Choosing the Right Tools for High-Speed Bus and System Interconnect Designs

Application Note 1413

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Who Should Read This Application Note?

This application note is written for high-speed digital design engineers working on high-speed interconnects and buses in digital systems.

Introduction

If you want to create accurate models for high-speed interconnects, eventually you will need to perform a measurement-based validation of your interconnect models. At that point, you need to decide which type of test equipment to use to accomplish the job. Ease of use, accuracy, and cost are factors that will influence your choice of instrumentation.

Time domain reflectometry (TDR) oscilloscopes and vector network analyzers (VNAs) are the two most common instruments used today for signal integrity measurements. Your choice between these two instruments may hinge on theoretical considerations of time- and frequency-domain measurements. For some people, the choice is based on personal belief in one domain's superiority over the other. In reality, there are appropriate times to use each instrument.
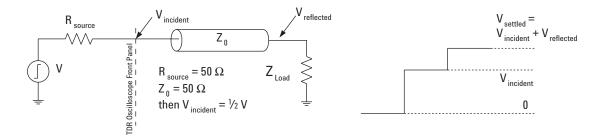
This application note analyzes the physics and mathematics of the relationship between time- and frequency-domain measurements. We will discuss practical aspects of testing, as well as ease-of-use and accuracy issues related to time- and frequency-domain measurement instruments. We also will provide practical suggestions on how to choose the right instrument for your application.

Agilent Technologies

The Mathematics of Time and Frequency Relationships

TDR oscilloscopes measure reflected and transmitted voltage to provide you with single-ended or differential time-domain reflection transmission (TDR/T) information. The following is the basic block diagram for a TDR measurement.

Figure 1. TDR measurement block diagram and a typical waveform shape

A fast rise-time step stimulus is sent to the device under test (DUT), and the oscilloscope measures the reflected and transmitted voltage. The reflected voltage also can be displayed as ρ (reflection coefficient) or Z (impedance). For a single impedance load, as shown in the figure above, the basic equations for ρ and Z will be

Equation 1

$$\rho = \frac{V_{reflected}}{V_{incident}} = \frac{Z_{load} - Z_0}{Z_{load} + Z_0}$$

Equation 2

$$Z_{load} = Z_0 \cdot \frac{1 + \rho}{1 - \rho} = Z_0 \cdot \frac{V_{settled}}{2 \cdot V_{incident} - V_{settled}}$$

If the impedance of your device under test (DUT) changes, the reflected voltage will change with time and can be displayed as a reflection coefficient or impedance vs. time.

Equation 3

$$\rho(t) = \frac{V_{reflected}(t)}{V_{incident\ amplitude}}$$

You also can determine the transmission coefficient τ using the following equation:

Equation 4

$$\tau(t) = \frac{V_{transmitted}(t)}{V_{incident\ amplitude}}$$

In reality, equations 3 and 4 only work for an ideal incident step. To include the non-ideality of the TDR oscilloscope incident step into the calculation, we use deconvolution instead of division.

The Mathematics of Time and Frequency Relationships (continued)

The VNA measures power, but versus frequency, and transforms it into scattering parameters (S-parameters). S-parameters are a ratio of the reflected or transmitted wave voltage to the incident wave voltage [4], and for a 2-port measurement, shown in figure 2, can be written in its simplified form as,
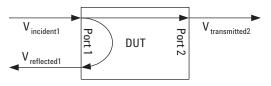

Figure 2. 2-port VNA measurement block diagram

Equation 5

$$S_{11}(f) = \frac{V_{reflected\,1}(f)}{V_{incident\,1}(f)} \qquad S_{21}(f) = \frac{V_{tramsmitted\,2}(f)}{V_{incident\,1}(f)}$$

$$S_{12}(f) = \frac{V_{transmitted\,1}(f)}{V_{incident\,2}(f)} \qquad S_{22}(f) = \frac{V_{reflected\,2}(f)}{V_{incident\,2}(f)}$$

The VNA can display S-parameters data versus frequency as real and imaginary values, magnitude and phase, or on a Smith chart. It is also worth noting that S_{11} and S_{21} parameters are frequently referred to as reflection and transmission coefficients, similar to reflection and transmission coefficients in TDR.

