Application Note

TDR and VNA Measurement Primer

TDR and VNA Basics

Two basic measurement techniques exist for signal integrity characterization of gigabit interconnects in digital systems - Time Domain Reflectometry (TDR) and frequency domain Vector Network Analysis (VNA).

The TDR instrument is a very wide bandwidth equivalent sampling oscilloscope with an internal step generator. The TDR sends a step stimulus to the DUT, and based on reflections from the DUT, the designer can deduce a lot of information about such DUT properties as location of failures, DUT impedance and time delay, and gain insight into the topology of the system. The user can also use Time Domain Transmission (TDT) measurement to measure crosstalk or to characterize lossy transmission line parameters, such as rise time degradation, return loss, and skin effect and dielectric loss. However, one cannot observe the frequency dependent behavior of the system directly on the instrument; additional software is required to achieve that.

TDR is visual and intuitive due to the transient nature of this measurement technique. The incident step propagates through the discontinuities in the DUT, and the reflections indicate the exact location of discontinuities and their size. The fast TDR rise time (25-35ps in currently available Agilent and Tektronix TDR oscilloscopes) ensures that a wide range of frequencies is captured during this broadband measurement, Figure 1.

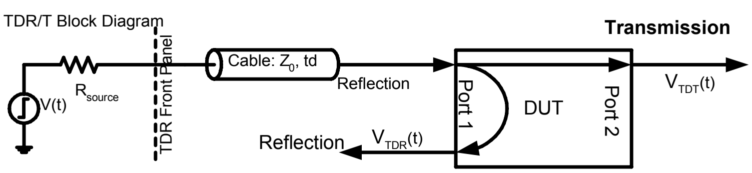

Figure 1. Time Domain Reflection and Transmission (TDR and TDT) block diagram. A similar diagram can be drawn for reverse measurements (from port 2 to port 1).

Any of these measurements can be performed in a differential or single ended fashion. In differential, common or mixed mode, the measurements require at least 2 synchronized sources and a 4-port measurement setup, as shown in Figure 2.

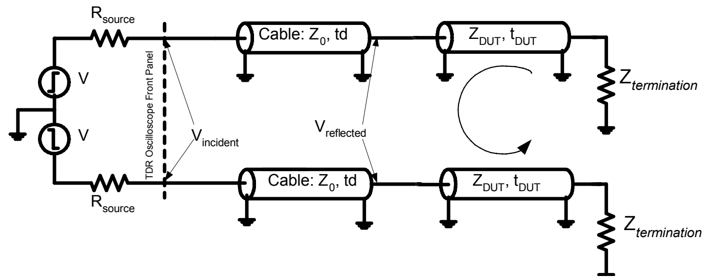

Figure 2. A differential, common mode or mixed mode measurement would require a 4-port measurement setup

The VNA uses sine waves as a stimulus, and uses a very narrow band filter at the receiver end. The measurement is performed by sweeping the source and the receiver in a synchronized fashion, making it a swept-frequency, steady state measurement. As a result of this measurement, the user obtains information about frequency domain performance (often referred to as S-parameters) and losses in the system (insertion and return loss). However, in order to gain insight into the topology of the DUT, as one does with a TDR measurement, one must convert the data into time domain using additional software.

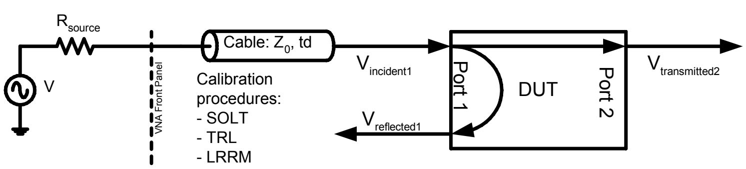

Figure 3. VNA measurement block diagram. A similar diagram can be drawn for reverse measurements (from port 2 to port 1). A differential, common mode or mixed mode measurement would require a 4-port measurement setup

The Similarities

When comparing the equations for time and frequency domain measurements, one cannot help noticing that they look very similar.

$$TDR: \quad \rho = \frac{V_{reflected}}{V_{incident}} = \frac{Z_{load} - Z_0}{Z_{load} + Z_0} \qquad Z_{DUT} = Z_0 \cdot \frac{1+\rho}{1-\rho} \qquad (1)$$

$$VNA: \quad S_{11} = \frac{V_{reflected1}}{V_{incident1}} = \frac{Z_{input(DUT)} - Z_0}{Z_{input(DUT)} + Z_0} \qquad Z_{input(DUT)} = Z_0 \cdot \frac{1+S_{11}}{1-S_{11}} \quad (2)$$

In fact, the two measurements are related via Fourier Transform. The time domain and transmission data can be obtained from frequency domain S-parameter measurements via Fast Fourier Transform (FFT) with

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the use of proper windowing and signal processing techniques. The VNA data can be converted into time domain either with the time domain option on the VNA, or with additional software (such as TDA Systems' IConnect®). At the same time, frequency domain data, such as insertion and return loss, and frequency dependent crosstalk can be obtained from the TDR oscilloscopes using the same software mentioned above. The correspondence between the time and frequency domain waveforms is shown on Figure 4 below. The differential stimulus, differential response (upper left) quadrant is most commonly used and most important for digital design and signal integrity analysis. The upper right and lower left quadrant are what is referred to as "mixed-mode" S-parameter quadrants, which are used in digital design least frequently.

