Application Note

Choosing Signal Integrity Measurement Tools: Time or Frequency Domain?

To obtain accurate models for high-speed interconnects, a signal integrity engineer eventually needs to perform a measurement-based validation of the interconnect models. At that point, a choice needs to be made about the type of test equipment to be used to accomplish the job. Ease of use, accuracy, and cost are only a few of the attributes that will dictate the right instrumentation. The Time Domain Reflectometry (TDR) oscilloscope and the Vector Network Analyzer (VNA) are the two most common instruments used today. The choice between these two sometimes moves to a more theoretical choice between time and frequency domain measurements. Occasionally, it becomes a choice of personal belief in one domain being superior over the other. In reality, there are appropriate times for the use of both instruments.

This paper will analyze the physics and mathematics of the relationship between time and frequency domain measurements. Practical aspects of testing will be discussed, as well as the ease of use and accuracy issues of the time and frequency domain measurement instruments. In conclusion, the paper will provide some practical suggestions on how to choose the right instrument for the application.

Mathematics of Time and Frequency Relationship

TDR oscilloscope measures reflected and transmitted voltage to provide the user with the Time Domain Reflection Transmission (TDR/T) information, single ended or differential. Figure 1 displays the basic block diagram for a TDR measurement [1], [2].

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 Figure 1 above, the basic equations for ρ and Z will be:

$$\rho = \frac{V_{reflected}}{V_{incident}} = \frac{Z_{load} - Z_0}{Z_{load} + Z_0} \qquad (1)$$

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

If the impedance of the Device Under Test (DUT) changes, the reflected voltage will change with time and can be displayed as reflection coefficient or impedance vs. time:

$$\rho(t) = \frac{V_{reflected}(t)}{V_{incident\ \ amplitude}} \qquad (3)$$

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

$$\tau(t) = \frac{V_{transmitted}(t)}{V_{incident\ \ amplitude}} \qquad (4)$$

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.

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, and for a 2-port measurement, shown in Figure

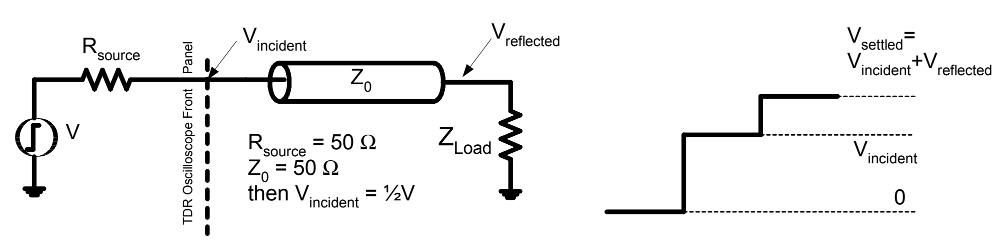

Figure 1. TDR measurement block diagram and a typical waveform shape

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2 below, can be written in its simplified form as, [3]

$$S_{11}(f)=\frac{V_{reflected1}(f)}{V_{incident1}(f)} \qquad S_{21}(f)=\frac{V_{tramsmitted2}(f)}{V_{incident1}(f)} \tag{5}$$
$$S_{12}(f)=\frac{V_{transmitted1}(f)}{V_{incident2}(f)} \qquad S_{22}(f)=\frac{V_{reflected2}(f)}{V_{incident2}(f)}$$

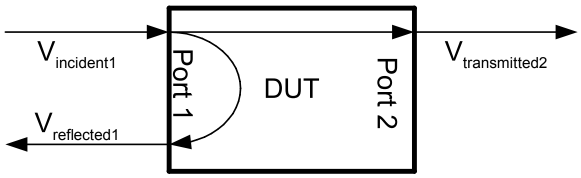


Figure 2. 2-port VNA measurement block diagram

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.

The basic block diagram of the TDR/T, compared to that of a 2-port VNA instrument, is shown on Figure 3 below. 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 fact that TDR is measuring voltage vs. time, while VNA is measuring power vs. frequency, as well as in the way data is displayed. Moreover, we observe clear similarity between equations (3), (4) and (5). Since we know from basic math that voltage in time and frequency domain are related by Fast Fourier Transform (FFT),[1] and deconvolution in time domain corresponds to division in frequency domain, we can easily see that there is a relationship between the TDR reflection and transmission coefficients and VNA S-parameters:

$$S_{11}(f)=FFT(\rho(t)) \quad \rho(t)=\frac{1}{N}IFFT(S_{11}(f))$$
$$S_{21}(f)=FFT(\tau(t)) \quad \tau(t)=\frac{1}{N}IFFT(S_{21}(f)) \tag{6}$$

VNAs measure both real and imaginary parts of the signal vs. frequency, whereas TDRs measure voltage versus time. However, as equations above clearly indicate, there is a clear one-to-one relationship between the real TDR data versus time and real/imaginary VNA data versus frequency. All the information about the frequency domain is contained in the TDR/TDT measurements.

