Measurements techniques for baluns

A balun consists of an "unbalanced" port and two "balanced ports". The balun is a passive and reversible device. Therefore the "unbalanced" port can be used as either an input or an output; likewise the "balanced" ports can be used as inputs or outputs.

Baluns are also frequently used as impedance-transforming devices. For historical reasons the most commonly used impedances of the "unbalanced" ports are 50 or 75 Ohms and simple transformation ratios of 1:1, 1:2, and 1:4 are widely used. This creates components with impedances in the ranges of 50:50, 50:100 and 50:200 Ohms for 50 Ohm system impedance and 75:75, 75:150 and 75:300 Ohms for 75 Ohm system impedances.

This document discusses some of the issues involving evaluating the performance of general baluns on different types of equipment. The techniques and pitfalls identified are general for all types of baluns and not just for the stripline version described here. There are two basic frequency domain methods and one time-domain method.

The first section describes the preferred method, which enables the user to get full S-parameters of the entire balun. This allows the user to gain significant insight into the performance of all aspects of the balun. Most of the same results can be obtained using the other approaches.

2-ports analyzer techniques

Using a 2-port analyzer to evaluate the performance of a 3-port device involves some switching of cables and performing multiple measurements to gather enough information to perform the calculation to evaluate the true balanced performance.

In the following section the "unbalanced" port is labeled P_1 and the corresponding return loss is labeled S_{11}, consequently return loss measured on the two "balanced" ports (P_2 and P_3) are labeled S_{22} and S_{33}. Furthermore the logical "balanced" port is labeled PD_2 and its corresponding return loss is labeled SD_{22}.

## Return loss measurements using 2-port analyzers

Terminating the "balanced" ports with the correct loads and performing a straightforward return loss measurement on the "unbalanced" port one can evaluate the "unbalanced" return loss.

Evaluating the performance of the "balanced" port requires several measurements and some transformation of single ended S-parameters into balanced. The following equation describes the relationship between the single ended measurements and the balance port measurements.

$$SD_{22} = 20 Log_{10} \left| \frac{1}{2} \left(S_{22}{}^2 + S_{33}{}^2 \right) - \frac{1}{2} \left(S_{23}{}^2 + S_{32}{}^2 \right) \right|$$

Equation 1

Equation 1 transforms the 2 sets of single ended return loss measurements combined with insertion loss measurements into balanced port impedance. Complex values of all the S-parameters must be
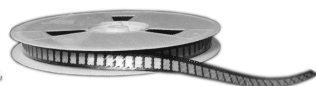
used to make the equation valid, and is to be used with data that has been deembedded and renormalized to the goal impedances.

Due to the way the baluns works (any balun, both Flux coupled and stripline version) one will find 6 dB worth of return loss measured singled ended onto either port 2 or port 3 of any balun.
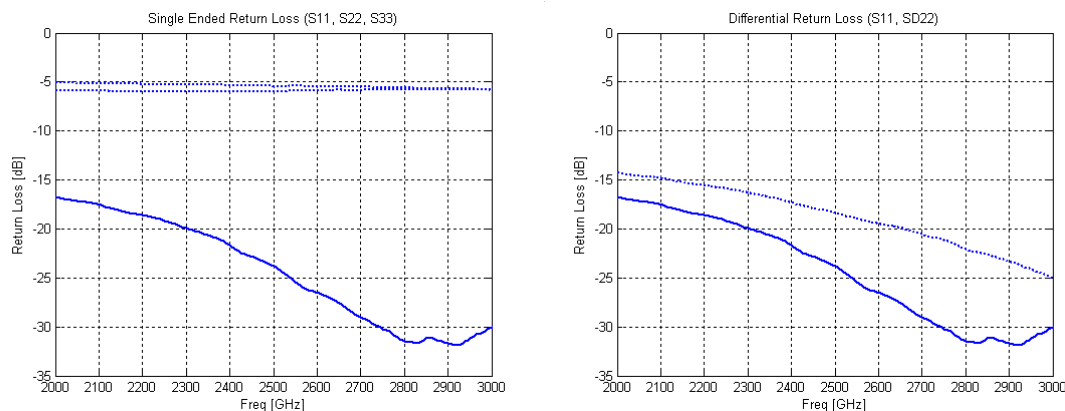

Figure 1 (left) Return loss of balun measured as a 3 ports device. (right) Return loss of balun measured as logical 2-port device.