A basic block diagram of the TDR/T, compared to that of a 2-port VNA instrument, is shown on figure 3, below.
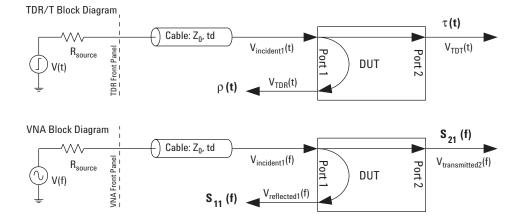

Figure 3. TDR/T measurement block diagram, compared to equivalent 2-port VNA measurement block diagram

The Mathematics of Time and Frequency Relationships (continued)

The close similarity between the two block diagrams of the two seemingly different measurement systems is obvious. The fundamental difference between the TDR and VNA instruments lies in the way they display data and the fact that a TDR scope measures voltage vs. time, while the VNA measures power vs. frequency. Moreover, we observe clear similarity between equations 3, 4 and 5. Since we know from basic math that voltage in the time and frequency domain is related by fast Fourier transform (FFT)[1], and deconvolution in the time domain corresponds to division in the frequency domain, we can easily see that there is a relationship between the TDR reflection and transmission coefficients and VNA S-parameters:

VNAs measure both real and imaginary parts of the signal vs. frequency, whereas TDR scopes measure voltage vs. time. However, as the equations above clearly indicate, there is a clear one-to-one relationship between the real TDR data vs. time and real/imaginary VNA data vs. frequency.

To illustrate, let us apply TDR equations 1, 2 and the corresponding VNA equations to a few simple examples, when $Z_{DUT} = 0$ (short termination), $Z_{DUT} = 50\ \Omega$ (matched termination) and $Z_{DUT} = \infty$ (open termination).

In these simple cases, the values of the TDR reflection coefficient and the VNA S_{11} parameter are constant and the same in both time and frequency domains.

	TDR, ρ	VNA, S_{11}
$Z_{DUT} = 0$ (short termination)	-1	$1\angle +180° = -1$
$Z_{DUT} = 50\ \Omega$ (matched termination)	0	0
$Z_{DUT} = \infty$ (open termination)	1	$1\angle 0° = 1$

Equation 6

$$S_{11}(f) = FFT(\rho(t)) \qquad \rho(t) = \frac{1}{N} IFFT(S_{11}(f))$$

$$S_{21}(f) = FFT(\tau(t)) \qquad \tau(t) = \frac{1}{N} IFFT(S_{21}(f))$$

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1 To be more exact, it is Fourier transform (FT) that relates time and frequency domains. Discrete Fourier transform (DFT) is the computational method for handling sampled data, and FFT is just a computationally efficient implementation of DFT.

TDR and VNA Instrumentation Background

TDR instruments were initially introduced for fault location in long electrical cables. Digital designers quickly realized the intuitive and visual nature of TDR could give them fast insight into their interconnect performance, so they began using TDR oscilloscopes for interconnect characterization and signal integrity work. Differential TDR functionality, which has existed for many years, allowed designers to use TDR instruments for differential interconnect characterization.

Currently, TDR oscilloscopes can provide multiport single-ended or differential capability. Software tools—such as IConnect TDR software from TDA Systems—expand the applications for TDR instruments by providing the ability to extract and validate interconnect models from measurements and compute S-parameters from TDR data.

Calibration and measurement routines for time domain network analysis (TDNA) have been designed to enhance the accuracy of TDR and time domain transmission (TDT) measurements in a manner similar to that of VNA calibration [8]-[10]. These routines yield data in both the time and frequency domain, and they are implemented in tools such as MultiCal software from the United States National Institute of Standards and Technology (NIST). This calibration capability brought the accuracy of TDNA to a level similar to that of network analyzers.

VNA instruments were originally developed as tools for microwave design and measurement. In microwave design, engineers were concerned primarily with narrowband and resonant systems, such as mixers, filters, resonators, and power splitters/combiners. Engineers required exact data about the frequency band over which the circuit can operate, center frequency and Q-factor. These requirements caused instrument manufacturers to continuously improve VNA accuracy. VNAs now achieve very high dynamic range (signal-to-noise ratio) in the frequency domain, easily reaching 100dB when careful measurement techniques are used.

This high dynamic range and accuracy were achieved through narrowband filtering at each frequency point, as well as through calibration procedures that allow the instrument to correct for imperfections in the measurement path. Short-open-load-thru (SOLT) was the most commonly used calibration procedure, and advanced calibration procedures, such as thru-reflect-load (TRL) were invented to improve instrument accuracy and extend frequency range [7]. Powerful microwave design tools, such as Touchstone, were developed for analysis and synthesis of microwave electronic systems.

