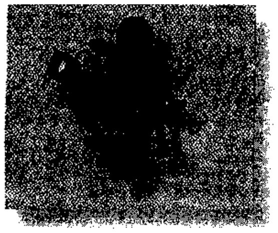

Application Notes

Microwave Connector Characterization

■ **Mark A. Goodberlet and James B. Mead**

Coaxial connectors can be used either to probe the electrical properties of microwave circuits (e.g., microstrip, stripline) or as a permanent interface to the circuit. When used as a permanent interface, connectors can degrade circuit performance unless their electrical properties are characterized and accounted for during circuit design. A convenient way to characterize connectors is with the circuit model shown in Figure 1, which utilizes impedance parameters [1] Z_{ij}, described by

$$Z_{ij} = \frac{V_i}{I_j} \text{ for } (I_k = 0,\ k \neq j), \tag{1}$$

where V_i and I_j are voltages and currents with conventional directions as shown in Figure 1. Although it is more common to characterize microwave devices using scattering parameters [1] S_{ij}, we have chosen to utilize impedance parameters since they simplify the derivation of equations presented in this article. Conversion between these parameter types is straightforward [2]. Note that the Z_{ij} have real and imaginary parts, both of which are functions of microwave frequency, and that the Figure 1 representation is valid only for reciprocal (i.e., $Z_{12} = Z_{21}$) devices [1], such as connectors.

Conventional methods of obtaining Z_{ij} for a connector include use of a three-dimensional (3-D) electromagnetic simulator [3], fitting measured data to simple-circuit approximations of the connector [4], [5], and generalized deembedding (two-tier calibration) [6], [7]; all of which are typically more complicated or costly to implement than the method described in the following.

The proposed measurement-based method for connector characterization is exact in the sense that its theoretical foundation uses no approximations or assumptions. Implementation of the method begins with construction of simple microwave networks, each consisting of a transmission line (T-line) terminated at both ends by the connector. Using the Figure 1 circuit topology to represent both the connectors and the T-line results in the Figure 2 representation for the network, where

$$A = Z_{11} - Z_{21} \text{ (connector Z-parameters)}, \tag{2}$$

$$B = Z_{22} - Z_{21} \text{ (connector Z-parameters)}, \tag{3}$$

$$C = Z_{21} \text{ (connector Z-parameters)}, \tag{4}$$

$$E = Z_{11} - Z_{21} \text{ (T-line Z-parameters)}, \tag{5}$$

$$F = Z_{21} \text{ (T-line Z-parameters)}. \tag{6}$$

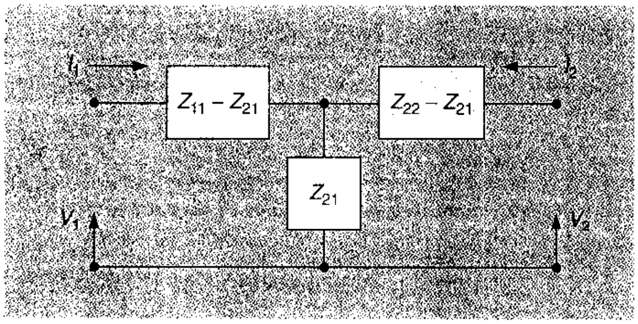

Figure 1. *Equivalent circuit representation for reciprocal two-port device.*

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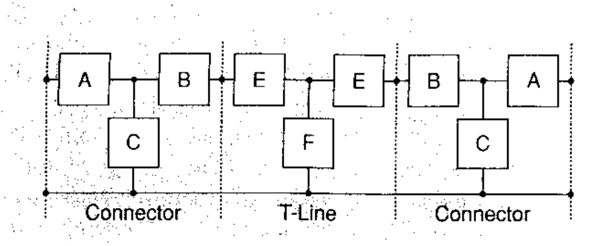

Figure 2. *Connector characterization network representation.*

Closed-form expressions relating the network Z-parameters to the connector parameters (A, B, C) are derived in the following. These expressions, together with actual measurements of the network Z-parameters, comprise a system of equations from which a solution for (A, B, C) is possible.

