Technical Note

Dynamic Range Determination and S-Parameter Accuracy Validation For High Frequency Time Domain Network Analyzer (TDNA) Measurements

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1.0 Purpose

As digital data rates rise ever faster, the need to understand an electrical interconnect's effect on system performance becomes more and more critical. Therefore, in the development of an interconnect product, it is often necessary to make S-parameter measurements to gain the knowledge of the electrical behavior of the interconnect device. The Time Domain Network Analyzer (TDNA) is one test method Samtec uses in the development of high speed connectors, cable assemblies, and flex circuitry.

The purpose of this paper is to demonstrate that with proper technique, the TDNA has adequate dynamic range for such applications and can be used to make accurate S-parameter measurements. The paper will focus on S-parameter magnitude characterization while phase resolution will not be addressed.

The paper will first focus on establishing a noise floor for a representative state-of-the-art TDNA measurement system. The relative accuracy of the TDNA system will then be evaluated by comparing TDNA results to those obtained from the National Institute of Standards and Technology (NIST) traceable network analyzer measurements.

2.0 Background

S-parameter measurements of electronic interconnects have been traditionally made with the Vector Network Analyzer (VNA). The VNA offers excellent dynamic range, accuracy, and traceability. However, the Time Domain Network Analyzer (TDNA) has recently grown in popularity because of its ease of use, and specifically, the ability to quickly change the measurement reference plane.

The TDNA is a Time Domain Reflectometer (TDR) with add-on software (an example being TDA Systems IConnect® Software). Some simple measurements using the TDR and Time Domain Transmission (TDT) capabilities of the TDR oscilloscope will show that the TDNA offers a good dynamic range and is capable of making accurate and traceable S-parameter measurements.

Possibly, the greatest advantage the VNA offers is a tremendous dynamic range. The VNA has a typical dynamic range of 100 dB. A rule of thumb for low level measurements is to insure that the dynamic range of the measurement system is at least 10 dB, or preferably 20 dB, below the level of the lowest signal of interest. For example, a dynamic range of 60 dB is more than adequate to differentiate a measured crosstalk signal from the noise floor when the crosstalk is as low as -40 dB.

VNA dynamic range can be improved by narrowing the Intermediate Frequency (IF) Bandwidth and increasing the number of averages. Both help filter unwanted responses, but also increase measurement time [1].

The TDR typically has a dynamic range of 40 to 50 dB. As with the VNA, the dynamic range of the TDR can be improved by increasing the number of measurement averages. Increasing the number of averages helps filter out the internal noise inherent to the TDR oscilloscope. Like the VNA, increasing the TDR's averages increases the measurement time.

A major concern in S-parameter measurements is establishing optimal accuracy. The VNA makes use of calibration and de-embedding techniques which use well-characterized calibration standards to establish measurement reference planes. All measurements are made relative to the established reference plane. The plane will typically be located at the end of the test cables.

Currently, the most commonly used calibration technique is referred to as “SOLT” (Short, Open, Load, Thru). With the SOLT method, well characterized short, open, load, and thru calibration structures are measured with the VNA. The known behavior of these devices allows the negative effects of the test system to be quantified and mathematically removed from later measurements.

After calibration, a significant challenge often encountered in the VNA measurement process is de-embedding test fixtures from the measurement. The test system and calibration standards are typically coaxial in construction, while the device under test (DUT) is often non-coaxial. This situation requires a transition fixture between the calibration reference plane and the DUT. These fixtures can have a serious impact on measurement accuracy.

The TDNA, however, can make use of reference waveforms for calibration. The reference plane can be located at the end of the adapter fixtures, thus effectively de-embedding the effects of the test fixtures from the measurement. The easily moveable reference plane and the ability to offer calibration after fixtures make the TDNA a valuable resource for developmental characterization of electronic interconnects.

3.0 TDNA Measurement Theory

To extract the S-parameters of an interconnect using the TDNA, two time domain measurements are required: a reference waveform and a DUT waveform. An additional measurement of a 50 ohm load can be included for enhanced accuracy.

The reference waveform is used to define the calibration plane. There are three types of reference waveforms that can be used: open, short, and TDT. The reference choice is dependent upon the type of measurement desired. For example, when extracting the return loss measurement (S_{11}), the reference waveform can be either a short or an open. The best results for insertion loss (S_{21}) are obtained when referenced to a TDT of the test fixtures. Using the test fixture TDT waveform as a reference automatically de-embeds the effects of the test fixture from the measurement.

The DUT waveform can be either a TDR reflection measurement of the DUT (for S_{11}) or a Time Domain Transmission (TDT) measurement for S_{21} .

To improve S11 accuracy, a 50 ohm calibration waveform can also be used by TDA System's IConnect® Measurement Xtractor™ as a reflection calibration, similar to the load calibration of a VNA.

3.1 TDR Theory

The TDR oscilloscope used here is a two port network capable of measuring in TDR and/or TDT modes, as shown in Figure 1.

