THRU-MATCH-SHORT CALIBRATION FOR TIME DOMAIN NETWORK ANALYSIS

L.A. Hayden and V.K. Tripathi

Dept. of Electrical and Computer Engineering
Oregon State University, Corvallis, OR 97331

Abstract

A technique for obtaining corrected two-port network parameters from Time Domain Reflection/Transmission (TDR/T) measurements is described. This method is based on the Thru-Match-Short (TMS) calibration procedure and allows for the extension of general Vector Network Analysis (VNA) techniques to the correction of time domain measurements.

Introduction

While frequency domain vector network analysis has become a sophisticated measurement technique, characterization of networks in the time domain has been slow to gain wide acceptance. Error correction techniques such as the TRL method [1], the LRL method [2], and the other methods encompassed by the generalized theory of Eul and Schiek [3] have greatly refined VNA accuracy and capabilities. Time Domain Network Analysis (TDNA) has been proposed over the last few decades [4-7] but the calibration techniques rely on long matched transmission lines to isolate the device under test (d.u.t.) with windowing of the portion of the response due to the d.u.t. interacting solely with these 'window' lines, see fig. 1.

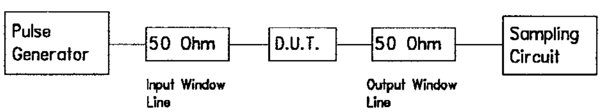

Fig. 1. Previously published calibration techniques used 50 ohm 'window' lines to isolate the D.U.T.

Previous efforts in TDNA predated the more sophisticated TDR systems that have recently become available. These systems use equivalent time sampling and have bandwidths that begin to rival VNA systems. Recent work with non-linear transmission line based samplers [8] has obtained 150 GHz TDR bandwidth. TDNA has unique characteristics that are useful particularly as frequencies increase. The microwave portion of the sampling head can be located remotely from the remainder of the system with only low frequency interconnections. It is conceivable that this portion could even be integrated with a microwave probe to use the close proximity to minimize cable and connector losses.

The purpose of this paper is to describe a calibration technique for correcting and de-embedding time domain measurements for the characterization of wide-bandwidth circuits and devices. The correction described in this paper provides general de-embedding and is useful for practical measurement systems. Frequency domain results from example measurements in both SMA and wafer probe environments using the TDNA technique presented in this paper are compared with VNA measurements for validation.

The TDNA System

TDR/T measurements using step-like waveforms incident to the d.u.t. at each port in turn and voltage measurements of the responses are used with known and partially known calibration standards to identify the characteristics of the measurement system (error boxes), see fig. 2.

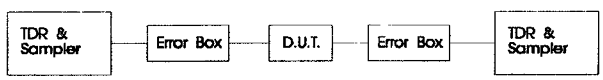

Fig. 2. The two-port Time Domain Network Analysis system.

Each port's non-idealities are grouped in a single two-port error box. Source impedance and excitation wave shape are also absorbed by the error box allowing the use of an ideal sampler and for mathematical convenience impulse excitation. A corresponding signal flow diagram is shown in fig. 3.

* This work is supported in part by the National Science Foundation Center for the Design of Analog and Digital Integrated Circuits and the International Society for Hybrid Microelectronics Educational Foundation.

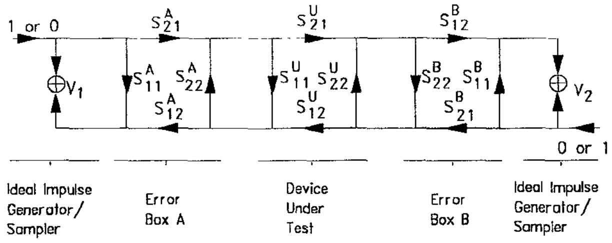

Fig. 3. Flow diagram of the two-port Time Domain Network Analysis System.

Thru-Match-Short Calibration

Measurement in the time domain has the advantage of natural time windowing since only a finite duration of response is acquired. A match termination is readily obtained with a reference impedance transmission line of sufficient length. This suggests that a likely choice for TDNA calibration could be the line obtained match as part of a thru-match-short (TMS) calibration using the standards for TRL. Here, however, the reflection coefficient of the short must be fully known. Suitable, high quality short circuit terminations are available and adequate for calibration in many transmission line structures.