Theoretical Foundation

Derivation of expressions that relate network Z-parameters to connector Z-parameters begins with the following observations about Figure 2:

1) Since an ideal T-line is both reciprocal and symmetric ($Z_{11} = Z_{22}$), it follows from Figure 1 that only two unique impedance blocks, (E and F), are needed to model the T-line.
2) The Z-parameters of the T-line can be accurately calculated from theory [8].
3) Since the entire network is both reciprocal and symmetric, it can be represented by the equivalent circuit shown in Figure 3 where

$$J = Z_{11} - Z_{21} \text{ (network Z-parameters)} \tag{7}$$

$$K = Z_{21} \qquad \text{(network Z-parameters)}. \tag{8}$$

Applying (1) to the Figure 2 circuit results in expressions for J and K that are functions of the connector parameters (A, B, C). These expressions, together with measurements of J and K, comprise a system of two equations in the three unknowns, (A, B, C). A unique solution for (A, B, C) requires a third equation, which can be formed using measurements of a second network. This second network must be different from the first, and this difference can be achieved by simply using a different length of T-line. Henceforth, these two networks will be referred to as #1 and #2. Solutions for (A, B, C) derived in this manner can be written as follows:

$$C = \pm\left\{\frac{-Y}{2X} \pm \left[\left(\frac{Y}{2X}\right)^2 + \frac{Z}{X}\right]^{0.5}\right\}^{0.5}, \tag{9}$$

$$B = -(F_1 + E_1 + C) \pm \left[F_1^2 + \frac{F_1 C^2}{K_1}\right]^{0.5}, \tag{10}$$

$$A = J_1 - \frac{C\,(B + E_1)}{B + E_1 + C}, \tag{11}$$

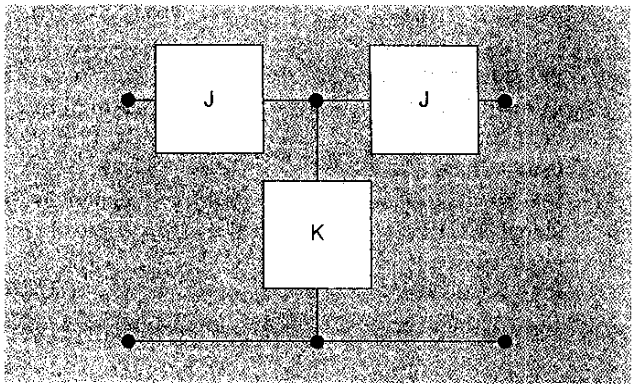

Figure 3. *Two-port representation of the Figure 2 network.*

where the subscripts on E, F, J, and K identify the network, and

$$P = (F_2 - F_1) + (E_2 - E_1), \tag{12}$$

$$Q = \left(P^2 - F_1^2 - F_2^2\right)/2, \tag{13}$$

$$R = \frac{F_1}{2\,K_1} + \frac{F_2}{2\,K_2}, \tag{14}$$

$$S = \frac{F_1\,F_2}{K_1\,K_2}, \tag{15}$$

$$X = S - R^2, \tag{16}$$

$$Y = S\,(F_1\,K_1 + F_2\,K_2) + 2\,Q\,R, \tag{17}$$

$$Z = Q^2 - (F_1\,F_2)^2. \tag{18}$$

The ± operations in (9) and (10) will generate a set of eight solutions for (A, B, C). Selecting the appropriate solution and other steps of the connector characterization procedure are discussed next.