Differential VNA capabilities were added recently to VNAs; currently, 4-port single-ended or 2-port differential capability is available. However, because high accuracy is required for narrowband microwave work, instrument developers focused on instrument accuracy, not on ease of use. As a result, digital designers without microwave design backgrounds may have long learning curves with VNAs. Designers and test engineers need to thoroughly understand and meticulously follow the calibration procedures in order to obtain good data from a network analyzer.

Practical Comparison of TDR and VNA for Signal Integrity Measurements

Signal integrity interconnects are typically complex multi-component structures. For example, a path from a driver to a receiver may begin in the driver package, go through several layers and vias on the printed circuit board (PCB), and go through a second package to reach the receiver. The signals that propagate through these interconnects are digital, and therefore broadband. When we measure these signals to search for signal integrity issues such as crosstalk, we typically do not require noise floor higher than 10 mV out of 1 V signal, which corresponds to about 40 dB dynamic range. Resonances may occur in digital interconnects, but they are typically not very sharp and do not require the same measurement dynamic range as resonances in a high-Q microwave resonator.

TDR oscilloscopes offer well-known advantages for time-domain interconnect characterization, such as intuitive and visual operation, and windowing capability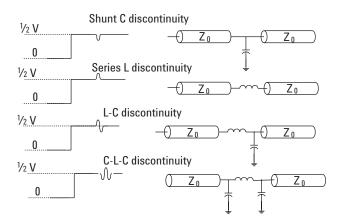. The visual nature of TDR measurements comes from the fact that TDR is a transient measurement, and each change in the TDR waveform can be correlated to an appropriate lumped or distributed circuit component (figure 4). Multiple reflections inside the DUT can obscure the correlation, but the true impedance profile for the DUT can be computed in IConnect TDR software.

For example, you can easily determine if a via in the signal path is capacitive or inductive by simply performing a TDR measurement and observing whether the TDR waveform goes up or down over the via region. You can easily window out the transmission lines surrounding the via and analyze the portion of the waveform related only to the via.

VNA measurements, on the other hand, are steady-state measurements. The same via, surrounded by two transmission lines, cannot be easily isolated from the transmission lines with a VNA instrument in the frequency domain. If the test structure allows you to isolate the via or de-embed the transmission lines, you can obtain via inductance or capacitance very accurately; if such de-embedding is possible, however, the via inductance can be obtained just as accurately with a TDR using techniques for package characterization [11], [12].

Figure 4. TDR waveform features can be easily correlated to the physical structure of the interconnect.

Practical Comparison of TDR and VNA for Signal Integrity Measurements
(continued)

For more complex interconnect structure characterization, a TDR oscilloscope, coupled with IConnect TDR software, gives you better ability to obtain a *SPICE or IBIS physical model* for the interconnect compared to VNA and VNA-based modeling tools. A physical model directly correlates inductances, capacitances and transmission lines to the interconnect geometrical features. A physical model gives you valuable insight into which components of the interconnect system—a package, a board trace, or a via—may be causing the most signal integrity problems, and therefore should be redesigned (figure 5). VNA-based modeling tools excel in creating single-element or multi-element behavioral models—models that will reproduce the S-parameter behavior over the specified frequency range.
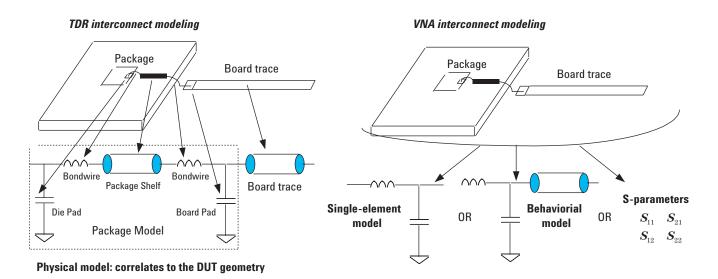
Figure 5. The intuitive and easy-to-use TDR modeling methodology allows you to extract a package model that correlates well with the physical layout of the package under test. VNA models are either single-element, behavioral models, or S-parameters. All of these VNA models will accurately match the frequency response of the circuit, but additional analysis is required to isolate the problem spots in the interconnect structure when you are using a VNA.

TDR instruments provide lower dynamic range than VNAs, as a result of both narrowband noise filtering in the frequency domain and advanced frequency-domain calibration techniques in VNAs. Typical TDR dynamic range is 25-40 dB, whereas VNAs can provide 100 dB, or even more, of dynamic range. However, as we pointed out above, high-speed interconnects do not normally require dynamic range higher that 40 dB, and the high dynamic range available from VNAs is not utilized on interconnect measurements.