Figure 1 shows the return loss of a typical balun depicted in both single ended and differential modes. Combining the measurements of S_{22} and S_{33} from Figure 1(left) with measurements of S_{23} and S_{32} using Equation 1 the differential mode return loss will be as shown in Figure 1(right)

Phase and amplitude measurements using a 2-port analyzer

To evaluate the phase and amplitude balance of a balun it is important to note that the system, in which it is measured, must be repeatable to within the tolerance of which the measurements are required.

So if a mechanical switch is employed to connect between the two differential ports and the analyzer it has to be repeatable enough not perturb the results. Likewise, if a simple approach of manually unhooking and re-hooking coaxial lines, good RF-measurements techniques should be followed.

Amplitude and phase balance is evaluated using the following equation:

$$AB = 20Log_{10}\left|\frac{S_{31}}{S_{21}}\right| \qquad\qquad Equation\ 2$$

$$PB = ang\left(\frac{S_{31}}{S_{21}}\right) \qquad\qquad Equation\ 3$$

It should be noted that if the parameters are used in the reverse order the results are still correct, but the balance will have an opposite sign. However, in most case the user is only interested in the absolute value and therefore the sign is of no importance.

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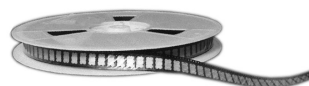
Back-to-Back measurements

This technique involves mounting two identical units in a Back-to-Back configuration. This enables the user to evaluate the insertion loss of both units in series and calculate the loss by dividing the results by 2. The drawback in evaluating the insertion loss of baluns in this manor is that balun #1 is used to match into balun #2 and assuming good production tolerances the result will become "too" good.

More representative insertion loss measurements are based on adding the measurements of S21 and S31 after each of the measurements have been deembedded and renormalized to the target impedances.

$$IL_{power} = 20Log_{10}\left(\left|S_{12}\right|^2 + \left|S_{13}\right|^2\right)$$

Equation 4

Equation 4 is used to determine the insertion loss of a balun. Equation 4 only looks at the transmitted energy and therefore the insertion loss due to miss-matched ports is accounted for.

However Equation 4 does not take into account insertion loss due to non-ideal phase and amplitude balance of the device, it evaluates the transmitted power from input of the balun to the 2 balanced outputs. This approach does not tell how well the energy got transformed into a balanced signal. However Equation 8(a-d) part (a) takes phase and amplitude into account.

$$IL_{1d} = 20\log_{10}\left|S_{1d}\right| = 20\log_{10}\left|\frac{1}{\sqrt{2}}(S_{12} - S_{13})\right|$$
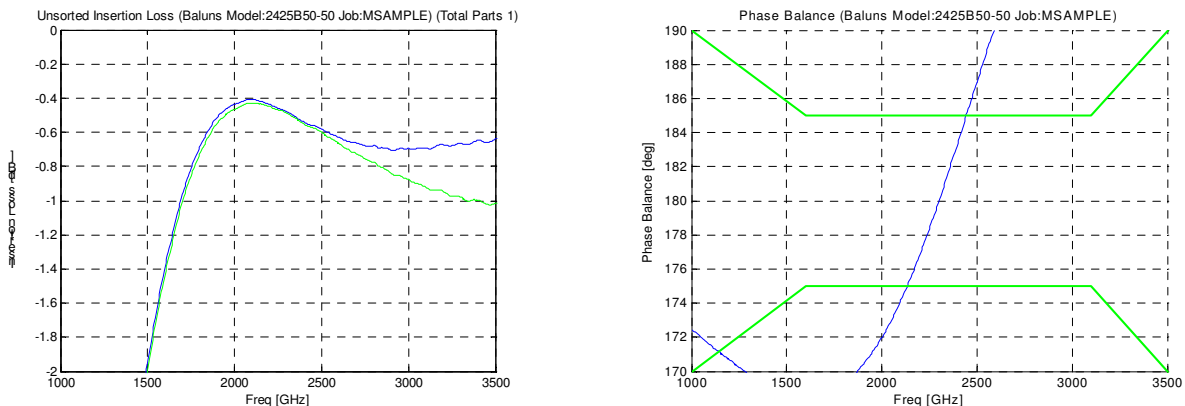
Equation 5

Figure 2 (left) Shows the insertion loss difference for a balun measured using the "power" approach (blue) versus the "balanced" approach (green). Note that the balanced approach will asymptotically approach that power approach, but never exceed. (right) Iindicates the phase performance of the unit used in the example.