Experimental Method

Experimental aspects of the proposed connector characterization procedure are:

1) Design and construct two connector characterization networks of the type shown in Figure 2; each with a different length T-line. The T-line impedance (i.e., width) should be the same as that used on the circuit board targeted for connector use.
2) Define the connector phase-reference planes. The phase-reference plane for the coax-side of most connectors is standard [9]. However, location of the phase-reference plane for the board-side of the connector is somewhat arbitrary (see the connector characterization example in the following for our recommended location).
3) Use equations described elsewhere [8] to calculate Z-parameters for the T-line in network #1 and convert them to values of (E_1, F_1) using (5) and (6). Similarly, calculate (E_2, F_2) for the T-line in network #2.
4) Measure S-parameters (magnitude and phase) for each network.
5) Insure that the S-parameters measured in 4) are both reciprocal and symmetric by setting $S_{12} = S_{21}$ and $S_{22} = S_{11}$. Alternatively, set $S_{22} = S_{11} = (S_{11} + S_{22})/2$

and $S_{12} = S_{21} = (S_{12} + S_{21})/2$, which may have the added benefit of improving solution accuracy by reducing measurement noise.

6) Convert S-parameters that were calculated in 5) to Z-parameters and then to values of (J_1, K_1) and (J_2, K_2) using (7) and (8).
7) Use values of (E_1, F_1) and (E_2, F_2) calculated in 3) along with (J_1, K_1) and K_2 from 6) in (9)–(18) to obtain eight solutions for (A, B, C).
8) Convert values of (A, B, C) computed in 7) to Z-parameters using (2)–(4), resulting in eight characterization solutions for the connector.
9) Identify the correct solution using the selection methods discussed in the following section.
10) Repeat steps 3–9 for each measurement frequency.

Solution Selection

For the most part, the correct solution for the connector Z-parameters can be identified from the eight possible solutions discussed previously by enforcing conservation of power for a passive two-port device [1].

$$|S_{11}|^2 + |S_{21}|^2 < 1, \tag{19}$$

$$|S_{22}|^2 + |S_{12}|^2 < 1, \tag{20}$$

where the complex number operation, $|\cdot|^2$, is magnitude squared. The additional needed selection criteria are discussed next.

TABLE 1. Microwave circuit board specifications.

Board material	Rogers Corporation, RT-5880
Substrate thickness	0.51 mm
Substrate dielectric constant	2.20 +/- 0.02
Substrate dissipation factor	0.0009
Copper cladding thickness	0.018 mm (1/2 oz)

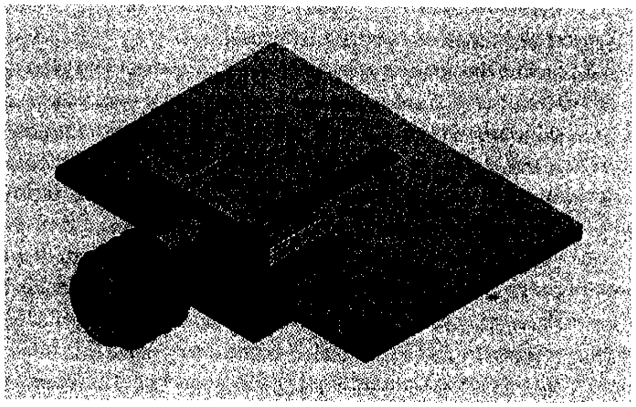

Figure 4. *Connector #140-0701-881 (gold) attached to microwave circuit board (gray). Also shown are a circuit trace and connector mounting pads, both etched from top-side copper (green) on the board.*

In general, the eight connector solutions can be organized into four pairs. The solutions in any particular pair differ only by the sign of Z_{21} or equivalently, by a 180° difference in through-phase $\angle S_{21}$. Tests (19) and (20) will generally eliminate only three of the four solution pairs. The reason that a solution-pair rather than a single solution remains after the tests is explained as follows. Microwave measurement and analysis typically confines $\angle S_{21}$ for any device to the range $[-180°, +180°]$. With this restriction in mind, note that the through-phase of the Figure 2 network is unchanged if the through-phase for each connector is changed by 180°. It is therefore a fundamental limitation of our method that connector through-phase will be determined with an ambiguity of 180° (i.e., the method produces two characterizations for the connector). In many applications, this ambiguity is irrelevant. However, the large size of the ambiguity should make it easy to select the correct solution when $\angle S_{21}$ does matter.