In addition, you can use digital averaging in a TDR oscilloscope, which has the same effect on the dynamic range as narrowband filtering in a VNA. As a matter of fact, every time you increase the averaging in a TDR oscilloscope two times, you increase the dynamic range by 3 dB. Therefore, by using 128 averages instead of 1 (i.e., instead of no averages), you can increase the scope's dynamic range by 21 dB, reaching the 40 dB dynamic range, which is more than sufficient for accurate interconnect measurements.

If a VNA has a time-domain option, it can be used in much the same way as a TDR oscilloscope. However, the VNA's advantages— high dynamic range and accuracy, resulting from advanced calibration procedures—result in more lengthy measurement processes, compared to those of TDR oscilloscopes.

Typical digital design engineers without microwave design background, may be uncomfortable dealing with differential and mixed-mode S-parameters and creating SPICE or IBIS models for high-speed digital interconnects from frequency-domain S-parameters. However, differential TDR measurements can be sufficiently intuitive for designers with past experience with differential signaling in digital designs.

Losses, Resonances and the Need for Frequency-Domain Measurements in TDR

As digital signal speeds increase dramatically into the gigahertz range, interconnect frequency-dependent losses become an important part of the interconnect model. Such losses result not only in signal attenuation and rise-time degradation, but also, together with crosstalk, they result in jitter and eye-diagram degradation.

Frequency-domain S-parameters are traditionally used to characterize losses, and such data can be very precise in describing the performance of the interconnect systems over the desired frequency range. However, S-parameter data can be difficult, if not impossible, to use directly with a SPICE or IBIS simulator. S-parameters need to be converted into a SPICE or IBIS model, which typically produces a behavioral model that normally does not correlate to the physical layout of the interconnect and can be very complex for an electrically long lossy interconnect transmission line.

IConnect TDR software offers a method to extract lossy line parameters directly from TDR and TDT measurements [14]. Since TDR oscilloscopes are more visual and easier for typical digital designers to use, this TDR-based loss extraction methodology may be more intuitive for most designers. The lossy line models that IConnect software extracts are designed to be used directly with off-the-shelf SPICE and IBIS simulators with lossy line simulation capabilities, thereby providing a very easy

and intuitive way to include transmission line loss in digital system simulations. Additionally, the software can compute single-ended, differential and mixed-mode S-parameters from TDR/T data acquired with an Agilent Infiniium DCA TDR oscilloscope—similar to many VNAs offering computational options to obtain TDR waveforms. Even though the dynamic range of this measurement is lower than dynamic range of a VNA, it is more than sufficient to analyze losses and resonances that may affect the digital signal integrity.

You need to take into account some digital signal processing issues—beyond the straightforward FFT computation—when you convert TDR data into S-parameters and VNA data into time domain. First, you must apply appropriate windowing techniques to obtain correct representation of the spectrum of the TDR signals, as well as to go from VNA S-parameters to time domain data [15]. Secondly, you need to keep in mind that there is a direct correlation between the frequency range f_{BW} of the data and its time step Δt, as well as between the frequency step Δf and the time range T:

Equation 7

$$f_{BW} = \frac{1}{2 \cdot \Delta t} \qquad T = \frac{1}{\Delta f}$$

This limitation, however, can be easily remedied by effective and accurate interpolation techniques. Finally, because a TDR oscilloscope uses a step-like waveform, its available incident power decreases as 1/f with frequency, resulting in lower

dynamic range at higher frequencies. On the other hand, VNAs do not measure dc values; instead they extrapolate the data to obtain the value. This may lead to errors when you are measuring broadband structures like digital interconnects.

For example, for a typical time domain window of 5 ns, with 10 ps time step and 500 points, we conclude that the computed S-parameter data will have 50 GHz bandwidth and 200 MHz step. Clearly, for a 20 GHz TDR oscilloscope, the usable bandwidth is limited by that of the oscilloscope or the step generator. However, the step of 200 MHz may or may not be sufficiently fine, and you may need to interpolate the TDR data. A similar effect occurs when you take the VNA data into the time domain: if you are measuring 20 GHz frequency sweep with 500 points, the resulting frequency step is 40 MHz, the time window will be 25 ns and time step 500 ps. This may not provide sufficient time resolution either, and you may need to interpolate the VNA data.