Differential stimulus, differential response (differential quadrant)

Common mode stimulus, differential response (mixed mode)

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

Differential stimulus, common mode response (mixed mode)

Common mode stimulus, common mode response (common mode quadrant)

Figure 4. Correspondence between time and frequency domain waveforms

In recent years, differential network analyzers have been introduced, which allow measurement of insertion and return loss in differential, common and mixed mode. At the same time, new TDR add-on modules on the market, such as those from Picosecond Pulse Labs, allow measurements up to much faster rise times and frequencies.

The Differences

The dynamic range of a VNA tends to be substantially higher than that for a TDR measurements (up 110 dB for VNA vs. 50-60 dB for TDR). It makes a big difference in microwave design world. However, in signal integrity and digital design, this difference is not as significant, as vast majority of the measurement tasks can be achieved with 40-50dB of dynamic range, and 80% of the measurements with even less. When evaluating this statement, it is worth remembering that -40dB measurement translates into mere 1% crosstalk in time domain, which many times can be simply ignored; or that a recent standard such as Serial ATA requires insertion loss measurement only on the order of -10dB. The larger dynamic range is obtained in VNA mainly through the use of narrow band filtering at the receiver, but the digital averaging in TDR achieves the same effect of increasing the dynamic range of the measurement.

The better frequency domain performance of a VNA comes at a price; a user typically is paying at least twice as much for a VNA compared to a TDR-based system with a similar rise time and bandwidth. When choosing an instrument, it is also important to remember that because of windowing and signal processing required to convert the data from one domain to another, a 20 Ghz VNA will not provide as fast of a rise time as 20 Ghz 35ps TDR; at the same time, a 20 Ghz, 35ps TDR will only provide meaningful data up to about 10-12 Ghz in frequency.

In summary, TDR is more intuitive to digital designers, and hence gets used more for digital design and signal integrity analysis. It is broadband in nature, and captures all the frequencies up to the highest defined by the rise time at the same time. It enables the user to window out the unwanted parts, but this has to be done with care to ensure the multiple reflections (discussed below) do not distort the measurement picture. The VNA, on the other hand, is more accurate, narrowband, and more intuitive for designer with RF or microwave background. The higher accuracy also comes at a substantial cost difference vs. a TDR with a comparable bandwidth.

Probing and Fixturing

The measurement instrument, whether it is a TDR or a VNA, is connected to the Device Under Test (DUT) via cables, probes and fixtures. Because most digital designers have somewhat under appreciated the importance of the probing, cabling and fixturing of the DUT, this connection to the DUT frequently becomes the weakest link. In case of a TDR measurement, cables, probes and fixtures used during the measurement can significantly degrade the rise time of the instrument, reduce the resolution, and decrease the impedance measurement accuracy. This rise time degradation can be evaluated using the following approximate equation:

$$t_{measured} = \sqrt{t_{TDR}^2 + 2 \cdot \left(\frac{0.35}{f_{3dB}} \right)^2} \qquad (3)$$

where t_{TDR} is the rise time measured on the TDR scope with no cable connected, and f_{3dB} is the 3dB bandwidth of the cable, probe and fixture combined. The factor of 2 this equation is due to the fact that the signal has to take a roundtrip through the cable before it is observed and measured as reflection on the oscilloscope. To avoid this degradation of the measurement performance, the user must ensure that the probes, cables and fixtures provide a connection for both a signal and a ground contacts during the measurement. The spacing between signal and ground must be small to ensure sufficient measurement bandwidth. The cable, probe and fixture performance must be adequate for the required measurement. For example, specifying a cable with a 3dB bandwidth (f_{3dB}) of about 10 Ghz for the scope with its own rise time of 30ps, will result in the rise time at the cable end of about 58ps.

In case of a VNA, the requirements for probing, fixturing and cabling are even more stringent, because of higher calibration requirements for the instrument. A VNA essentially cannot perform its functions to any level of accuracy without an advanced calibration routine and appropriate calibration standards, whereas a TDR is perfectly functional with just a basic vertical and timebase calibrations. In addition, these VNA calibration standards must enable calibration to the end of the designer's probe, cable, or fixture, or else it is impossible to de-embed those from the measurement. Gating techniques can help somewhat, but they perform the same function as windowing for TDR, and thus suffer from the same limitations caused by multiple reflections effects.