The corrected two-port S-parameters, S_{xx}^U, are obtained from the measurements V_{ij}^X where j is the excitation port, i is the measurement port and the superscript X denotes the standard or unknown being measured. The solution is then given by,

$$S_{11}^U = \frac{\rho_A - S_{22}^B T_1 T_2}{1 - S_{22}^A S_{22}^B T_1 T_2}, \qquad S_{22}^U = \frac{\rho_B - S_{22}^A T_1 T_2}{1 - S_{22}^A S_{22}^B T_1 T_2} \quad (1)$$

$$S_{21}^U = T_1\left[1 - S_{22}^U S_{22}^B\right], \qquad S_{12}^U = T_2\left[1 - S_{11}^U S_{22}^A\right], \quad (2)$$

where

$$T_1 = \frac{V_{21}^U V_{12}^T\left[1 - S_{22}^A \rho_A\right]}{V_{12}^T V_{21}^T - V_{11}^{TM} V_{22}^{TM}}, \qquad T_2 = \frac{V_{12}^U V_{21}^T\left[1 - S_{22}^B \rho_B\right]}{V_{12}^T V_{21}^T - V_{11}^{TM} V_{22}^{TM}}, \quad (3)$$

$$\rho_A = \frac{M_u^A \rho_S}{M_u^A \rho_S S_{22}^A + 1 - S_{22}^A \rho_S}, \qquad \rho_B = \frac{M_u^B \rho_S}{M_u^B \rho_S S_{22}^B + 1 - S_{22}^B \rho_S}, \quad (4)$$

$$S_{22}^A = \rho_S V_{22}^{TM}\left[1 - \frac{V_{11}^{TM}\left(V_{22}^{TM} - V_{22}^{SM}\right)}{V_{12}^T V_{21}^T V_{22}^{SM}}\right], \quad (5)$$

$$S_{22}^B = \rho_S V_{11}^{TM}\left[1 - \frac{V_{22}^{TM}\left(V_{11}^{TM} - V_{11}^{SM}\right)}{V_{12}^T V_{21}^T V_{11}^{SM}}\right], \quad (6)$$

$$M_u^A = \frac{V_{11}^{UM}}{V_{11}^{SM}}, \qquad M_u^B = \frac{V_{22}^{UM}}{V_{22}^{SM}}, \quad (7)$$

where $V_{xx}^{IJ} = V_{xx}^I - V_{xx}^J$ and ρ_S is the short circuit reflection coefficient.

Experimental Results

Example measurements were made using a Tektronix 11801 TDR system with an SD-24 20 GHz dual sampling head. For coaxial measurements APC-3.5 calibration standards from the Hewlett-Packard 8510B vector network analyzer were used. Wafer probe measurements used standards available on a Cascade Microtech calibration tile. VNA measurements using standard short-open-match-thru calibrations were also taken for comparison with the TDNA results.

The example measurements were made on a simple SMA 20 dB attenuator and a 20 dB attenuator on the Cascade calibration tile. Figs. 4 and 5 show the TDNA and VNA results from the coaxial attenuator, while figs. 6 and 7 show the results from measurement of the calibration tile pad. Return loss dynamic range exceeds 40 dB (at least at low frequencies) for both cases. Careful use of sampling head smoothing and waveform averaging was used to reduce the noise bandwidth of the measurement system and retain as great a signal-to-noise ratio as possible.

Careful selection of fft and inverse fft methods [9] allows complete recovery of the de-embedded d.u.t. TDR/T responses. One such measurement for the SMA attenuator is shown in fig. 8. Accurate voltage magnitude and delay values are readily obtained.

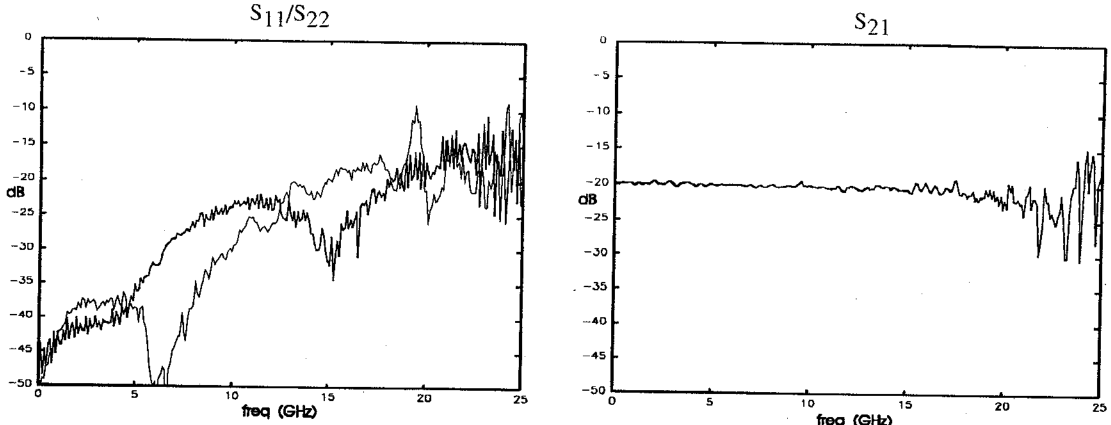

Fig. 4. TDNA measurements of an SMA 20 dB attenuator. Thru-Match-Short calibration was used with measurements from a Tektronix 11801 TDR system with an SD-24 dual TDR sampling head.