These constraints lead to the fact that a 20 GHz TDR oscilloscope with 35 ps reflected rise time really could not provide 20 GHz S-parameters. A more reasonable range for S-parameters computed from TDR measurements would be 4-6 GHz without any calibration, or 8-12 GHz with SOLT or other calibration [8]-[10]. Conversely, a 20 GHz network analyzer, such as the Agilent 8720, produces a much slower rise time than a 20 GHz Agilent 86100A Infiniium DCA TDR oscilloscope.

TDR Resolution and the Need for Time-Domain Measurements in VNAs

The ability of a TDR instrument to resolve small features in the DUT is determined by the rise time of the TDR oscilloscope. Wide-band network analyzers with a time-domain option—50, 60 and 110 GHz systems—can provide faster TDR rise time to increase the available measurement resolution in the time domain and allow measurements to a faster rise time.

A TDR oscilloscope can resolve two discontinuities if they are separated by at least half the TDR rise time. Since typical TDR oscilloscope rise time is in the 30 ps range, that limits the separation between two discontinuities to no less than 15 ps. In a vacuum, that corresponds to physical distance of about 180 mils, or 4.5 mm. In FR4, a typical printed circuit board material with e_r of approximately 4, this distance is 90 mils or 2.3 mm.

Some small interconnects, such as board vias, package leads, and socket connections may be shorter than the physical distance computed above. Incorrectly applying the analysis above, some designers conclude that a 50 GHz or 110 GHz network analyzer with a TDR option is required to compute SPICE models for their interconnects. But the analysis above applies to the distance between two interconnects, not to the length of single interconnects. You can easily analyze a single interconnect with a length of less than 1 mm—probably as small as 0.2-0.5 mm—with a standard TDR oscilloscope with a 30 ps rise time, by using relative TDR measurements and package modeling techniques [11], [12]. Interconnect parasitics in the 100 fF range for capacitance and 100 pH range for inductance can be extracted using these package modeling techniques. If the interconnect length is in the range of 0.1 mm or less, however, a faster rise time is indeed necessary.

Faster TDR rise time also is necessary when you attempt to resolve two separate discontinuities when you analyze board or package-component failures. If the rise times of the device output drivers are slower than the rise time of your TDR oscilloscope, the TDR will not be able to separate these two discontinuities. However, this fact is irrelevant from a signal integrity standpoint, because the signal generated by the output drivers will not be able to separate these two discontinuities either. Therefore, the only time you may need a faster rise time is when the output drivers of the design are faster than the rise time of a TDR oscilloscope. Few of the rise-time specifications or actual driver designs in the current digital signaling technologies approach the rise time of the TDR oscilloscopes currently on the market.

Practical Comparison of TDR and VNA for Signal Integrity Measurements
(continued)

Rambus® Memory Board Example

Consider the following example of a Small Outline Rambus Inline Memory Module (SO-RIMM™) used predominantly in laptop computer applications. The probe inductance is de-embedded in this measurement using the normalization procedure in the Agilent 86100A Infiniium DCA TDR oscilloscope. This is a simpler procedure than the frequency domain calibration of network analyzers and produces similar de-embedding results. The corresponding TDR waveforms and the true accurate impedance measurement profile computed in IConnect TDR software is shown on figure 6.

In this figure, the only limitation for accurate impedance measurements and SPICE/IBIS modeling of the trace is the multiple reflections in the TDR waveform. IConnect TDR software can correct these multiple reflections and produce accurate impedance measurement results. It is worth noting that a network analyzer, due to the steady-state nature of VNA measurements, cannot recover information lost due to multiple reflections, unless the data is converted into the time domain and the multiple reflection correction from IConnect software is applied to the converted data.

IConnect TDR software produces S-parameter results from TDR/T measurements acquired with an Agilent Infiniium DCA TDR oscilloscope using a procedure much simpler than that of a network analyzer. You must use an open reference waveform when computing S-parameters
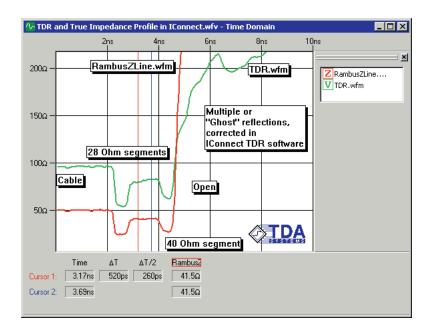

Figure 6. TDR and true impedance profile for the Rambus notebook module. Each segment of the true impedance profile can be easily correlated to a physical structure in the module trace. Multiple reflections in TDR waveforms are corrected in TDR software to produce an accurate impedance measurement.