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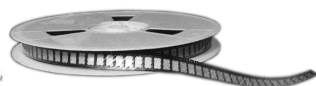
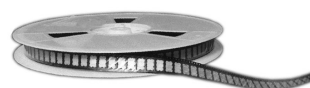### Evaluating balun performance of non 50 Ohm units

The technique of deembedding is a significant obstacle in evaluating the actual performance of any microwave system. For microwave devices like baluns, the test board must be deembedded correctly to achieve correct S-parameters when performing a renormalization of the port impedances.

If the impedance or line lengths are incorrect in the deembed files, the performance measured could differ significantly from the performance of the part in an actual system. Here is a list of parameters that are directly affected by the deembed files:

1. For the phase and amplitude balance results to be correct, the deembed files have to represent the test board used within the accuracy of the test being performed.
2. For the return loss to be correct the correct length of the test board is crucial or the consequent renormalization will fail.
3. For overall insertion loss both the length and insertion loss of the test board is important to know accurately.

In the following we will outline a couple of popular approaches to obtain deembedded and renormalized data.

1. Using a ENA (or equivalent) multi port (3 or more) analyzer to perform the measurements and post-measurement deembedding and renormalization.
    a. Setup ENA to measure baluns.
    b. Upload provided deembed files to ENA
    c. If necessary enable deembedding to obtain the correct impedances.

2. Using Linear Simulators
    a. Take measurements using a 2 or more port analyzer.
    b. Load data into a linear simulator.
    c. Apply a "Negative" S2P file block (Genesis) with provided deembed files.
    d. If necessary change the port impedances to trigger a deembedding to obtain the correct impedances.

3. Using Matlab
    a. Take measurements using a 2 or more port analyzer.
    b. Load data into Matlab
    c. Apply deembed files using the Matlab code included in Appendix C
    d. If necessary change the port impedances by using included code in appendix B

Refer to table in below to correlate actual test boards to deemed files.

	Test Boards	Deembed Files	
	Nominal Test Board	Unbalanced Side (Input)	Balanced Side (Output)
1515 Baluns	58148-G001 (Green)	DeShort_FB537.s2p	DeLong_FB537.s2p
0805 Baluns	58982-0002 (0805 inverted)	DeEm58982-0002All.s2p	DeEm58982-0002All.s2p
	58982-0003 (0805 Alt. inverted)	Call Factory	Call Factory
	58982-0005 (0805 Combiner)	Call Factory	Call Factory
	58982-0006 (0805 Marshan, Gold)	58982-6-P1.s2p	58982-6-P23.s2p
	58310-G001 (0805 Marchan Green)	DeShort.s2p	DeLong.s2p
	58982-0050 (0805 Marshan, Gold)	58982-6-P1.s2p	58982-6-P23.s2p
0603 Balun	59503-0001 (0603 Standard)	MR59503-0011-DE1.s2p	MR59503-0011-DE23.s2p
	59503-0002 (0603 DC)	MR59503-0011-DE1.s2p	MR59503-0011-DE23.s2p
0603 X-ov	59503-0007 (0603 X-Over) 4port	Mr59503-0016-DE2.s2p	Mr59503-0016-DE5.s2p
	59503-0004 (0603 X-Over) 6 port	Mr59503-0016-DE2.s2p	Mr59503-0016-DE5.s2p
		Mr59503-0016-DE3.s2p	Mr59503-0016-DE6.s2p
1008 Filter balun	2425B50-50E (Green)	0.24dB @ 2450MHz	none
	2425B50-50E (Gold)	0.31dB @ 2450MHz	none

Figure 3 Cross-reference list for Anaren Consumer Components Test boards and deembed files to use.

If any problems occur in trying to perform deembedding do not hesitate to call or E-mail the factory.