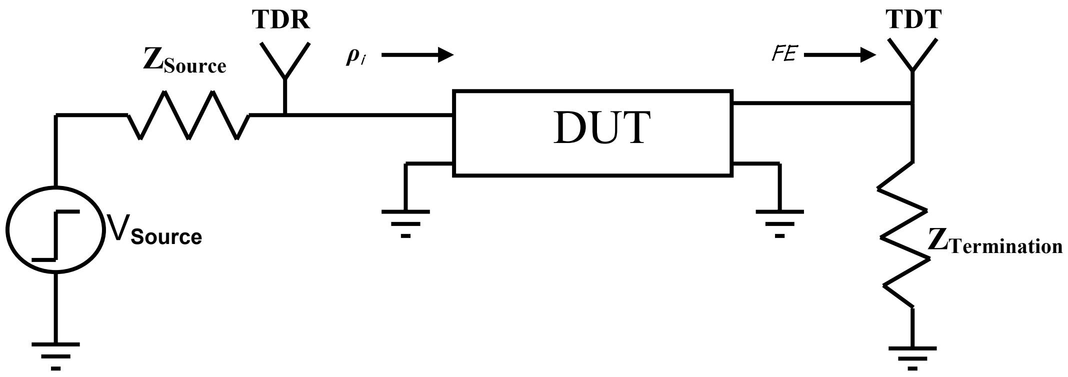


Figure 1: TDR.

Drawing from transmission line theory, when a voltage pulse ($V_{Incident}$) is launched into the TDR, a portion of the signal is reflected back to the source from the DUT. The magnitude of this reflection can be described by the input reflection coefficient ($\rho_i(t)$), which is defined by Equation 1 below [2]:

$$\rho_i(t) = \frac{Z_{DUT}(t) - Z_{Source}(t)}{Z_{DUT}(t) + Z_{Source}(t)} \tag{1}$$

From Equation 1, when the DUT is an open, $\rho_i(t) = +1$. When the DUT is a short, $\rho_i(t) = -1$. And when $Z_{DUT} = Z_{Source}$, $\rho_i(t) = 0$.

The portion of the incident voltage that is not reflected by the DUT encounters another discontinuity at the termination impedance, and a reflection is then sent back to the source from the far-end. This reflection is described by the far-end reflection coefficient ($\rho_{FE}(t)$) which is given by Equation 2 [3]:

$$\rho_{FE}(t) = \frac{Z_{Termination}(t) - Z_{DUT}(t)}{Z_{Termination}(t) + Z_{DUT}(t)} \qquad (2)$$

The portion of the signal that is not reflected, but is transmitted through the discontinuities, is described by the transmission coefficient (τ (t)), which is defined by Equation 3 [4]:

$$\tau(t) = \frac{2Z_{Termination}(t)}{Z_{Termination}(t) + Z_{DUT}(t)} \qquad (3)$$

3.2 The Two Port Network

Removing the source, the source impedance, and the termination impedance in Figure 1 reduces the TDR to the two port network shown in Figure 2. This two port network model will be used for determining the dynamic range of the TDNA.

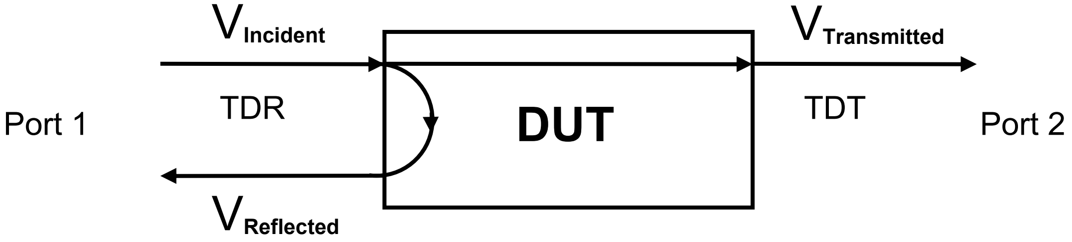


Figure 2: Two Port Network.

An incident voltage pulse is launched into the two port network system at Port 1. If there is an impedance discontinuity between Port 1 and the DUT, when $V_{Incident}$ reaches the DUT, a portion of $V_{Incident}$ is reflected ($V_{Reflected}$) back to Port 1.

Port 2 receives the transmitted voltage ($V_{Transmitted}$) which is $V_{Incident}$ minus $V_{Reflected}$. Referencing $V_{Reflected}$ (from Port 1) to $V_{Incident}$ establishes the ratio $V_{Reflecte}$d/ $V_{Incident}$ which is defined as the reflection coefficient ($\rho_i(t)$). Therefore,

$$\rho_i(t) = \frac{V_{Reflected}}{V_{Incident}} = \frac{Z_{DUT}(t) - Z_{Source}(t)}{Z_{DUT}(t) + Z_{Source}(t)} \qquad (4)$$

Referencing $V_{Transmitted}$ (from Port 2) to $V_{Incident}$ establishes the ratio $V_{Transmitted}$/ $V_{Incidents}$ which is defined as the transmission coefficient (τ(t)) [2].

$$\tau(t) = \frac{V_{Transmitted}}{V_{Incident}} = \frac{2Z_{Termination}(t)}{Z_{DUT}(t) + Z_{Termination}(t)} \qquad (5)$$

The S-parameters extracted by the TDNA are related to the reflection and transmission coefficients. The S-parameters are calculated using a Fast Fourier Transform (FFT) to process the time domain coefficients. The FFT is a computational method based on the mathematical relationship between the time domain and the frequency domain.