Multiple reflections

As the TDR signal propagates through multi-impedance interconnect, the incident voltage at each discontinuity changes, since at each discontinuity portion of the signal energy is reflected back to the oscilloscope, and only portion of the signal energy continues to propagate. Moreover, the signal traveling back to the oscilloscope is re-reflected back into the DUT. As a result, the signal begins to bounce back and forth within the DUT, creating the effect of multiple, or "ghost", reflections. The impedance measurement error in the oscilloscope quickly adds up, resulting in incorrect impedance readouts. An impedance deconvolution algorithm, such as that implemented in TDA Systems' IConnect software, must be used to allow the designer to de-embed the multiple reflections and accurately compute the true impedance profile for the each segment in the multi-impedance DUT, Figure 5.

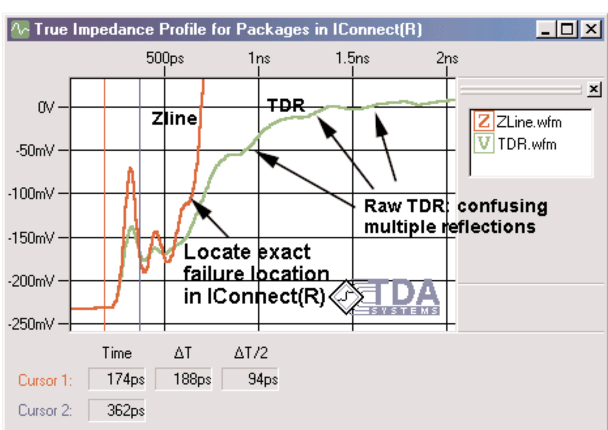
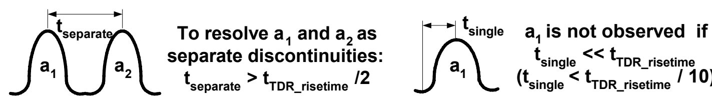


Figure 5. Exact failure location can be determined much more easily after the impedance profile has been computed in IConnect software

The multiple reflections occur both in waveforms generated by both TDR instrument directly, and by the computation based on the VNA measurements. This is why both windowing of TDR waveforms and gating of VNA-generated time domain waveforms will suffer from multiple reflection. The only time we won't be observing multiple reflections is when we are dealing with a single impedance interconnect without any discontinuities within the interconnect itself - such as a test coupon on a PCB.

Time domain resolution and rise time

The issues of time domain resolution are often misunderstood or misrepresented, because the time domain resolution is believed to be completely governed by the following rule of thumb. Two small discontinuities, such as two vias in a PCB, can still be resolved as two separate ones, as long as they are separated by at least ½ the TDR rise time:



(6a) (6b)

Figure 6. TDR resolution rules of thumb

However, in real-life situation, the designer typically is looking to observe or characterize a single discontinuity, such as a single via, or a single bondwire in a package, rather than separate several of such vias or bondwires. In this case, the above rule is totally irrelevant, and TDR can allow the designer to observe discontinuities of 1/10 to 1/5 of the TDR rise time, bringing the numbers above to 5ps or less than 1mm (25milliinches) range (Figure 6b). Even better resolution can be achieved with an addition of Picosecond Pulse Labs module to standard Tektronix or Agilent TDR equipment. Furthermore, there are well-developed relative TDR procedures for observing and characterizing even smaller discontinuities.

Signal Integrity Modeling

The similarities and differences between the two instruments dictate their application to different aspects of gigabit interconnect modeling. With addition of software such as TDA Systems' IConnect and MeasureXtractor, the user can use either instrument to generate gigabit interconnect SPICE/IBIS models and to analyze eye-diagram, jitter, losses, crosstalk, reflections and ringing in PCBs, flexboards, packages, sockets, connectors, and cable assemblies.

Using time domain-based analysis will provide the user with topological interconnect models, which have one-to-one correlation between the model components and the physical interconnect structure. Such model can include frequency dependent losses and resonances, and they are most convenient for troubleshooting the causes of signal integrity problems.

Using frequency domain-based analysis will provide the user with a behavioral model, which may provide a better overall frequency domain match, but does not necessarily provide a good insight into the interconnect topology. The behavioral models sometimes are referred to as "black-box" model, because the user cannot use them to trouble-shoot pieces of the overall interconnect link. However, because the algorithms for these models are more automated, they provide better model extraction efficiency - and sometimes faster simulation time. They are more convenient for quickly creating a model for a component that does not have a supplier-provided model, but that can be easily measured - and this measurement converted into a behavioral model.

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