As the equations above indicate, scattering-parameter computation is just as valid for TDT (transmission) measurements as it is for TDR (reflection) measurements. TDT results in insertion loss (S_{21}), TDR in return loss (S_{11}).

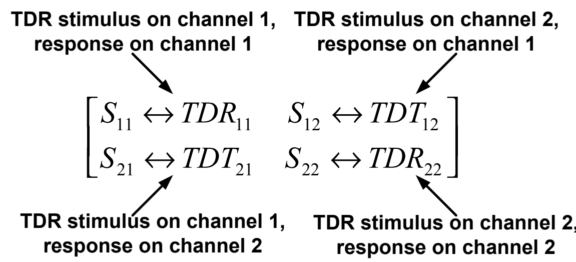


Figure 4. There is a clear relationship between TDR and TDT measurements in time domain and network analyzer measurements in frequency domain

As an example, consider the simple cases of Z_{DUT}=0 (short termination, ρ=-1), Z_{DUT} = 50 Ohm (matched termination, ρ=0) and Z_{DUT} = ∞ (open termination, ρ=+1). For all three cases, both TDR and VNA provide the same reflection coefficient measurement result, as indicated above.

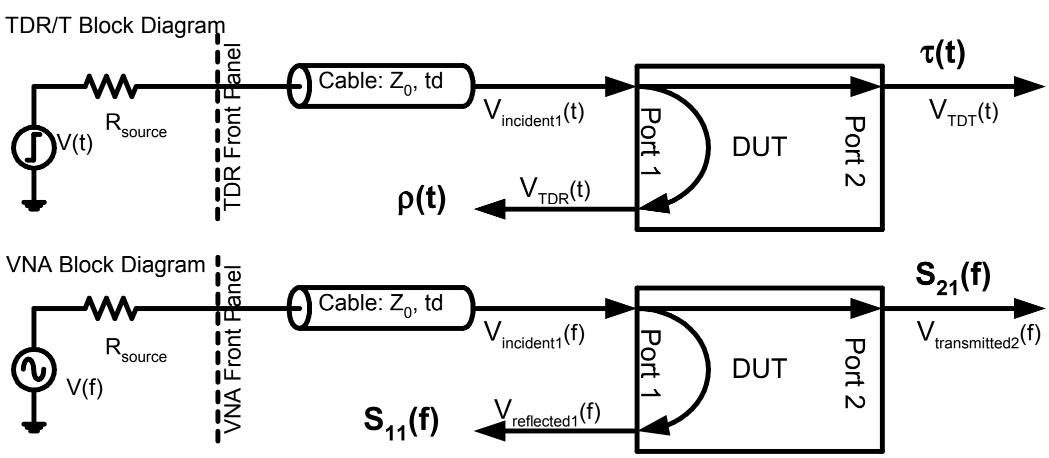


Figure 3. TDR/T measurement block diagram, compared to equivalent 2-port VNA block diagram

[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. TDR oscilloscopes quickly found their way into interconnect characterization and signal integrity work, where the intuitive and visual nature of TDR allowed the digital designers to quickly gain insight into their interconnect performance. Differential TDR functionality has existed for many years, which allowed the TDR instruments to assist designers with differential interconnect characterization. Currently, TDR oscilloscopes can provide multiport single-ended or differential capability. Software tools for extracting and validating interconnect models from measurements and even for computing S-parameters from TDR data, such as IConnect® TDR software from TDA Systems, have been developed, expanding the applications for the TDR instruments. Furthermore, Time Domain Network Analysis (TDNA) calibration and measurement routines, designed to enhance the accuracy of TDR and TDT measurements in a manner similar to that of VNA calibration, yielding data in both time and frequency domain, have been reported [4]-[6] and implemented in tools such as MultiCal software from United States National Institute of Standards and Technology (NIST). The calibration brought the accuracy of TDNA to the level similar to that of network analyzers.