The TDNA derives the S-parameters across a broad range of frequencies from the equations:

$$\begin{aligned} S_{11}(f) &= 20\log_{10}[FFT(\rho(t))] \\ S_{21}(f) &= 20\log_{10}[FFT(\tau(t))] \end{aligned} \qquad (6)$$

4.0 Dynamic Range

Noise, by definition, is undesirable energy that falls within the pass band of a signal [5]. When measuring interconnects, some noise is present in the TDR oscilloscope. This noise is internal to the device itself and is generated mostly in the sampling module. Typically, this noise has a very low power level.

Such internal noise creates the lower limit signal that can be detected by the test system and is often referred to as the “noise floor”. In other words, this is the lowest energy level that can be measured with the TDR oscilloscope. The noise floor establishes the dynamic range [6].

4.1 Measurement of Dynamic Range

Measuring the dynamic range of the TDNA can be accomplished by making an S_{11} and an S_{21} measurement of the TDR oscilloscope.

In this study, all TDNA measurements were made using a Tektronix CSA8000 Communications Signal Analyzer (TDR/T), two Tektronix 80E04 Sampling Modules, and TDA System’s IConnect® Measurement Xtractor™, Version 3.5.0.

The setup used on the CSA8000 was 500ps/div time base, 4000 point data record (1.250ps step), and 128 averages. The calibration standards used were from an Agilent 85052B 3.5mm Calibration Kit.

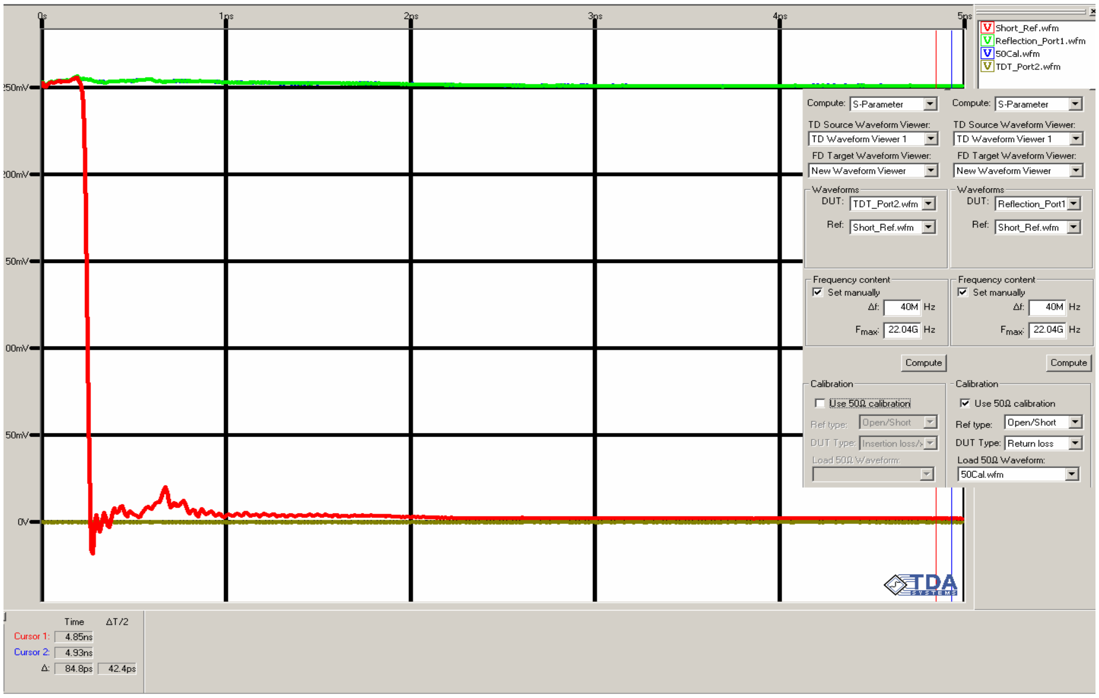
For the S_{11} measurement, the following waveforms were acquired at Port 1: a reference, a matched reflection of the DUT, and a 50 ohm calibration waveform. Equation 1 becomes useful when selecting the reference. An open circuit would be the most logical choice for the reference waveform because $\rho_i(t) = +1$. However, due to the fringing effects inherent to a non-ideal open, a reflection coefficient of exactly +1 is difficult to achieve.

On the other hand, a short reference does not have fringing effects. A non-ideal short will, however, have excess inductance. But the error introduced by this inductance is often less than that introduced by a non-ideal open. Therefore, a coefficient close to -1 is more easily obtained making the short a more effective reference.

For the S_{21} noise floor response, the only waveform needed is a TDT waveform captured on Port 2. When acquiring the TDT waveform, Port 2 is terminated using a standard 50 ohm load. Acquiring the TDT when Port 2 is terminated in a load requires that Port 2 be in acquisition mode. The time domain waveforms for S_{11} and S_{21} noise floor measurements are shown in Figure 3.