Practical Comparison of TDR and VNA for Signal Integrity Measurements
(continued)

from TDR or TDT data in IConnect TDR software to ensure the correct polarity of the phase. The S-parameter data produced from a TDR does not require the same complexity of calibration as that of a VNA. The normalization procedure of an Infiniium DCA is quite adequate for high-speed digital device S-parameter measurements. As we stated before, the dynamic range of a TDR measurement can be increased with advanced calibration procedures [8]-[10], but the 40 dB dynamic range required for high-speed digital work does not require it. For example, consider the following frequency domain data produced from a TDR measurement of the same Rambus module trace, figure 7.

The information that you require from the frequency-domain data display (i.e. the frequencies and amplitudes of the resonances)

correlates well to the electrical lengths of the lines on the module in the time domain. The overall slope of the amplitude waveform indicates the amount of loss in the trace. You can extract additional skin-effect and dielectric-loss SPICE models in IConnect TDR software. Such lossy line models can then be used to predict amplitude loss, jitter and eye diagram degradation due to interconnect performance. The frequencies of resonances are seen, but are observed even better on S_{11} plot generated from the TDR measurements. The far end of the line was terminated with 50Ω, but even without this termination, we could observe these frequencies. In addition, it is clear from figure 7 that we do hit the noise floor of the TDR measurement system at about 45 dB, but we do not run out of dynamic range required to perform this measurement.
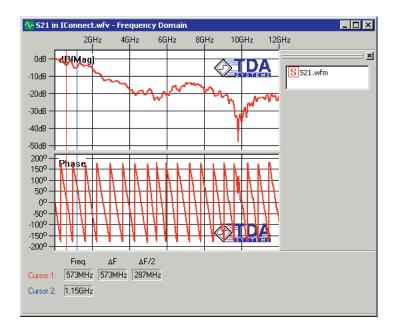

Figure 7. S_{21} produced in IConnect from the TDT measurement

Practical Comparison of TDR and VNA for Signal Integrity Measurements
(continued)

Taking the TDR information about the DUT even further, it is possible to extract the model for the interconnect in IConnect TDR software. This can produce good correlation between simulation and measurement in the time domain as shown in figure 8.

A sample listing of a simplified transmission line model is given in figure 8. This model extracted in IConnect TDR software may contain lossy and lossless transmission lines, inductances, and capacitances (as required to create a physical model for the DUT[2]). Good correlation at 45 ps rise time of the TDR oscilloscope, such as that shown on figure 8, above, indicates excellent accuracy of the model. Clearly, this model will accurately predict all the important signal integrity effects in the interconnects, including loss, jitter, eye-diagram, crosstalk, ringing, and reflections. It is interesting to observe the correlation between these two waveforms in the frequency domain, as well. This correlation can be obtained by computing and comparing the spectra of the two waveforms in IConnect TDR software as shown on figure 9. There is as much as 1-2 dB of discrepancy at 2.5 GHz. However, this discrepancy is not significant enough to have an effect on the time domain measurement, and therefore can be ignored for digital-design purposes.
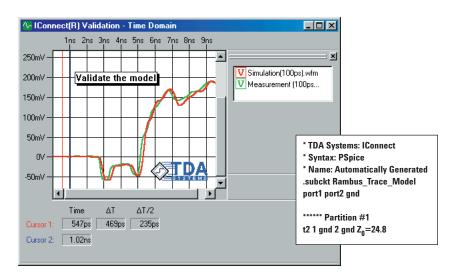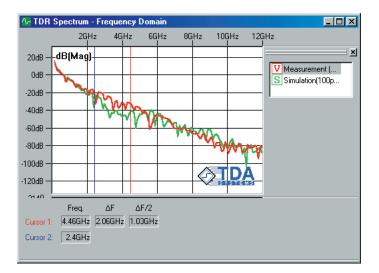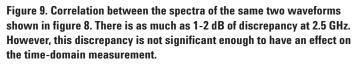

Figure 8. Correlation between simulation of the interconnect modeling produced in IConnect TDR software and the original TDR measurement. Such good correlation at 45 ps rise time of the TDR oscilloscope indicates excellent accuracy of the model.

Figure 9. Correlation between the spectra of the same two waveforms shown in figure 8. There is as much as 1-2 dB of discrepancy at 2.5 GHz. However, this discrepancy is not significant enough to have an effect on the time-domain measurement.

2   The procedure for extracting such interconnect models from TDR measurements is discussed in [3], [14] and other publications from TDA Systems.