VNA instruments were originally developed as a microwave design and measurement tool. In microwave design, engineers were concerned primarily with narrowband and resonant systems, such as mixers, filters, resonators, 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 and achieve very high dynamic range (signal-to-noise ratio) in 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 the instrument accuracy and extend its frequency range [7]. Powerful microwave design tools, such as Touchstone, were developed for analysis and synthesis of microwave electronic systems.

Differential VNA capabilities have not been added to VNAs until very recently; currently, a 4-port single ended or 2 port differential capability is available. However, because high accuracy is required for narrowband microwave work, the focus of development for these instruments was on this accuracy, rather than ease of use, making them less amenable to digital designers without microwave design background. The designer or test engineer needs to really understand and meticulously follow the calibration procedures in order to obtain the data from a network analyzer.

Practical Comparison of TDR and VNA Measurements

Signal integrity interconnects are typically complex multi-component structures. For example, a path from a driver to 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 1V signal, which corresponds to about -40dB in frequency domain (Figure 5). Resonance in digital interconnects may happen, but they are typically not very sharp and do not require the same measurement dynamic range as a resonance in a high-Q microwave resonator.

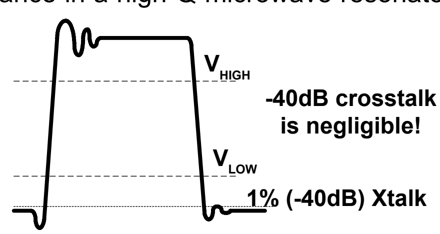


Figure 5. Crosstalk of -40 dB translates into 1% crosstalk in time domain. Such crosstalk typically is significantly below threshold and is ignored in digital system design

Digital designers live and design in time domain, and for them TDR offers well known advantages for time domain interconnect characterization, such as its intuitive, 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 6). Multiple reflections inside the DUT can obscure the correlation, but the true impedance profile for the DUT can be computed in IConnect TDR software.

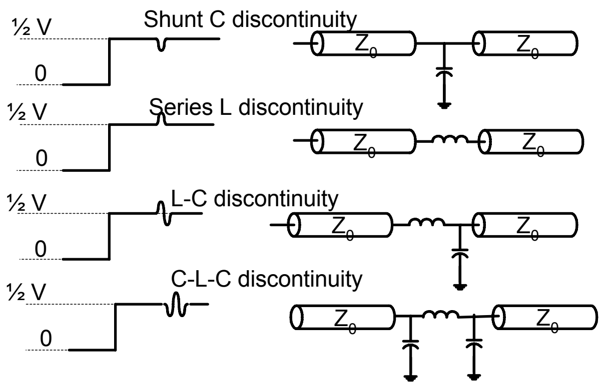


Figure 6. TDR waveform features can be easily correlated to the physical structure of the interconnect

For example, one 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. The transmission lines, surrounding the via, can be easily windowed out, and the portion of the waveform related to the via only can be analyzed.

VNA measurements, on the other hand, are steady state measurements. The same via, surrounded by two transmission lines, can not be easily isolated from the transmission lines with a VNA instrument in frequency domain. If the test structure allows the designer to isolate the via or de-embed the transmission lines, via inductance or capacitance can be obtained very accurately; if such de-embedding is possible, however, the via inductance can be obtained just as accurately with TDR using the technique for package characterization discussed in [8], [9].

For more complex interconnect structure characterization, the ability of a TDR instrument, coupled with IConnect TDR software, to obtain a *SPICE or IBIS physical model* for the interconnect exceeds that of VNA and VNA-based modeling tools. A physical model directly correlates its inductances, capacitances and transmission lines to the interconnect geometrical features. Such a physical model provides valuable insight into which components – a package, a board trace, or a via – of the interconnect system may be causing the most signal integrity problems, and therefore, must be redesigned (Figure 7). VNA-based modeling tools excel in creating a single element or on a multi-element behavioral model – that is, a model that will reproduce the S-parameter behavior over the specified frequency range. This behavioral model can be quite accurate, but it does not provide a designer with an insight into which portions of the interconnect (connectors? PCB vias? Packages?) are the main causes of signal integrity problems, and therefore must be replaced with an electrically better performing component or material. In addition, for long transmission line structures, such behavioral models can be quite large and cumbersome to utilize.