Using the short reference waveform, the matched reflection waveform, and the 50 ohm calibration waveform, S_{11} is calculated by the TDA software. S_{21} is extracted using the short reference waveform and the TDT waveform acquired on Port 2.

Figure 4 shows the dynamic range of the TDNA. The S_{11} and S_{21} responses show that the TDNA has a noise floor of -60dB to -50dB up to 12 GHz . This dynamic range is sufficient to differentiate the S-parameter test sample measurement from the TDNA's noise floor.



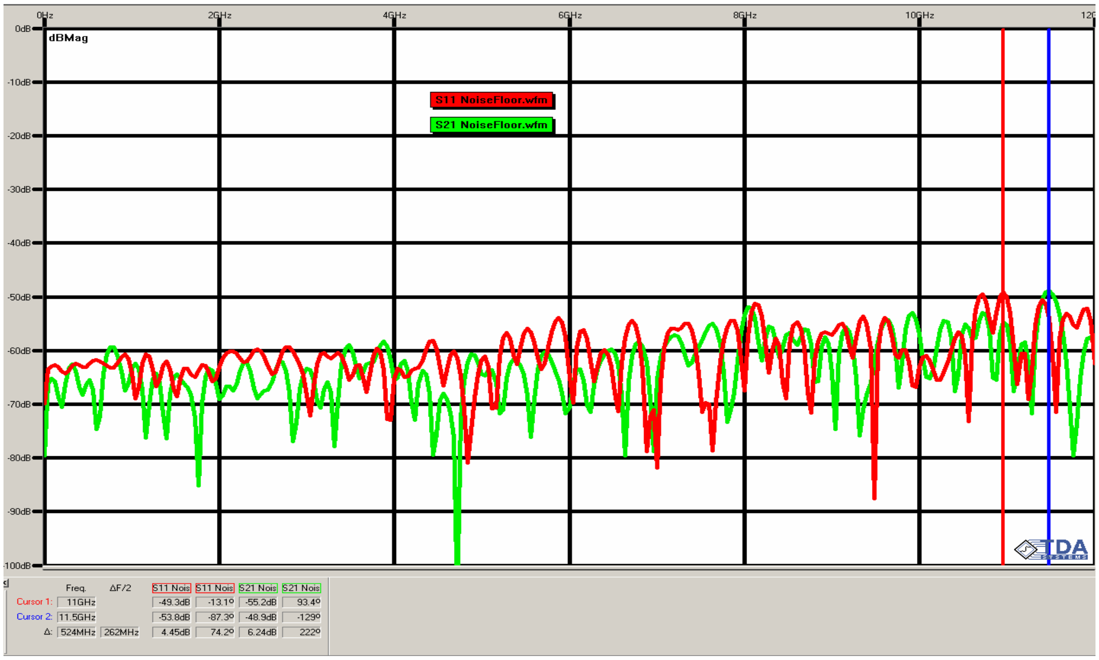
V Short_Ref.wfm
V Reflection_Port1.wfm
V 50Cal.wfm
V TDT_Port2.wfm

Compute: S-Parameter
TD Source Waveform Viewer: TD Waveform Viewer 1
FD Target Waveform Viewer: New Waveform Viewer
Waveforms
DUT: TDT_Port2.wfm
Ref: Short_Ref.wfm
Frequency content
☑ Set manually
Δf: 40M Hz
F_{max}: 22.04G Hz
Compute
Calibration
☐ Use 50Ω calibration
Ref type: Open/Short
DUT Type: Insertion loss/
Load 50Ω Waveform:

Compute: S-Parameter
TD Source Waveform Viewer: TD Waveform Viewer 1
FD Target Waveform Viewer: New Waveform Viewer
Waveforms
DUT: Reflection_Port1
Ref: Short_Ref.wfm
Frequency content
☑ Set manually
Δf: 40M Hz
F_{max}: 22.04G Hz
Compute
Calibration
☑ Use 50Ω calibration
Ref type: Open/Short
DUT Type: Return loss
Load 50Ω Waveform: 50Cal.wfm

```
              Time      ΔT/2
Cursor 1:   4.85ns
Cursor 2:   4.93ns
      Δ:    84.8ps    42.4ps
```

Figure 3: Time Domain Measurements of 2 Port Network.



```
              Freq.     ΔF/2      S11 Nois   S11 Nois   S21 Nois   S21 Nois
Cursor 1:    11GHz                -49.3dB     -13.1º    -55.2dB      93.4º
Cursor 2:   11.5GHz               -53.8dB     -87.3º    -48.9dB      -129º
      Δ:    524MHz    262MHz       4.45dB      74.2º     6.24dB       222º
```

Figure 4: Dynamic Range of the TDNA. S11 and S21 Noise Floors.

5.0 Measurement Accuracy

Accuracy is achieved when the response of a known device yields an expected value that falls within acceptable tolerances. Several methods can be employed to verify the accuracy of the TDNA measurement. One is to simply measure the 0 dB level of the TDNA. However, achieving greater confidence requires some degree of traceability of the measurement. Data can be validated by measuring a known or quantifiable device and comparing the measurement results to the expected results.

