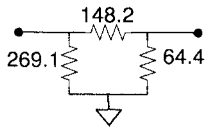


Fig. 4. Equivalent circuit of the test load, as measured with a dc ohmmeter.

Using (7) with measurements of five standards results in a system with more equations than unknowns. An exact solution to the system is not likely. The singular value decomposition can be used to find a least squares solution [6].

After the actual balun scattering matrix is determined, it can be deconvolved from the measurement and an ideal balun substituted. The easiest way to do this is with chain-matrix or scattering chain-matrix representations of the actual and ideal baluns.

IV. Verification of the Procedure

Several companies sell special high-bandwidth highly balanced baluns for use in evaluation of a twisted pair cable and connecting hardware. These baluns have a nearly ideal scattering matrix like the one of (2), and are specified for use from 3 to 300 MHz. To show how the balun calibration procedure works, one of these special baluns was used in measurements from 100 kHz to 1.8 GHz. This was the frequency range of the network analyzer used, and is a bandwidth much larger than the balun bandwidth, as specified for by the manufacturer. The five loads used in the calibration process were constructed using small circuit boards. Shorts were constructed from a small section of wire. The circuit board pads with no connections to them served as opens. For the loads, 603 chip resistors were used.

Five known loads were used to calibrate the baluns. Three test loads were measured with the baluns and then corrected using the calibration data.

V. Results

Typical results of a measurement and calibration process are presented in this section. The test load in this case is a π network of chip resistors. After construction, the π network was measured with an ohmmeter. The resistance across the left-hand-side, right-hand-side, and center terminals measured 118.8, 55.78, and 102.65 Ω, respectively. This indicates that the constructed load can be modeled as shown in Fig. 4.

This load is assumed to be frequency independent. The calculated s-parameters of this load measured through an ideal balun described by (2) are shown in the bottom graph of Fig. 5. This load measured through an ideal balun would have a scattering matrix of

$$S_{\text{mid}} = \begin{bmatrix} -0.0322 & 0.2069 \\ 0.2069 & 0.0630 \end{bmatrix}.$$

The scattering parameters measured through the balun by the network analyzer are shown in the top graph of Fig. 5. The raw reflection coefficient of the loaded balun is around 0.1 (-20 dB) for both the balanced- and common-mode ports. The middle graph of Fig. 5 shows the result of the balun calibration process.

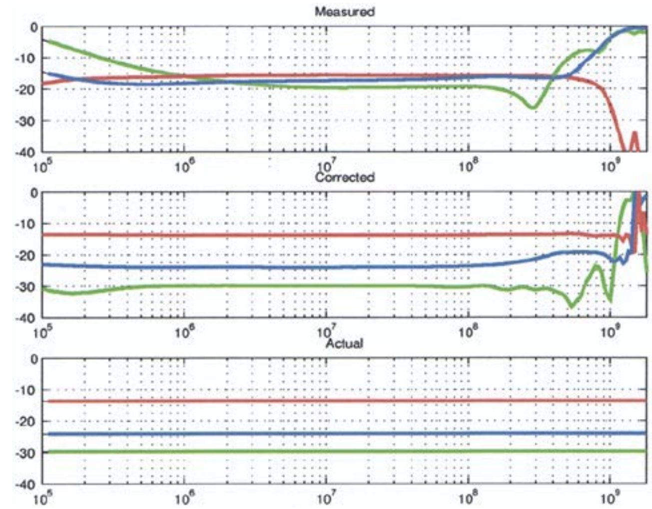


Fig. 5. Three scattering parameters of a two-port resistive load seen through a high-quality balun. The traces are the magnitudes of the balanced reflection coefficient (green), the common mode reflection coefficient (blue), and the balanced- to common-mode conversion factor (red).

At middle frequencies (10.1 MHz), measurements through the balun resulted in

$$S_{\text{meas}} = \begin{bmatrix} -0.0990 + j0.0305 & 0.1637 - j0.0142 \\ 0.1631 - j0.0196 & 0.1338 + j0.0094 \end{bmatrix}.$$

After the correction process, the result is

$$S_{\text{corr}} = \begin{bmatrix} -0.0316 + j0.0005 & 0.2055 - j0.0004 \\ 0.2054 - j0.0002 & 0.0625 + j0.0004 \end{bmatrix}.$$

By using the balun calibration, the useful bandwidth of the measurements is extended, and the return loss of well-matched loads is no longer hidden by the return loss of the baluns.

Similar results were obtained with other test loads.

VI. Summary

By identifying the characteristics of a balun transformer through measuring known loads, a calibration process has been developed to increase the accuracy and bandwidth of balanced- and common-mode measurements. In this paper, it has been shown that the errors in a balun transformer can be calibrated out by measuring five known simple two-port loads and using the results of those measurements to correct measurements of a DUT.

Acknowledgment

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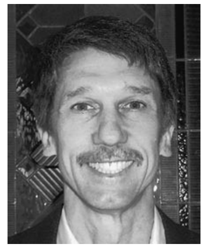

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