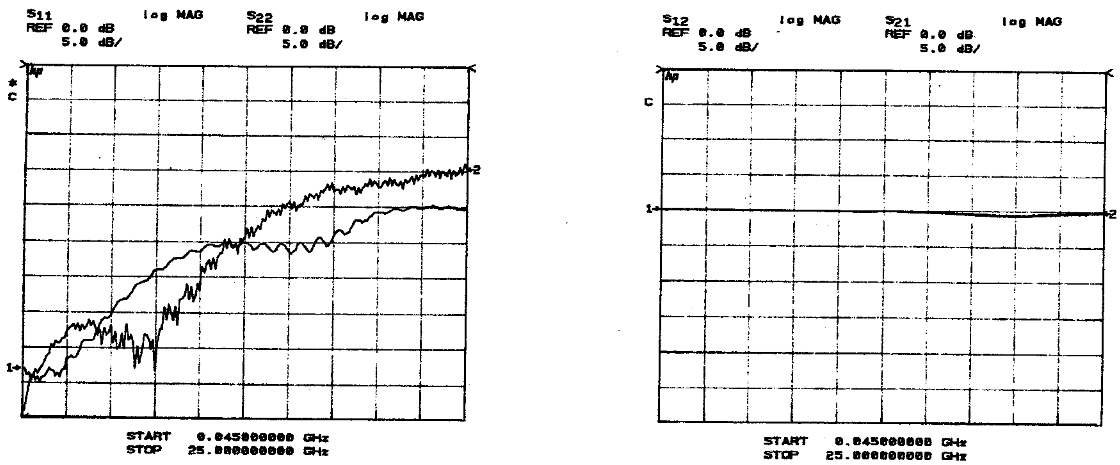

Fig. 5. VNA measurements of the SMA 20 dB attenuator. Standard Open-Short-Load-Thru calibration was used on a Hewlett-Packard 8510B Vector Network Analyzer.

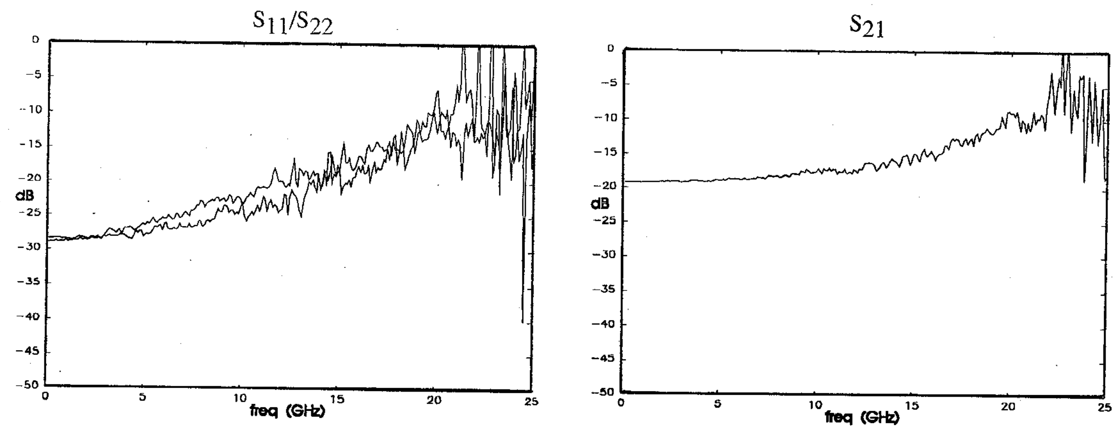

Fig. 6. TDNA wafer probe measurements on a 20 dB attenuator on a Cascade Microtech calibration tile.