5.1 0 dB Method

One of the simplest methods for determining the accuracy of the measurement is to measure the 0 dB thru connection level of the TDNA. Measuring 0 dB requires a S_{11} measurement of Port 1 when that port is terminated in a short and a S_{21} measurement when Port 1 is connected to Port 2. For the S_{11} measurement, consider the TDR in Figure 1. Making the DUT a short reduces the TDR in Figure 1, relative to Port 1, to the TDR in Figure 5.

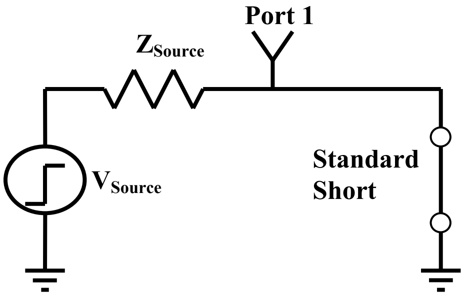


Figure 5: Port 1 Terminated in a Short.

For S_{21}, connecting Port 1 to Port 2, in theory, eliminates the DUT thus creating a circuit as shown in Figure 6. However, in order to connect Port 1 to Port 2, a standard thru is used, creating a match between Z_{DUT} and $Z_{Termination}$, Then, by Equation 2, $\rho_{FE}(t) = 0$ and Equation 6 $S_{21} = 0$ dB.

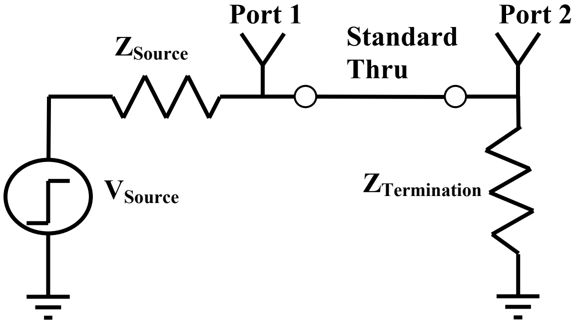
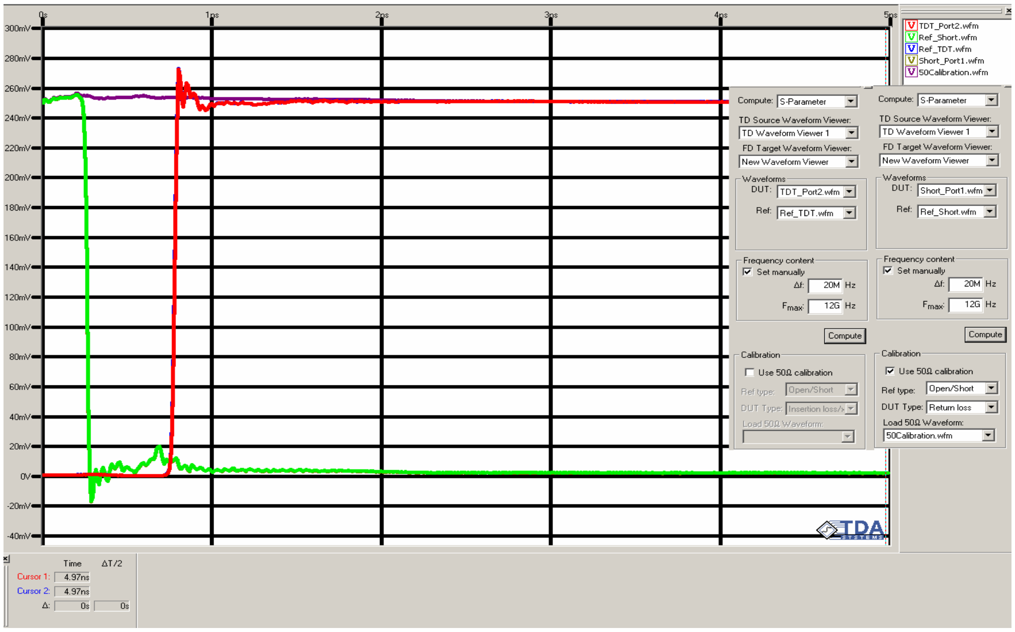


Figure 6: Port 1 Connected to Port 2.

The 0 dB time domain waveforms are shown in Figure 7, and the extracted S-parameters for a 0 dB measurement are shown in Figure 8.



V TDT_Port2.wfm
V Ref_Short.wfm
V Ref_TDT.wfm
V Short_Port1.wfm
V 50Calibration.wfm