The solution pairs for the connector can be numbered (e.g., 1–4). However, one cannot expect that the pair containing the correct solution will always correspond to a specific numbered pair. Generally, one should use tests (19) and (20) to select the solution pair instead of trying to identify a selection pattern based on solution pair numbering. If solutions at multiple frequencies are to be calculated, then enforcing continuity of $\angle S_{21}$ from frequency-to-frequency helps identify the one correct solution. An exception to this continuous through-phase test is when $\angle S_{21}$ jumps by 360° as a result of the conventional $[-180°, +180°]$ limitation for expressing $\angle S_{21}$.

Our experience indicates that occasionally, (for ~10% of solutions) the tests in (19) and (20) will eliminate only two of the four solution pairs. A third solution pair can usually be eliminated by imposing a lower limit, in addition to the current upper limit, for tests (19) and (20). This new restriction sets a lower limit for the absorptive loss of the connector and values of about 1 dB (0.8 linear) have worked well.

On occasion, tests (19) and (20) will eliminate all four solution pairs. This is usually a sign that either 1) the laboratory measurements of the Figure 2 networks are insufficiently accurate or 2) insufficient care was used to assemble the networks (e.g., connectors not consistently soldered to the board). The former problem requires recalibration of the laboratory test equipment. The latter problem can be partially corrected by the actions described in step 5) of the experimental method. However, every effort should be made to attach connectors to the circuit board in a consistent manner. Construction and use of several characterization networks is also good practice, both as a cross-check of results and because some networks may provide more accurate solutions at specific frequencies than others.

Connector Characterization Example

The board-edge SMA connector, part# 142-0701-881, made by Johnson Components Inc., Waseca, Minnesota, was used to interface with 16-GHz microstrip circuitry on a board described by Table 1. Connector attachment to the board is described by Figures 4 and 5, which show copper

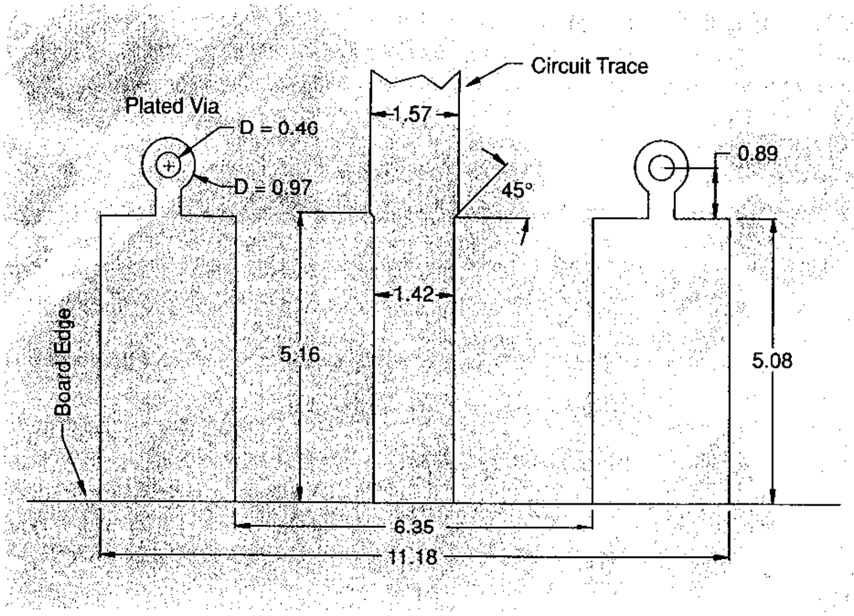

Figure 5. *Top view of circuit board showing circuit trace and connector mounting pads (dimensions in mm).*