TDR instruments do provide lower dynamic range than VNA instruments, which is a result of both narrowband noise filtering in frequency domain and advanced frequency domain calibration techniques in VNAs. Typical TDR dynamic range is in 25-40 dB, whereas VNA can provide 100dB or even more of dynamic range. However, as noted 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, a TDR user can use digital averaging in a TDR oscilloscope, which has the same effect on the dynamic range as narrowband filtering in the VNA. As a mat-

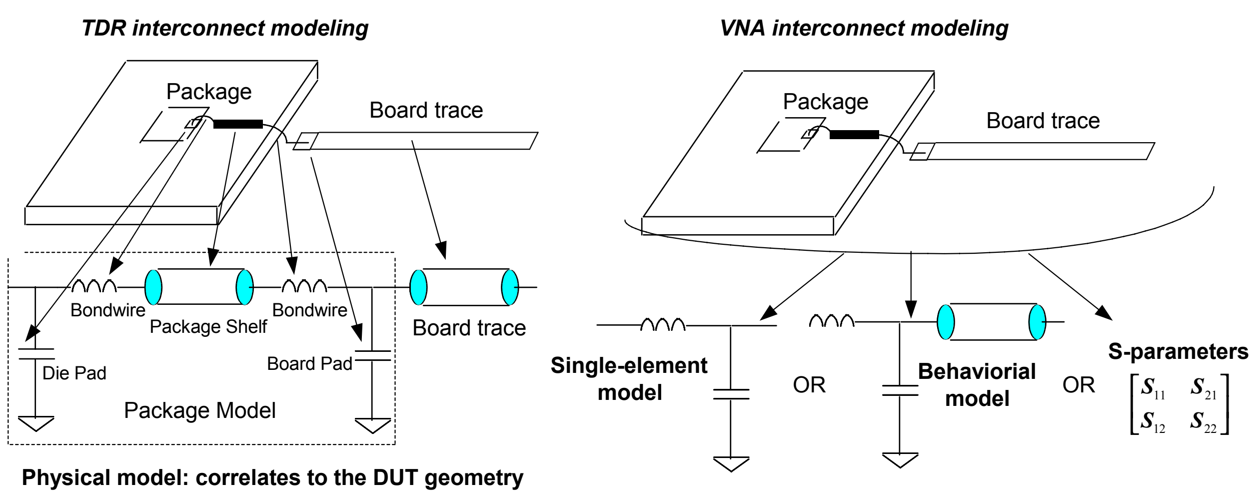


Figure 7. The intuitive and easy to use TDR modeling methodology allows the designer to extract a package model that correlates well with the physical layout of that package. VNA models are either single-element, or behavioral models, or S-parameters. All of these VNA models will match the frequency response of the circuit, but additional analysis is required to isolate the problem spots in the interconnect structure when using VNAs

ter of fact, every time the TDR oscilloscope user increases the averaging in the oscilloscope two times, he or she increases the dynamic range by 3dB. Therefore, by using 128 averages instead of 1 (i.e., instead of no averages), one can increase dynamic range of the scope by 21dB, easily reaching the 40dB dynamic range, which is more than sufficient for accurate interconnect measurements.

Without the frequency domain calibration, the accuracy of any frequency domain data is limited by the frequency at which the measurement fixturing or probing becomes nonideal. In fact, uncalibrated S-parameter measurements are a valid way of qualitatively determining the maximum frequency to which your fixturing setup is accurate.

If a VNA has a time domain option, it can be used much the same way as a regular TDR oscilloscope can be used. However, the same advantages that VNA instruments have – high dynamic range and accuracy, resulting from advanced calibration procedures – result in more lengthy measurement process and higher learning curves for digital design engineers, compared to those of TDR oscilloscopes. We just *briefly* discussed the theory of S-parameters; for a typical digital design engineer, without microwave design background, dealing with frequency domain S-parameters and VNAs is a daunting task, and creating a SPICE or IBIS model for high-speed digital interconnects from frequency domain S-parameters is certainly not an intuitive process. The comfort level of this digital designer when dealing with differential and mixed mode S-parameters may be even lower - whereas differential TDR measurements can be sufficiently intuitive for this designer because of past experience with differential signaling in digital designs. The designer needs SPICE or IBIS models in order to simulate signal integrity in the digital system interconnects, and a VNA-based solution may be unnecessarily complex and difficult to understand.