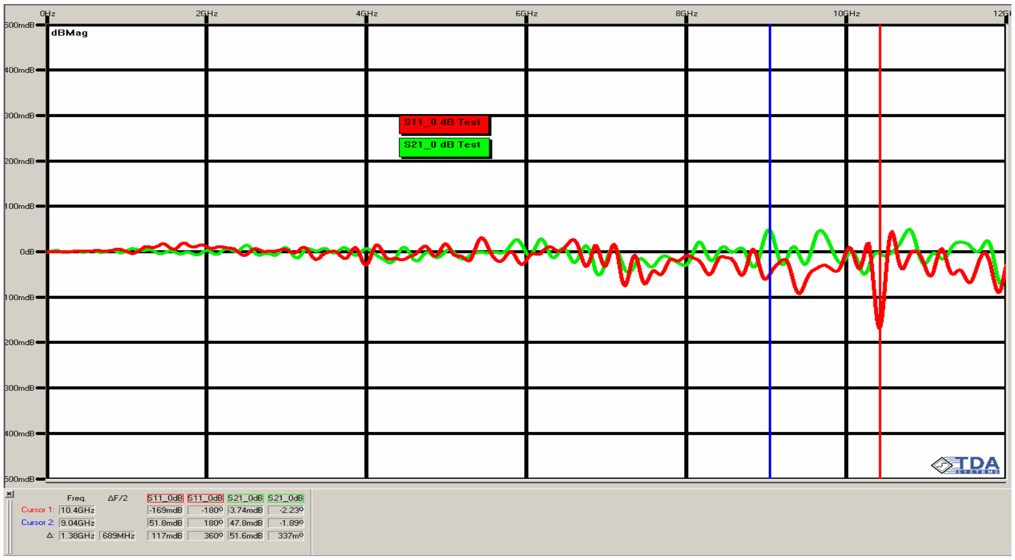
Compute: S-Parameter
TD Source Waveform Viewer: TD Waveform Viewer 1
FD Target Waveform Viewer: New Waveform Viewer
Waveforms
DUT: TDT_Port2.wfm
Ref: Ref_TDT.wfm
Frequency content
☑ Set manually
Δf: 20M Hz
Fmax: 12G Hz
Compute
Calibration
☐ Use 50Ω calibration
Ref type: Open/Short
DUT Type: Insertion loss/
Load 50Ω Waveform:

Compute: S-Parameter
TD Source Waveform Viewer: TD Waveform Viewer 1
FD Target Waveform Viewer: New Waveform Viewer
Waveforms
DUT: Short_Port1.wfm
Ref: Ref_Short.wfm
Frequency content
☑ Set manually
Δf: 20M Hz
Fmax: 12G Hz
Compute
Calibration
☑ Use 50Ω calibration
Ref type: Open/Short
DUT Type: Return loss
Load 50Ω Waveform: 50Calibration.wfm

	Time	ΔT/2
Cursor 1:	4.97ns	
Cursor 2:	4.97ns	
Δ:	0s	0s

Figure 7: 0 dB Time Domain Waveforms.

The measurement results vary from 0 dB by < ±0.050 dB which show a good correlation to expected results.



	Freq.	ΔF/2	S11_0dB	S11_0dB	S21_0dB	S21_0dB
Cursor 1:	10.4GHz		-169mdB	-180º	3.74mdB	-2.23º
Cursor 2:	9.04GHz		51.8mdB	180º	47.8mdB	-1.89º
Δ:	1.38GHz	689MHz	117mdB	360º	51.6mdB	337mº

Figure 8: 0 dB Frequency Response.

5.2 Validation by Comparison to a Standard

Once the 0 dB measurement is confirmed, accuracy comparison using different approaches can be performed. Such measurements can verify the accuracy of the TDNA by providing a level of traceability.

Traceability is defined by the US National Institute of Standards thusly:

"… traceability is the result of a measurement, not of an instrument or calibration report or laboratory. It is not achieved by following any one particular procedure or using special equipment." [7]

Applying that logic here, a sample DUT was chosen which could be accurately characterized by both a NIST traceable VNA and the TDNA. The DUT chosen consists of two commercial grade Pasternack 3dB SMA attenuators (part number PE7005-3) concatenated together by a Kings Electronics Company SMA male to SMA male adapter. Two attenuators were connected back-to-back so that the DUT would be directly insertable into the measurement path of both test set-ups with out requiring adapters.

A picture of the DUT is shown in Figure 9.

Figure 9: DUT used for Validation Comparison.

To achieve a high degree of confidence, the results of the TDNA measurements are compared to those acquired from two different VNA test systems.

The first VNA used was a Hewlett Packard 8720ES S-Parameter Network Analyzer (VNA). The DUT was connected to the VNA using Huber Schuner Inc., Sucoflex 104PE 3.5mm cables. A standard SOLT calibration was performed using commercial grade calibration standards to establish a reference plane at the end of the 3.5mm cables.