Common Mode Rejection Ratios

Common Mode Rejection Ratio is a commonly used figure of merit used to describe the performance of balanced circuits, but depending on what industry the particular designer is coming from the measure could be known as; "Common Mode Attenuation", "Common Mode Filtering" and a host of other names.

Common Mode Rejection Ratio is defined and the ratio between the differential mode insertion loss/gain versus the common mode signal loss or gain.

$$CMRR = \frac{S_{1c}}{S_{1d}}$$

Equation 6

Most network analyzers are currently single-ended, but many of the newer test sets have mixed mode capabilities that have been implemented in software based on a set of linear equations. From the literature[1] a set of linear equation describing the transformation from single-ended 3 port parameters to a mixed mode 2 port, where port 1 is a single ended port and port is differential can be obtained.

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[1] D. E. Bockelman and W. R. Eisenstadt, "Combined differential and common mode scattering parameters: Theory and simulation," IEEE Trans. On Microwave Theory and Tech, vol. MTT-43, July 1995, pp. 1530-1539.

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Equation 7 shows a typical single-ended S-parameter, where [A] is the stimulus and [B] is the response to the [S] parameter matrix. On the right is a mixed mode representation of the same matrix, by ports 2 and 3 have been combined to form a differential mode port.

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} \Leftrightarrow \begin{bmatrix} b_1 \\ b_d \\ b_c \end{bmatrix} = \begin{bmatrix} S_{11} & S_{1d} & S_{1c} \\ S_{c1} & S_{dd} & S_{dc} \\ S_{d1} & S_{cd} & S_{cc} \end{bmatrix} \begin{bmatrix} a_1 \\ a_d \\ a_c \end{bmatrix}$$

Equation 7

It can be shown that the transformation from mixed mode to single ended mode can be performed using the Equation 2 and 3. The significance of each of the mixed mode parameters will be described as the transformation sets are presenting in the following section.

In the mixed mode formulation S_{11} is equivalent to the single ended formation The remaining parameters are compound performance parameters.

The two most common mixed mode parameters are S_{c1} and S_{d1} with there respective reverse; S_{1c} and S_{1d}. S_{1d} and S_{d1} is the transmission parameters from port 1 to the mixed mode port while evaluating the mixed ports as a differential port. S_{1c} and S_{c1} is the mixed mode transmission parameters from port 1 to the mixed mode port while evaluating the port as a common mode port.

$$S_{1d} = \frac{1}{\sqrt{2}}(S_{12} - S_{13}) \text{ [a]} \qquad S_{d1} = \frac{1}{\sqrt{2}}(S_{21} - S_{31}) \text{ [b]}$$

$$S_{1c} = \frac{1}{\sqrt{2}}(S_{12} + S_{13}) \text{ [c]} \qquad S_{c1} = \frac{1}{\sqrt{2}}(S_{21} + S_{31}) \text{ [d]}$$
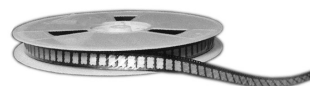
Equation 8(a-d)

The return loss performance of the mixed port is evaluated by S_{dd} and S_{cc}. S_{dd} gives the differential return loss, while S_{cc} gives the common mode return loss. The last two parameters S_{cd} and S_{dc} gives transmission parameters from common to differential mode signals.

$$S_{dd} = \frac{1}{2}(S_{22} - S_{23} - S_{32} + S_{33}) \quad S_{dc} = \frac{1}{2}(S_{22} + S_{23} - S_{32} - S_{33})$$

$$S_{cc} = \frac{1}{2}(S_{22} + S_{23} + S_{32} + S_{33}) \quad S_{cd} = \frac{1}{2}(S_{22} - S_{23} + S_{32} - S_{33})$$

Equation 9

With these transformations we can now evaluate CMRR from Equation 9. CMRR is a simply the relationship between differential mode insertion parameters and common mode insertion parameters. Put into different terms, CMRR gives the difference between common mode and differential mode insertion loss.

