Technical Brief

S-parameters, Insertion and Return Loss Measurements Using TDR Oscilloscope

Introduction to S-parameters

Frequency-domain scattering parameters (S-parameters) are a useful way to visualize the electrical properties of a system. They are a dual representation of the time domain data in the frequency domain. S_{11} is related to Time Domain Reflection (TDR), and S_{21} is related to Time Domain Transmission (TDT), via an enhanced FFT algorithm developed in the early 90's at the US National Institute of Standards and several universities [1], [2].

Although S-parameters have historically been measured in the frequency domain using a network analyzer, much of the same information is contained in TDR and TDT measurements.
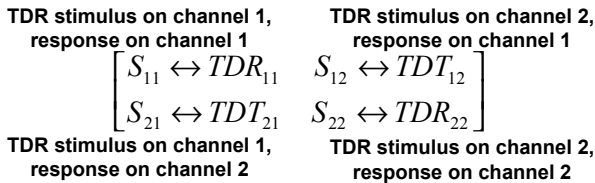
TDR stimulus on channel 1,   **TDR stimulus on channel 2,**
response on channel 1   **response on channel 1**

$$\begin{bmatrix} S_{11} \leftrightarrow TDR_{11} & S_{12} \leftrightarrow TDT_{12} \\ S_{21} \leftrightarrow TDT_{21} & S_{22} \leftrightarrow TDR_{22} \end{bmatrix}$$

TDR stimulus on channel 1,   **TDR stimulus on channel 2,**
response on channel 2   **response on channel 2**

Figure 1. Relationship between the TDR/T data and the single-ended S-parameters

Scattering-parameter computation is just as valid for TDT (through) measurements as it is for TDR (reflection) measurements. TDT results in insertion loss (S_{21}), TDR in return loss (S_{11}). Differential and mixed mode S-parameters can also be obtained from corresponding TDR oscilloscope data.

Differential TDR stimulus,   **Common mode TDR stimulus,**
differential response   **differential response**

$$\begin{bmatrix} S_{11dd} \leftrightarrow TDR_{11dd} & S_{12dd} \leftrightarrow TDT_{12dd} & S_{11dc} \leftrightarrow TDR_{11dc} & S_{12dc} \leftrightarrow TDT_{12dc} \\ S_{21dd} \leftrightarrow TDT_{21dd} & S_{22dd} \leftrightarrow TDR_{22dd} & S_{21dc} \leftrightarrow TDR_{21dc} & S_{22dc} \leftrightarrow TDR_{22dc} \\ S_{11cd} \leftrightarrow TDR_{11cd} & S_{12cd} \leftrightarrow TDT_{12cd} & S_{11cc} \leftrightarrow TDR_{11cc} & S_{12cc} \leftrightarrow TDT_{12cc} \\ S_{21cd} \leftrightarrow TDT_{21cd} & S_{22cd} \leftrightarrow TDT_{22cd} & S_{21cc} \leftrightarrow TDT_{21cc} & S_{22cc} \leftrightarrow TDR_{cc} \end{bmatrix}$$

Differential TDR stimulus,   **Common mode TDR stimulus,**
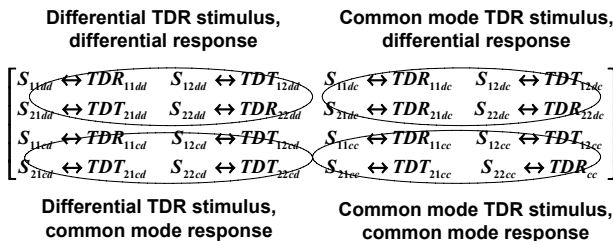**common mode response**   **common mode response**

Figure 1. Relationship between the TDR/T data and the differential S-parameters

From practical standpoint, TDR/T-based S-parameters are much simpler and quicker to obtain, while providing more than sufficient dynamic range. In addition, if a designer already has a TDR oscilloscope, he or she can save money by postponing the purchase of a network analyzer, and using TDR oscilloscope with IConnect TDR software instead.

S-parameter Measurements

In order to obtain high-quality S-parameter diagrams, the designer has to follow sound measurement practices when working with the 18-20 Ghz TDR oscilloscope, such as: letting the instrument warm up for 20-30 minutes before performing measurements, using good quality low loss cables and good probes with small signal-to-ground spacing, using averaging in the TDR oscilloscope to reduce noise. Two waveforms need to be acquired: the DUT and the reference open waveforms - without changing the timebase on the TDR oscilloscope.

For the TDR-based S-parameter measurement, it is particularly important to select an acquisition window that is long enough that it allows the DUT waveforms to completely settle to its steady state DC level. We are about to start making high-frequency analysis of the DUT, and we need to allow the signal to settle to perform this analysis accurately. At the same time, the window must not be any longer than necessary, to maximize the effective dynamic range and accuracy of the measurement.