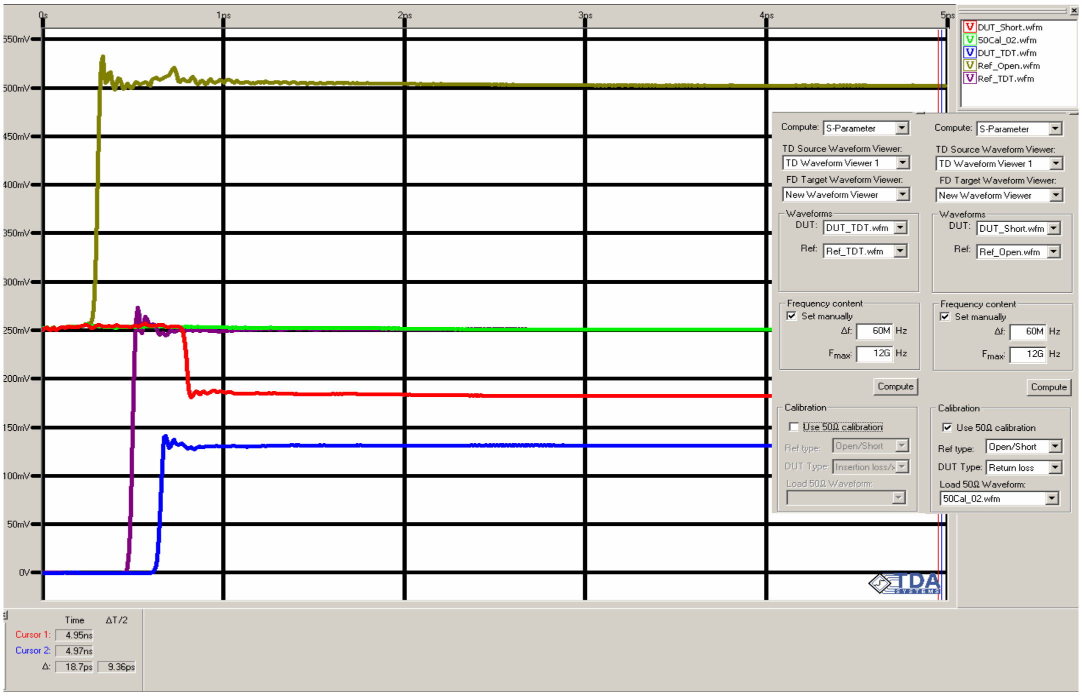
The second VNA measurement was performed using an Agilent Technologies E8664B PNA Series Network Analyzer with Physical Layer Test System software, Version 2.500 (PLTS). The DUT was connected to the PLTS system using WL Gore 3GW40 2.4mm cables with Pasternack PE9654 2.4mm female to SMA male and PE9070 SMA female to female adapters. A standard SOLT calibration was performed at the end of the SMA adapters.

The PLTS system should be considered the “standard” in this experiment because its calibration status, and the calibration standards used in its measurement were NIST traceable at time of the test. The 8720 and its associated calibration standards met all applicable mechanical standards at the time of the test, but the VNA was not covered by a NIST traceable calibration certificate.

The TDNA setup was the same as Sections 3.1 and 4.1, where the maximum frequency was 12 GHz and the frequency step was 60 MHz. The VNA was set up to deliver a frequency sweep of 50 MHz to 12 GHz using 16 averages and 201 points. This produced a frequency step of about 60 MHz. The PLTS was set to deliver a frequency sweep of 50 MHz to12 GHz with 1 average (the default value) and 201 points, which yielded a frequency step of about 60 MHz.

When the far-end of a 3 dB attenuator is shorted, the S_{11} is expected to be approximately -6 dB. Concatenating two 3 dB attenuators and terminating them in a short should produce an S_{11} of -12 dB. The expected S_{21} of this particular DUT is -6 dB.

The S_{11} time domain waveforms acquired for the TDNA are an open reference, a reflection of the DUT with the far-end terminated in a short, and a 50 ohm matched reflection. For S_{21}, a TDT reference and a TDT of the DUT are both acquired at Port 2. The time domain waveforms are shown in Figure 10.



V DUT_Short.wfm
V 50Cal_02.wfm
V DUT_TDT.wfm
V Ref_Open.wfm
V Ref_TDT.wfm

Compute: S-Parameter
TD Source Waveform Viewer: TD Waveform Viewer 1
FD Target Waveform Viewer: New Waveform Viewer
Waveforms
DUT: DUT_TDT.wfm
Ref: Ref_TDT.wfm
Frequency content
☑ Set manually
Δf: 60M Hz
F_{max}: 12G Hz
Calibration
☐ Use 50Ω calibration
Ref type: Open/Short
DUT Type: Insertion loss/
Load 50Ω Waveform:

Compute: S-Parameter
TD Source Waveform Viewer: TD Waveform Viewer 1
FD Target Waveform Viewer: New Waveform Viewer
Waveforms
DUT: DUT_Short.wfm
Ref: Ref_Open.wfm
Frequency content
☑ Set manually
Δf: 60M Hz
F_{max}: 12G Hz
Calibration
☑ Use 50Ω calibration
Ref type: Open/Short
DUT Type: Return loss
Load 50Ω Waveform: 50Cal_02.wfm

	Time	ΔT/2
Cursor 1:	4.95ns	
Cursor 2:	4.97ns	
Δ:	18.7ps	9.36ps

Figure 10: Time Domain Accuracy, -3dB Attenuator.

Figures 11 and 12 show the comparative results of the S-parameters extracted using the TDNA, VNA, and the PLTS.