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CMRR can be abbreviated to the following set of single ended parameters.

$$CMRR = \frac{S_{1c}}{S_{1d}} \Leftrightarrow \frac{\frac{1}{\sqrt{2}}\left(S_{12} + S_{13}\right)}{\frac{1}{\sqrt{2}}\left(S_{12} - S_{13}\right)} \Leftrightarrow \frac{S_{12} + S_{13}}{S_{12} - S_{13}}$$

Equation 10

A Matlab® script was developed to fill up a 100x100 array of S-parameters with varying amplitude and phase error between S_{12} and S_{13}. The Common Mode rejection ratio is the calculated on the entire array and plotted using a contour plot function in Matlab®. The result can be seen in figure 1.

The conclusion of the analysis is that tradeoffs can be made of amplitude balance versus phase balance and still achieve the same system performance in regards to CMRR. Figure 1 can guide the user as to what parameters are acceptable for a given system architecture and overall system considerations.

Furthermore it can be seen from Equation 10 that there is no direct relationship between. However this does not mean that there is no correlation of input and output match to CMRR. There are secondary effects of how well a given design is grounded, and by varying the reference impedances the ground reference could/will move accordingly.
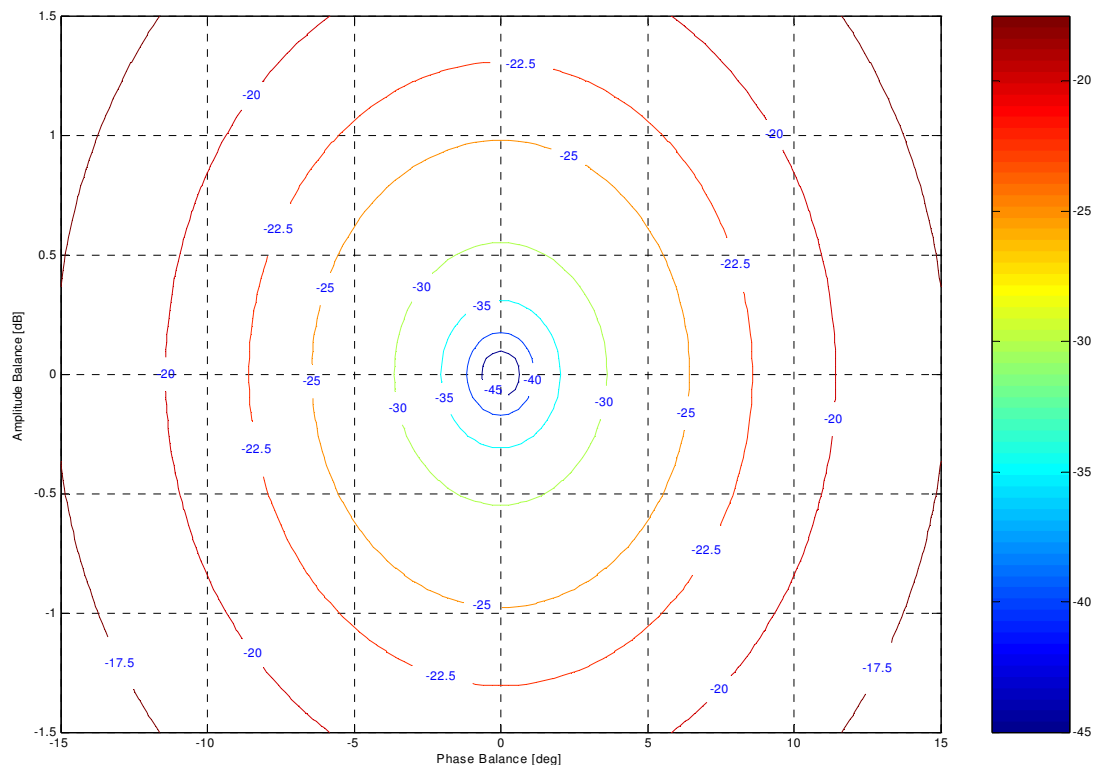
Figure 4 Contour plot of Common Mode Rejection values for common values of phase and amplitude error for balanced circuits. Each of the concentric ovals represent equal values of Common Mode Rejection (CMRR), the values are depicted in [dB].

Multi-ports analyzer techniques

Multi-port analyzers have made the evaluation of balun significantly easier, but still not without pitfalls. When evaluating the overall performance of a balun one can look at the balun as either a 3 ports device or a logical 2-port device, where one of the ports is balanced. The results that the analyzer will present are significantly different and will be covered in the following section.