Frequency Domain Measurements Using TDR

As the digital signal speed increases 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 characterized losses, and such data can be very precise in describing the performance of the interconnect systems over the desired frequency range. However, these S-parameter data can be difficult, if at all possible, to use with a SPICE or IBIS simulator directly. S-parameters need to be converted into a SPICE or IBIS model, which as noted above, 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 [10], as well as, based on this lossy line data, to predict the eye diagram degradation in the interconnect. Since TDR is a more visual and easy to use instrument for a typical digital designer, this TDR-based loss extraction methodology may be more intuitive for the same designer as well. The lossy line models that IConnect 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 for a digital designer to include the transmission line loss in the digital system simulations. Additionally, the software can compute single-ended, differential and mixed mode S-parameters from TDR/T data acquired with the TDR oscilloscope - similar to many VNAs offering computational options to obtain TDR waveforms. Even though the dynamic range of this measurement is lower than the dynamic range of a VNA, it is more than sufficient to analyze losses and resonances that may affect the digital signal integrity.

One has to take into account some digital signal processing issues, however, when converting the TDR data into S-parameters and VNA data into time domain, beyond the straightforward FFT computation. First, appropriate windowing techniques must be applied in order to obtain correct representation of the spectrum of the TDR signals, as well as to go from VNA S-parameters to time domain data [11], [12]. Secondly, one has 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:

$$f_{BW} = \frac{1}{2 \cdot \Delta t} \qquad T = \frac{1}{\Delta f} \tag{7}$$

This however, can be easily remedied by effective and accurate interpolation techniques. Finally, because the 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 value, but rather extrapolate the data to obtain that value. This may lead to some errors when measuring such broadband structure as the digital interconnect.

For example, for a typical time domain window of 5ns, with 10ps time step and 500points, 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, whereas the step of 200 Mhz may or may not be sufficiently fine, and interpolation of the TDR data may be necessary. A similar effect occurs when taking the VNA data into time domain: when measuring a 20 Ghz frequency sweep with 500 points, the resulting frequency step is 40Mhz, time window will be 25ns, and time step 500ps. This may not provide sufficient time resolution either, and interpolation of the VNA data may be necessary.

All these constraints lead to the fact that a 20Ghz TDR oscilloscope with 35-40ps reflected rise time really could not provide 20Ghz 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 normalization, SOLT, or other calibration as described in [4]-[6]. Conversely, a 20 Ghz network analyzer produces a much slower rise time than a 20 Ghz TDR oscilloscope.

TDR Resolution and 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 time domain option – 50, 60 and 110 Ghz systems – can provide faster TDR rise time to increase the available measurement resolution in time domain and allow measurements to a faster rise time. Let us examine this issue in more detail.

It is known that 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 30ps range, that limits the separation between two discontinuities to no less than 15ps. In vacuum, that corresponds to physical distance of about 180 milli inches (mils), or 4.5mm. In FR4, typical printed circuit board material with er of approximately 4, this distance is 90 mils or 2.3mm.

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 50Ghz or 110Ghz network analyzer with TDR option is required in order to compute SPICE models for their interconnects. The missing point is that the analysis above applies to a distance between two interconnects, not to the length of the single interconnects.

Faster TDR rise time is also necessary when the designer attempts to resolve two separate discontinuities when performing failure analysis of a board or package component. If the rise time of the device output driver is slower than the rise time of a 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 (Figure 8).

Figure 8. Slow device rise time will not be affected by a small discontinuity

Therefore, the only time a designer may wish for a faster rise time is when the output drivers of the design becomes 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.

Rambus Memory Board Example

Consider the following example of a Small Outline Rambus Inline Memory Module (SORIMM) used predominantly in laptop computer applications. The probe inductance is de-embedded in this measurement using the TDR normalization procedure.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 9.

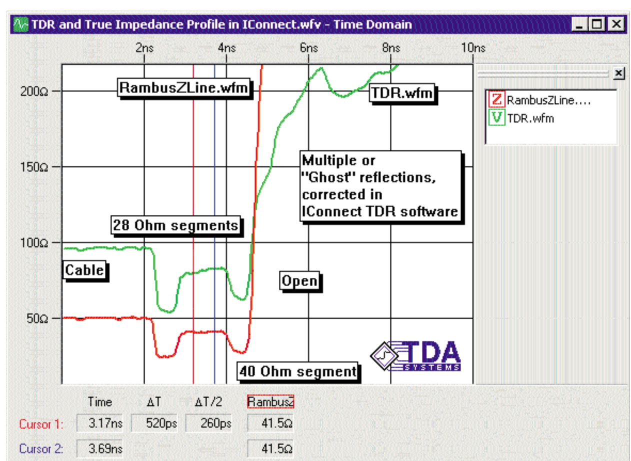


Figure 9. TDR and true impedance profile for the Rambus notebook module. Each segment of the true impedance profile can be correlated to a physical structure in the module trace. Multiple reflections in TDR waveform are corrected in IConnect to produce an accurate impedance measurement

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 from TDA Systems 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, can not recover information lost due to multiple reflections, unless the data is converted into time domain and the multiple reflection correction from IConnect is applied to the converted data.