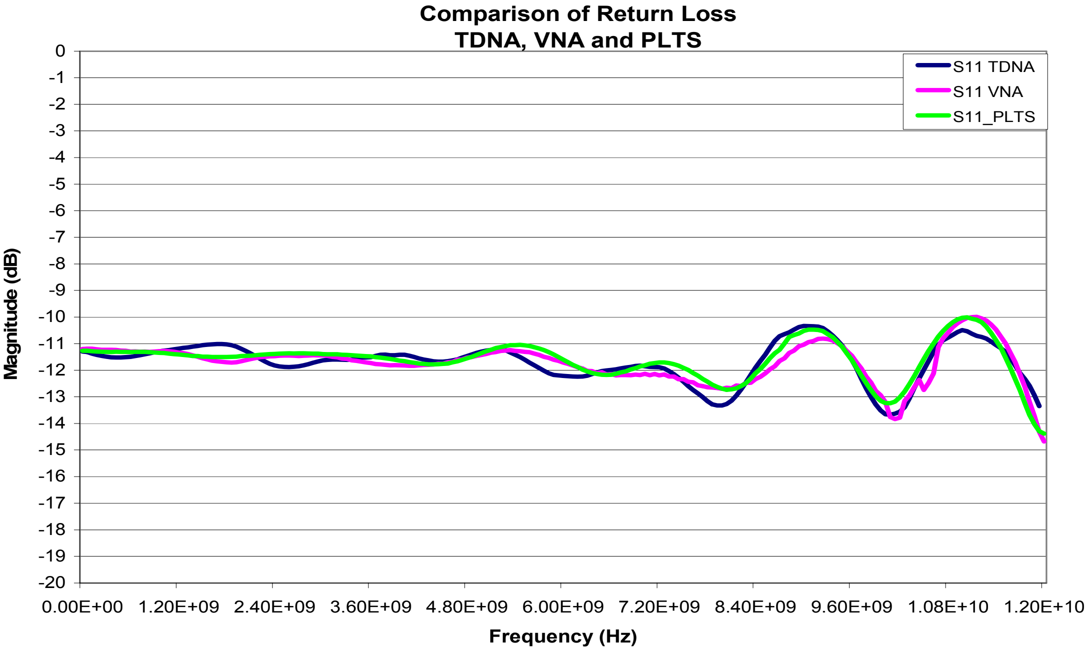


Figure 11: Return Loss.

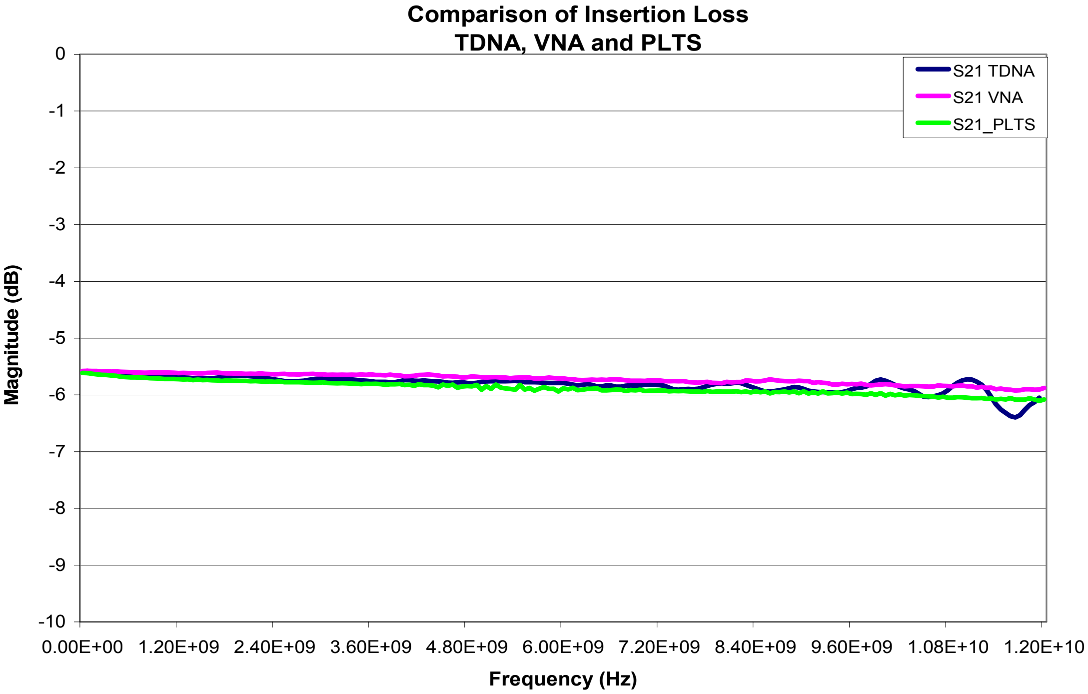


Figure 12: Insertion Loss.

Figure 11 shows that the S_{11} results vary by <1.0 dB at the higher frequencies, thus a good correlation between the three different methods.

The S_{21} results shown in Figure 12 also vary by <1.0 dB. Once again, this shows good correlation between the three different methods.

6.0 Conclusion

It has been shown that the TDNA as implemented has a dynamic range of 50 dB to 60 dB. This range allows the user to produce S-parameters with sufficient accuracy for the development of most high speed electronic interconnects.

A few simple measurements of a DUT with predictable performance verified the accuracy of the measurement process. The TDNA has been shown to produce S-parameters that are within 1 dB of a NIST traceable VNA (PLTS) measurement up to 12 GHz. This degree of correlation provides the confidence needed to secure the use of TDNA measurements in the development of high speed digital interconnects.

7.0 References

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