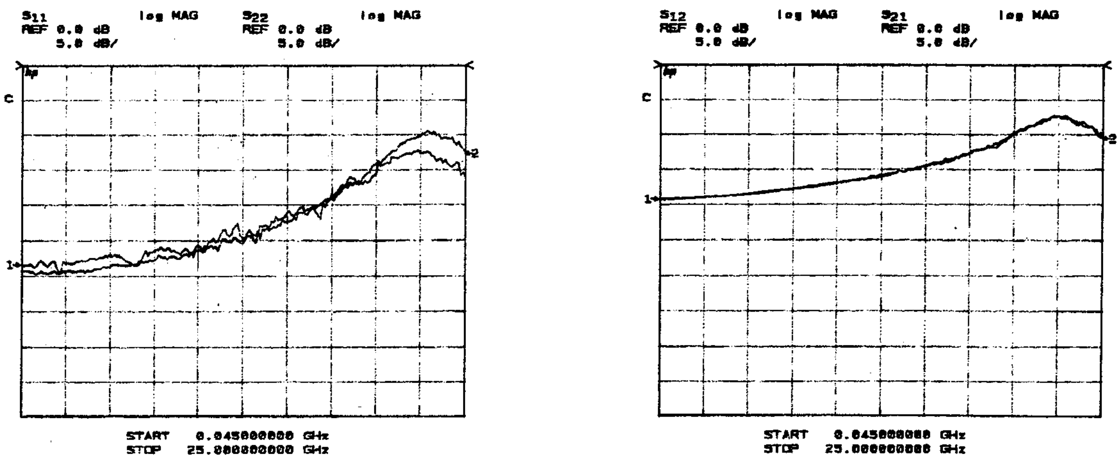

Fig. 7. VNA measurements of the calibration tile 20 dB attenuator.

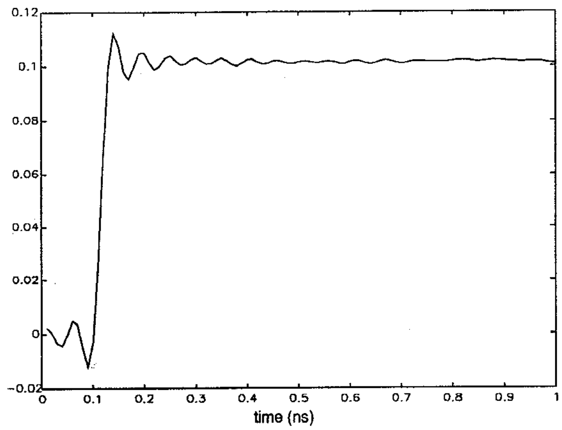

Fig. 8. De-embedded TDT response of the SMA attenuator, g_{21}, equivalent to the integrated impulse response, h_{21}.

Conclusions

An accurate calibration technique for Time Domain Network Analysis using a Thru-Match-Short calibration set has been demonstrated. The calibration is complete and accounts for both source and load mismatches and pass-thru errors as well as the shape of the excitation waveform. Recent developments in broadband TDR systems such as the non-linear transmission line system described in [8] suggest that network characterization in the time domain may become a practical alternative to frequency domain methods, particularly at higher frequencies.

References

1. G.F. Engen and C.A. Hoer, "Thru-reflect-line: An improved technique for calibrating the dual six port automatic network analyzer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, Dec. 1979, pp. 987-993.

2. C.A. Hoer and G.F. Engen, "Calibrating a Dual Six-Port or Four-Port for Measuring Two-Ports with any Connectors," *Proc. of 1986 IEEE MTT Symposium,* pp. 665-668.

3. H.J. Eul and B. Schiek, "A Generalized Theory and New Calibration Procedures for Network Analyzer Self-Calibration," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-39, April 1991, pp. 724-731.

4. A.M. Nicolson, "Broad-Band Microwave Transmission Characteristics from a Single Measurement of the Transient Response," *IEEE Trans. on Inst. & Meas.*, Vol. IM-17, No. 4, Dec. 1968, pp. 395-402.

5. H.M. Cronson and P.G. Mitchell, "Time-Domain Measurements of Microwave Components," *IEEE Trans. on Inst. & Meas.*, Vol. IM-22, No. 4, Dec. 1973, pp. 320-325.

6. J.R. Andrews, "Automatic Network Measurements in the Time Domain," *IEEE Proc.,* Vol. 66, No. 4, April 1978, pp. 414-423.

7. N.S. Nahman et. al., "Applications of time-domain methods to microwave measurements," *IEE Proc.*, Vol. 127, Pt. H, No. 2, April 1980, pp. 99-106.

8. R.Y. Yu et. al., "A 2.3ps Time-Domain Reflectometer for Millimeter-Wave Network Analysis," *IEEE Microwave and Guided Wave Letters,* Vol. 1, No. 11, Nov. 1991, pp. 334-336.

9. A.M. Shaarawi and S.M. Riad, "Computing the Complete FFT of a Step-Like Waveform," *IEEE Trans. on Inst. & Meas.*, Vol. IM-35, No. 1, March 1986, pp. 91-92.