Evaluating the performance of a balun as 3 port device

On a multi-port analyzer this is a straightforward technique, which gives full S-parameters of the balun. Each of the measurements must be combined in the same fashion as described in the previous section. All the same discussions apply and the same equations should be used to evaluate performance parameters.

Evaluating the performance of a balun as logical 2-port device

Many of the newer Agilents multiport Network analyzer models have the capabilities to make balanced measurement by transforming the analyzer from a 3-port network analyzer into a 2-port analyzer with one or two balanced ports. The transformations described in the previous section are
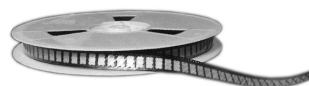
now done in firmware. This approach lets the user set up any type of measurements of the balun and evaluate the actual performance of the circuit in real-time on the screen of the analyzer.

Evaluating balun performance of non 50 Ohm units

The discussion about deembedding from the previous sections is also important for 3-port analyzers and will not be discussed any further here.

Time Domain techniques

Anaren does not use the time Domain technique very often, but some customers in their evaluations have employed it.

A part was tested using a 2.4 GHz source, driving an equal split power divider. One of the power divider outputs was connected to the trigger and the other was used to drive the balun circuit (mounted on the test board). The two outputs of the balun (two terminals of the differential port) were then connected to the two oscilloscope channels via phase and amplitude matched cables.

This technique is capable to get an indication of phase and amplitude balance, but this technique is not capable of measuring the return loss performance. Likewise, evaluating the insertion loss is cumbersome and potentially inaccurate.

The following figure shows actual measurements performed on a 2.45 GHz balun in a 50 Ohm system.
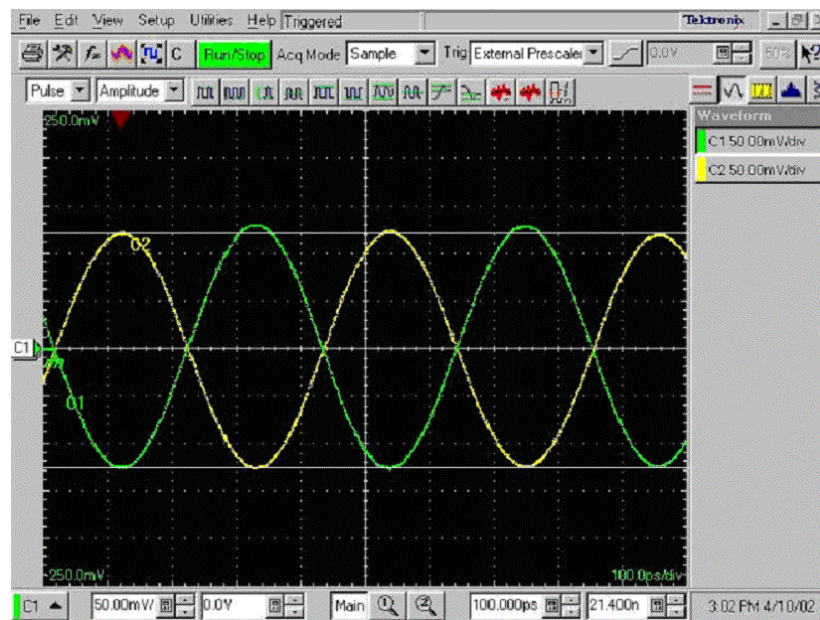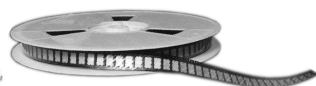

Figure 5 Time domain data taken on a Tektronix 20GS/s oscilloscope.