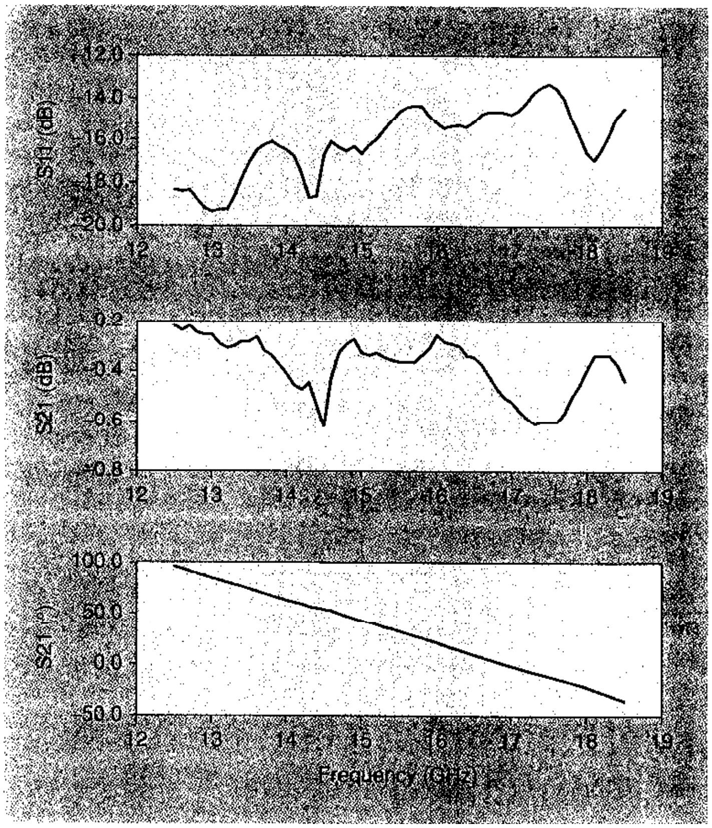

Figure 6. *Derived S-parameters for connector 142-0701-881.*

pads on the top side (circuit side) of the board to which the connector housing is soldered. The connector housing is also soldered to the copper ground plane on the bottom side of the board. Dimensions of the connector pads are those recommended by Johnson Components for this connector and board thickness. The phase-reference plane for the board side of the connector was chosen to be 5.16 mm from the board edge (see Figure 5), because this is where the microstrip trace with 1.57 mm width and 50 Ω impedance begins. T-lines used in the Figure 2 characterization networks were also 50 Ω and were chosen (somewhat arbitrarily) to have lengths of 44.09 mm and 40.77 mm.

Characterization of connector #142-0701-881 on the RT5880 board was performed using the experimental method described previously. Resulting S-parameters over the frequency range of 12.5–18.5 GHz are shown in Figure 6.

Conclusions

The concepts discussed in this paper are closely related to the topic of deembedding [6]. However, the usual focus of deembedding is to measure electrical properties of a device-under-test (DUT); the connectors/ probes being simply an interface mechanism that can add error to the DUT measurement process. As such, some deembedding techniques do not explicitly characterize the connectors/probes and instead simply remove or calibrate out their effects [7]. Another feature that distinguishes our method from typical deembedding is that it utilizes two-port rather than one-port measurements. Classical one-port deembedding [6], [7] requires use of three calibration loads, which are typically a short, open, and resistive (50 Ω) termination. When these loads must be implemented using microstrip or stripline, their electrical characterization is difficult, which in turn makes accurate deembedding difficult. In comparison, our proposed method utilizes T-line sections instead of loads whose construction and characterization seem far easier and more accurate. Furthermore, the fact that our characterization network (see Figure 2) consists of two back-to-back connectors suggests some redundancy of measurement, which has been shown to reduce error [6].

One deembedding method [10] utilizes multiple T-lines in a manner similar to that proposed in this article, however, use of this method is restricted by certain simplifying assumptions (e.g., $Z_{11} = Z_{22}$). In this regard, it is noted that our proposed connector characterization method can be simplified to use only one T-line network instead of two when assuming $Z_{11} = Z_{22}$ for the connector. However, as originally presented, our method does not utilize simplifying assumptions.

In summary, a measurement-based method for characterizing microwave connectors used in board-to-coax interfaces has been presented. Implementation is straightforward, and closed form calculations lead to rapid computation of the results. One should bear in mind that a connector characterization is typically valid only for a specific board type, board thickness, circuit trace width, and connector mounting pad geometry. When any of these factors change, a new connector characterization experiment must be performed.

Acknowledgments

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