IConnect TDR software produces S-parameter results from TDR/T measurements acquired with a TDR oscilloscope using a procedure much simpler than that of a network analyzer. It is required that you use an open reference waveform when computing S-parameters from TDR or TDT data in IConnect, in order to ensure the correct polarity of the phase. The S-parameter data produced from TDR does not require the same complexity of calibration as that of a VNA. The normalization procedure is quite adequate for high-speed digital device S-parameter measurement. As we stated before, the dynamic range of a TDR measurement can be increased with the advanced calibration procedures discussed in [4]-[6], but the 40 dB dynamic range required for high-speed digital work does not require that. For example, consider the following frequency domain data produced from a TDR measurement of the same Rambus module trace, Figure 10.

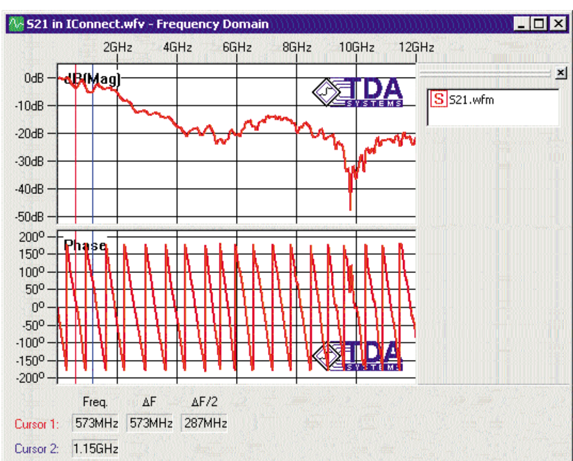
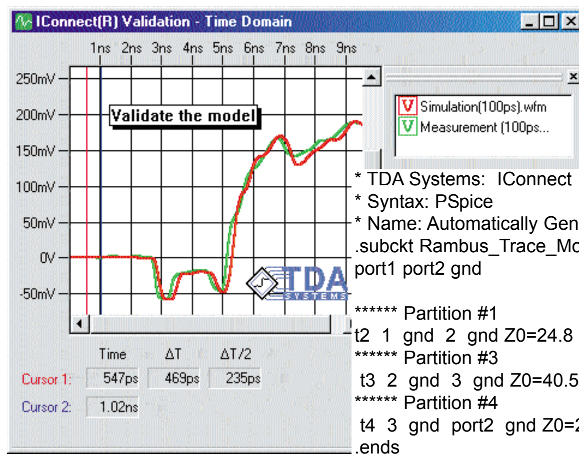


Figure 10. S_{21} produced in IConnect from the TDT measurement

The information that a digital designer requires 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 time domain. The overall slope of the amplitude waveform indicates the amount of loss in the trace. Additional skin effect and dielectric loss SPICE models can be extracted 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 the S_{11} plot generated from TDR measurement. The far end of the line was terminated with 50 Ohm, but even without this termination we could observe these frequencies. In addition, it is clear from Figure 10 that we do hit the noise floor of the TDR measurement system at about 45 dB , which provides sufficient dynamic range to perform this measurement.

Taking the TDR information about the DUT even further, it is possible to extract the model for the interconnect in IConnect. This model will produce a good correlation between simulation and measurement in time domain as shown in Figure 11.

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* TDA Systems:  IConnect
* Syntax: PSpice
* Name: Automatically Generated
.subckt Rambus_Trace_Model
port1 port2 gnd
****** Partition #1
t2  1  gnd  2  gnd Z0=24.8 TD=273p
****** Partition #3
 t3  2  gnd  3  gnd Z0=40.5 TD=645p
****** Partition #4
 t4  3  gnd  port2  gnd Z0=27 TD=273p
.ends
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Figure 11. 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

A sample listing of a simplified transmission line model is given in Figure 11. 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). The procedure for extracting such interconnect models from TDR measurements is discussed in [10], [13] and other publications from TDA Systems. Such good correlation at 45 ps rise time of the TDR oscilloscope as that shown on Figure 11 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 those two waveforms in IConnect as shown on Figure 12. 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.