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Appendix A

Matlab Script to generate to CMRR plot show in Figure 4

```matlab
% Clear all registers, variables and graphs
cla;
clear;

% Set maximum phase and amplitude error to evaluate
PE = 15;
AE = 1.5;

% Generate two array with phase and amplitude error data for S12
amp_error = 0.5-(10^(AE/20)*0.5);
amp_S12 = (0.5-amp_error):(2*amp_error)/100:(0.5+amp_error);
phase_S12 = -PE:(2*PE)/100:PE;

% Generate 100x100 matrix of S-parameters describing phase
% and amplitude error as set up by the variables PE and AE
SS12 = amp_S12'*cos(phase_S12*pi/180)+j*amp_S12'*sin(phase_S12*pi/180);

% Generate two arrays with "Perfect" phase and amplitude data for S13
amp_S13 = 0.5*ones(1,101);
phase_S13 =180*ones(1,101);

% Generate 100x100 matrix of S-parameters all having perfect phase
% and amplitude
SS13 = amp_S13'*cos(phase_S13*pi/180)+j*amp_S13'*sin(phase_S13*pi/180);

% Calculate the Common Mode Rejection Matrix
CMRR = (SS12+SS13)./(SS12-SS13);

% Convert to dB and make sure that the middle value gets deleted for
% graphing reasons.
CMRR_db = 20*log10(abs(CMRR));
CMRR_db(51,51) = -50;

% Set up contour lines
cc_lines = [-45 -40 -35 -30 -25 -22.5 -20 -17.5 -15];

% Plot definitions
figure(1)
[c,h] = contour(phase_S12,20*log10(0.5./amp_S12),CMRR_db,cc_lines);
colorbar;
axis([-15 15 -1.5 1.5]);
grid on;
clabel(c,h,'fontsize',10,'color','b','rotation',0);
xlabel('Phase Balance [deg]')
ylabel('Amplitude Balance [dB]')
```
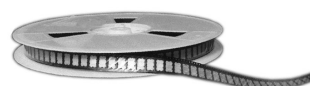
Appendix B

Matlab Script to renormalize port impedances in Matlab. This script will renormalize a 3-port s-parameter network into different impedances. The algorithm could quickly be expanded to include other than 3 ports.

```matlab
% Renormalize Ports
    for nn = 1:Numpts

        % Load the S matrix with S-parameter data, all values are in Real and Imaginary
        S = [[S11(nn) S12(nn) S13(nn)],
             S21(nn) S22(nn) S23(nn)],
             [S31(nn) S32(nn) S33(nn)]];

        % Load the Zr matrix with values for resulting port impedances both Real and Imaginary
        Zr = [[RenormP1 0 0]
            [0 RenormP2 0]
            [0 0 RenormP3]];

        % Assuming initial impedance of 50Ohm for all ports
        I = eye(ports);
        Zo = 50*I;

        % Renormalizing algorithm
        Zn = sqrt(Zo)*inv(I-S)*(I+S)*sqrt(Zo);
        Sn = sqrt(inv(Zr)) * (Zn-Zr) * inv(Zn+Zr) * sqrt(Zr);

        % Unload S Matrix back into individual S-parameters arrays of Real and Imaginary
        S11(nn) = Sn(1,1);
        S12(nn) = Sn(1,2);
        S13(nn) = Sn(1,3);
        S21(nn) = Sn(2,1);
        S22(nn) = Sn(2,2);
        S23(nn) = Sn(2,3);
        S31(nn) = Sn(3,1);
        S32(nn) = Sn(3,2);
        S33(nn) = Sn(3,3);
    end
```

Appendix C

```matlab
% MD contains Measured data in Matrix format (Real and Imaginary)
% L contains LEFT hand side s-parameter file in Matrix format (Real and
% Imaginary)
% R contains RIGHT hand side s-parameter file in Matrix format (Real and
% Imaginary)

% Resulting file will be D, which will contain a deembedded s-parameter file
% in Matrix format (Real and Imaginary)

    I_i   =  MD(2,2)*R(2,2)-delta_R;
    I(1,1) = (R(2,2)*s2delta(MD)-MD(1,1)*delta_R)/I_i;
    I(1,2) = (MD(1,2)*R(1,2))/I_i;
    I(2,1) = (MD(2,1)*R(2,1))/I_i;
    I(2,2) = (MD(2,2)-R(1,1))/I_i;

    D_d   =  L(2,2)*I(1,1)-delta_L;
    D(1,1) = (I(1,1)-L(1,1))/D_d;
    D(1,2) = (I(1,2)*L(2,1))/D_d;
    D(2,1) = (I(2,1)*L(1,2))/D_d;
    D(2,2) = (L(2,2)*s2delta(I)-I(2,2)*delta_L)/D_d;

% Finds delta_S og 2x2 S matrix
function [delta] = s2delta(S);
delta = S(1,1)*S(2,2)-S(1,2)*S(2,1);
```

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