Differential Interconnects in the Time and Frequency Domains

Differential transmission is becoming more and more popular in high-speed digital work because differential signals are less susceptible to common mode noise and have better electromagnetic interference (EMI) characteristics. TDR oscilloscopes have always been differential instruments; they have been used for differential interconnect characterization since the technology was developed. Differential TDR measurements are understood and standardized. Novel differential interconnect modeling techniques have been developed and reported [13].

Recently, differential test sets have been developed for 6 and 20 GHz network analyzers. However, a TDR instrument is still about half the price of a network analyzer with a comparable frequency range and rise time. As we discussed above, these differential VNAs do provide higher dynamic range, but the improvement in dynamic range is not necessary and is not used in digital interconnect characterization.

Because of their intuitive nature and ease of use, TDR oscilloscopes continue to find wider application in differential interconnect characterization. In addition, IConnect TDR software is capable of producing differential and mixed-mode S-parameters from the TDR data, allowing you to view the frequency-domain response, insertion and return loss.

In typical time-domain analysis, designers look for various combinations of stimulus and response. Figure 10, below, shows the four major stimulus/response combinations than can be easily obtained with the Agilent TDR. They are differential stimulus and differential response; common-mode stimulus and differential response; differential stimulus and common-mode response; and common-mode stimulus and common-mode response. The following is the S-parameter matrix in the frequency domain equivalent to TDR/T data in the time domain.

The upper left quadrant represents differential signal propagation, the lower right is the common-mode signal propagation, and the other two quadrants represent signal mode conversion from differential to common mode. The lower left quadrant represents generated EMI and the upper shows electromagnetic susceptibility. With TDR and differential time domain measurements, the specific location of the signal trace that generates EMI can be located by stimulating the trace with differential stimulus and observing common-mode response and its location in time (i.e., performing an S_{11cd} measurement with a TDR oscilloscope in the time domain). This matrix is further simplified, because for passive structures such as high-speed digital interconnects, $S_{21} = S_{12}$ for each of the four quadrants.

Differential TDR stimulus, differential response

Common-mode TDR stimulus, differential response

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

Differential TDR stimulus, common-mode response

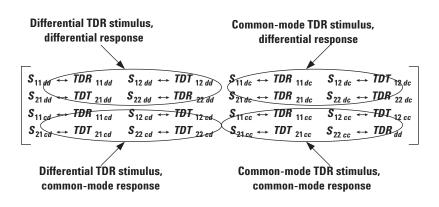**Common-mode TDR stimulus, common-mode response**

Figure 10. A differential and mixed-mode S-parameter matrix can be produced from TDR measurements in IConnect TDR software.

Differential Interconnects in the Time and Frequency Domains

InfiniBand Reference Board Example

In the following example, we used an Agilent Infiniium DCA TDR oscilloscope to make InfiniBand reference board measurements. To improve measurement accuracy, the connector from the probe to the board was de-embedded by acquiring a TDR waveform of a 50 Ω termination (100 Ω differential) at the end of the probe and subtracting it from the TDR/T waveforms in the time domain. This technique works well if you have a good time-base stability in your TDR oscilloscope. A high-fidelity TDR step with minimal overshoot is needed to accurately de-embed the fixturing involved in your TDR measurements [8].

As with any de-embedding, you need to ensure repeatability of the DUT and de-embedding measurement. The structure must be de-embedded from both the DUT measurement and the reference open or short measurement. De-embedding is used for the impedance profile computation, signal integrity modeling and S-parameter computation. The same technique could be used for single-ended TDR measurements.
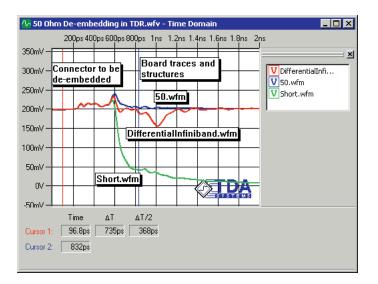

Figure 11. De-embedding the probe effects by subtracting the reference 50 Ω waveform. You can clearly see that we can remove the probe connector effects by subtracting the 50 Ω reference waveform from the DUT and reference short waveforms.

Now, using the de-embedded waveforms, we can compute the even and odd impedance profiles and create a SPICE/IBIS model for these InfiniBand board interconnects (see procedure in reference [13]). Let us focus here, however, on computing differential and mixed-mode S-parameters for these data. We acquired the differential TDR for three differential traces of different lengths. The de-embedded TDR results and the corresponding S_{11dd} for each trace are shown in figure 12.