In addition, we need to make sure that a sufficient number of data points is selected in the oscilloscope acquisition window. This is particularly critical for analyzing long interconnects, such as cables. The frequency step and the upper frequency limit of your measurement is determined as

$$f_{upper} = \frac{1}{2t_{step}} = \frac{N}{2t_{window}} \qquad f_{step} = \frac{1}{t_{window}} \qquad (1)$$

where N is the number of points in the acquisition window, T_{step} is the time step, and T_{window} is the acquisition window length. Thus, to get S-parameter data to the desired upper frequency f_{upper}, you will need to make sure that the ratio between the number of points and window length is sufficient. To get the desired frequency step, you will need to make sure that the window length is sufficient.

When working with long cables, it is generally a good idea to keep the number of points at the maximum number allowed for a given instrument.

Furthermore, to increase the dynamic range of the measurements, it is important to keep number of averages and number of points to the maximum, and the window as short as possible. 128 averages will give extra 20dB of dynamic range; use at least that many if your instrument averages quickly. At the same time, it is important to keep the acquisition window as short possible, to maximize the effective power.

Differential S-parameters

When dealing with differential measurements, you need to make sure that your signals arrive to the DUT at the same time. You can follow the procedure in the oscilloscope manual and, having observed the difference in delays between the two channels in differential mode, adjust for half of that difference by using delta TDR function in the scope.

For differential, common mode and mixed mode S-parameters, the same applies - a reference and a DUT waveforms are required. For differential stimulus waveforms, the oscilloscope must have the two stimulus signals switching in opposite direction. For common mode stimulus waveforms, the oscilloscope must have the stimuli switching in the same direction. For differential response, subtract one response channel from the other. For common mode response, add the two response channels together.
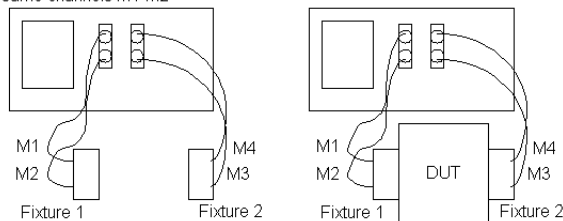

Figure 3. Fixture settings for differential S-parameter measurements using IConnect TDR software

TDR waveform in the S-parameter computation must be acquired with the 50-Ohm cables connected to both DUT ports, thus ensuring a 50-Ohm termination at the far end of the DUT. The cables, probes and fixtures used to connect the DUT to both channels of the TDR oscilloscope are assumed by the IConnect to be of the same length. Please note that even if you are taking

only TDR (return loss) measurement, the far end of the device must be terminated with 50 Ohm on each port. 100 Ohm differential termination is acceptable for differential response measurements.

In differential mode, both transmission and reference must be differential (that is, negative switching channel subtracted from the positive switching channel). For a symmetric interconnect, we can use odd mode waveforms, acquired on the positive switching channel with the stimulus being in differential mode.

S-parameter Correlation Data

Despite the simplicity of the S-parameter measurement process in IConnect, we would like to address the correlation questions of the S-parameters obtained in IConnect from TDR/T measurements versus the S-parameters measurements using a vector network analyzer by providing the correlation data up to 12 Ghz on Figure 4 below.
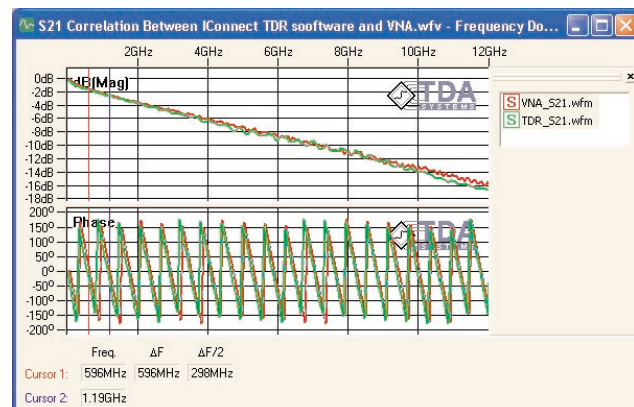

Figure 4. Differential insertion loss correlation

With quality fixtures, cables and connectors the S-parameters obtained in IConnect are often accurate well past 12 GHz.

Bibliography

[1] L.A. Hayden, V.K. Tripathi, "Calibration Methods for Time Domain Network Analysis,"-IEEE Transactions on Microwave Theory and Techniques, Vol 41, No. 3, March 1993, pp. 415-421

[2] T. Dhaene, L. Martens, D. De Zutter, "Calibration and Normalization of Time Domain Network Analyzer Measurements,"-IEEE Transactions on Microwave Theory and Techniques, Vol. 42, No. 4, April 1994, pp. 580-589