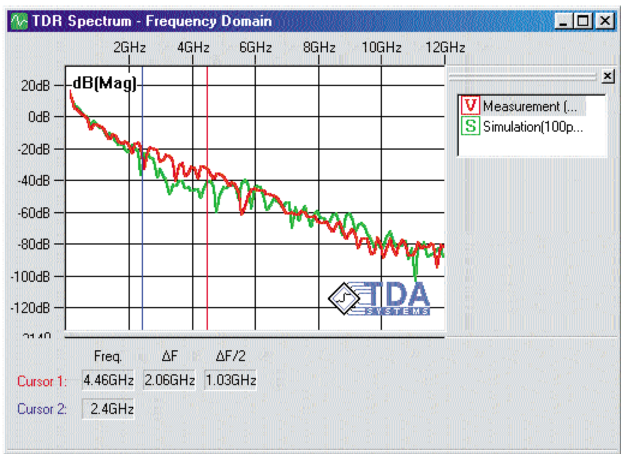

Figure 12. Correlation between the spectra of the same two waveforms shown in Figure 11. There is as much as 1-2 dB of discrepancy at 2.5 GHz. However, this discrepancy is not significant enough to have an effect on the time domain measurement

Differential Interconnects in 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 has always been a differential instrument because differential interconnect characterization has been its goal from the very inception of the technology. Differential TDR measurements have been understood and standardized. Novel differential interconnect modeling techniques have been developed and reported [14].

Recently, differential test sets for the 6 and 20 Ghz network analyzers have been developed. 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 this improvement in dynamic range is not necessary and is not utilized on the digital interconnect characterization. The complexity of use of such differential VNAs, however, may outweigh the accuracy enhancements. 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 the users 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 13 below shows the four major stimulus/response combinations that can be easily obtained with the TDR instrument. They are Differential Stimulus & Differential Response, Common Mode Stimulus & Differential Response, Differential Stimulus & Common Mode Response, and Common Mode Stimulus & Common Mode Response. The following is the S-parameter matrix in frequency domain equivalent to TDR/T data in time domain:

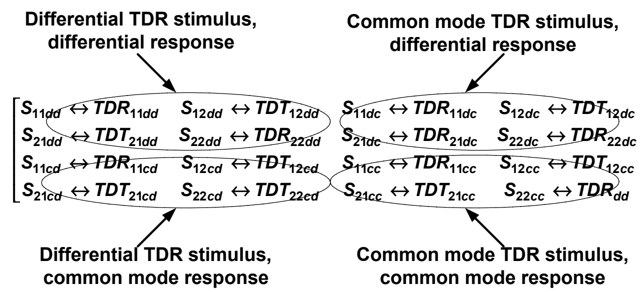

Figure 13. Differential and mixed mode S-parameter matrix can be produced from TDR measurements in IConnect TDR software

The upper left quadrant is responsible for differential signal propagation, lower right for the common mode signal propagation, and the other two quadrants are responsible for signal mode conversion from differential to common mode. The lower left quadrant is responsible for generated EMI and upper right for 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 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.

Infiniband Reference Board Example

Consider the following example of Infiniband Reference Board measurements. To further improve measurement accuracy, the connector from the probe to the board was de-embedded by acquiring a TDR waveform of a 50-Ohm termination (100 Ohm differential) at the end of the probe and subtracting it from the TDR/T waveforms in 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 TDR measurements [15].

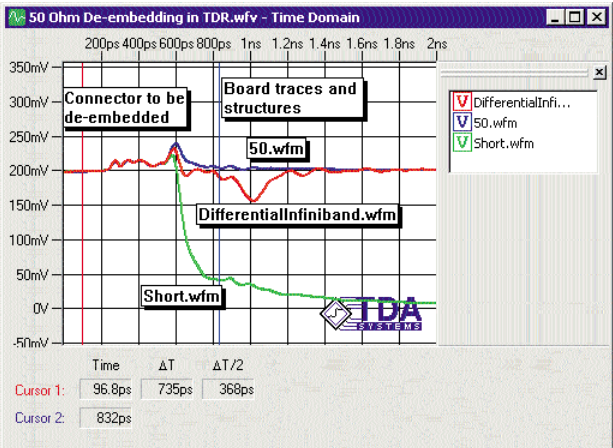

Figure 14. De-embedding of the probe effects by subtracting the reference 50-Ohm waveform. One can clearly see that we can remove the probe connector effects by subtracting the 50-Ohm reference waveform from the DUT and reference short waveforms

Just as with any de-embedding, the designer needs 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. This 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.