You can see these three lines are different lengths and the corresponding S-parameter picture—computed from the TDR data by the software—reflects that through the differences in phase and resonant frequencies in the structure. Furthermore, to characterize differential crosstalk, you could stimulate one differential pair and observe the induced crosstalk on the adjacent pair on the Agilent Infiniium DCA. The modeling capabilities of IConnect TDR software can then predict the crosstalk in this differential system.

If you were looking for sources of EMI, then the common-mode response to a differential stimulus would be the most informative (figure 13).

The segments where the common mode is generated from the differential stimulus will be the main EMI sources in this differential pair. The corresponding S-parameter data would not provide the same location information.
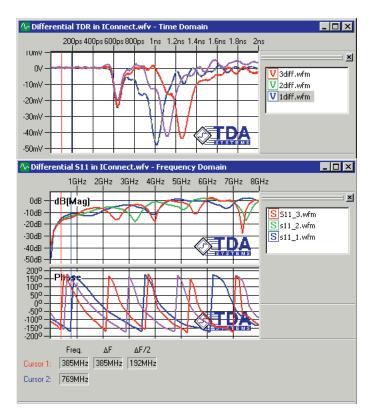

Figure 12. Differential TDR measurement and corresponding S-parameter measurement computed in IConnect TDR software. The frequency domain S_{11} data is displayed up to 8 GHz.
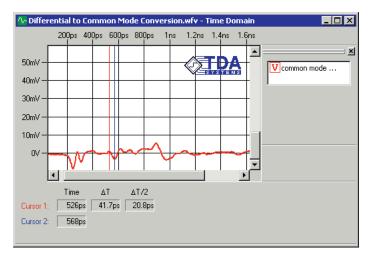

Figure 13. Differential to common-mode conversion in IConnect TDR software. The segments where the common mode is generated from the differential stimulus will be the main EMI sources in this differential pair.

Comparison Summary and Recommendations

Because of its ease of use and intuitive nature, TDR is better suited for wideband, medium-dynamic-range structures such as digital interconnects. For these reasons, TDR remains the tool of choice for high-speed digital designers. With the ability of IConnect TDR software to produce 2-port and differential S-parameter results from Agilent Infiniium DCA TDR oscilloscope measurements, you can obtain a complete characterization picture for interconnects. This includes the important extraction of lossy line SPICE/IBIS modeling information.

On the other hand, VNAs are definitely the preferred choice for analog and narrowband resonant system measurement. High-speed interconnects, however, are not strongly resonant, and the significantly higher dynamic range offered by VNAs is not put to good use on the interconnect measurements.

With certain TDR step generator accessories (see reference [16]), you can realize faster rise time steps. These accessories allow even higher frequencies to be characterized with TDR, and enables TDR to resolve even smaller features. This extends the range of applications for which these instruments are suitable even further.

The 50-110 GHz VNA is the instrument of choice if:

• even with the accessories, the rise time of the TDR oscilloscope is not sufficient for your high-speed digital application

• you require a frequency range of higher than 20 GHz for loss characterization

• you require the ultimate dynamic range of a VNA for sharp resonance in a digital package

These situations are not commonplace today in high-speed digital design.

VNA are very useful instruments in microwave and RF system design, wireless design, and other narrowband systems design. With the wireless communication revolution well under way, there will be no shortage of need for these powerful instruments. Some signal integrity engineers, having come from a microwave design background, will always prefer a VNA. For a majority of other signal integrity engineers who come from the digital-design world, TDR will be the clear choice for most of their signal integrity measurements.

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Glossary

TDR Time-domain reflectometry, or the measurement of reflected and transmitted voltage

TDR/T Time-domain reflection transmission

S-parameters Scattering parameters. S-parameters are a ratio of the reflected or transmitted wave voltage to the incident wave voltage.

Smith Chart For transmission systems, a Smith Chart helps you translate a reflection coefficient into impedance. You can download an interactive Smith chart at
http://www.educatorscorner.com/experiments/spectral/SpecAn9.shtml

VNA vector network analyzer

FFT Fast Fourier Transform, a computationally efficient implementation of a discrete Fourier transform, which is an algorithm used to transform time domain data into frequency domain

Related Literature

Publication Title	Publication Type	Publication Number
Time Domain Reflectometry Theory, AN 1304-2	Application Note	5966-4855E
Improving TDR/TDT Measurements Using Normalization, AN 1304-5	Application Note	5988-2490EN
86100A Infiniium DCA Time Domain Reflectometry	Product Overview	5988-0573EN

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