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 [14]). 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 15.

It is seen that these three lines are of different length, and the corresponding S-parameter picture, computed in IConnect from the TDR data, reflects that through the differences in phase and resonant frequencies in the structure. Furthermore, to characterize differential crosstalk, one could stimulate one differential pair and observe the induced crosstalk on the adjacent pair. The modeling capabilities of IConnect TDR software can then predict the crosstalk in this differential system.

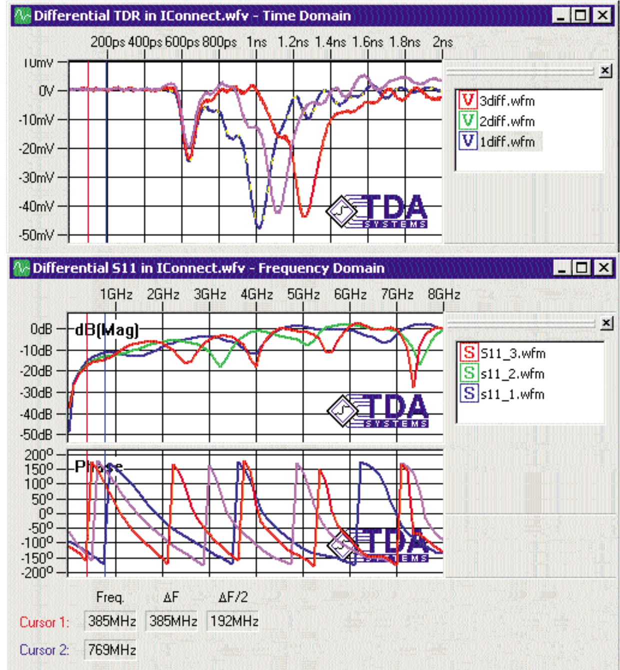

Figure 15. Differential TDR measurement and corresponding S-parameter measurement computed in IConnect. The frequency domain S11 data is displayed up to 8Ghz

If we were looking for sources of EMI, then the common mode response to a differential stimulus would be the most informative (Figure 16).

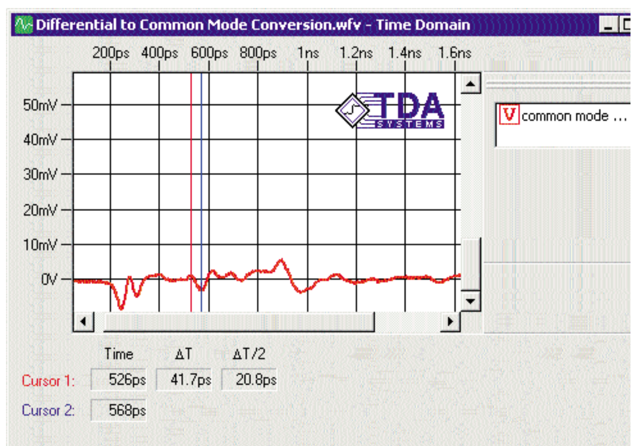

Figure 16. Differential to common mode conversion in IConnect TDR software. The segments where the common mode is generated from the differential stimulus will be the main EMI sources in this differential pair

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 and will not be of interest here.

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 the TDR oscilloscope measurements, a digital designer 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]), faster risetime steps can be realized. These accessories allow even higher frequencies to be characterized with TDR, and enable TDR to resolve even smaller features. This extends even further the range of applications for which these instruments are suitable. If, even with these enhancements, the rise time of the TDR oscilloscope is not sufficient for the given high-speed digital application, or if the frequency range of higher than 20 Ghz is required for loss characterization, or the ultimate dynamic range of the VNA is required for a sharp resonance in a digital package, the 50-110Ghz VNA is the instrument of choice; however, these situations are rare in high-speed digital design today.

VNAs are very useful instruments in microwave and RF system design, wireless design, and other narrowband system 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 microwave design background, will always prefer a VNA. For a vast majority of other signal integrity engineers, who come from the digital design world, TDR will become the clear choice for most of their signal integrity measurements.

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