Limitations and Accuracies of Time and Frequency Domain Analysis of Physical Layer Devices

White Paper

Agilent Technologies

Contents

Overview

This paper discusses the differences of the time domain reflectometer and the vector network analyzer for characterizing and troubleshooting physical layer devices. The limitations in accuracy, dynamic range, spatial resolution, frequency coverage (faster rise-times) effect characterization, and modeling typical structures are discussed in detail.

This paper was presented at DesignCon 2005, Santa Clara Convention Center, Santa Clara, CA, on January 31, 2005.

Introduction

The time domain reflectometer (TDR) has long been the standard measurement tool for characterizing and troubleshooting physical layer devices, and are common in all signal integrity labs. With the push towards higher speed differential signaling, and the need for more accurate characterization and modeling of differential interconnects (such as cables, connectors and printed circuit boards), the vector network analyzer (VNA) is becoming more common in signal integrity labs as well. The VNA brings more accuracy, dynamic range, and frequency coverage (faster rise-times) to this characterization and modeling. It also costs more than a TDR, and may not be as familiar to use by the signal integrity engineer.

Depending upon the data rates and complexity of the structure, measurements and modeling can be done in either the frequency domain using a vector network analyzer (VNA) or the time domain using a time domain reflectometer (TDR). With commercially available software, it is easy to move between the time and frequency domains and between single-ended measurements and differential measurements including measurements of mode conversion. How to perform comprehensive measurements for complete and accurate device or interconnect characterization with either system will be discussed.

To get high quality measurements, an understanding of the instruments' architecture, calibration, and specifications such as dynamic range, accuracy, noise, and stability will be presented. How each of these affects or limits the quality of the measurement will be discussed in detail. Several calibration techniques are available to remove sources of error in making measurements. These techniques will be compared using results of actual measurements. The differences between the TDR and VNA will be used to show the limitations of specific measurement techniques as well as their impacts on developing models for these structures.

A comparison of TDR and VNA measurements of various devices will be discussed. These devices include single-ended traceable devices such as air lines, mismatched lines, and attenuators, and typical differential structures such as backplanes, connectors, and cables. Measurement comparisons will include typical frequency and time domain measurements as well as eye diagrams based on the specific measurements.

The limitations of these measurement techniques as well as their impacts on developing models for these structures will be summarized with guidelines and recommendations on when to use specific instruments and calibration techniques.

Equipment Setup

The measurement equipment used in this paper consists of a four channel TDR with an 18 GHz bandwidth and a 4-port 20 GHz vector network analyzer. High quality phase stable cables were used to connect to the devices under test and comparable settings were used on each measurement instrument to achieve as fair a comparison as possible. The specific description and setup is:

- Agilent Infiniium DCA 86100A with 54754A differential TDR modules
- Tektronix CSA8000 with 80E04 differential TDR modules
- All TDR measurements were taken with a timebase of 5 ns, varying rise-time (with Agilent box), ~2000 pts, and 16 averages
- All PNA measurements 10 MHz to 20 GHz measured on an E8362B PNA Series analyzer with a N4419B S-parameter test set
- PNA measurements are taken over a 10 MHz to 20 GHz frequency range, ~2000 pts, and a 300 Hz IF bandwidth, and 1 average
- Standard GORE 1M cables were used for both TDR and PNA measurements of 3.5 mm and 7 mm devices

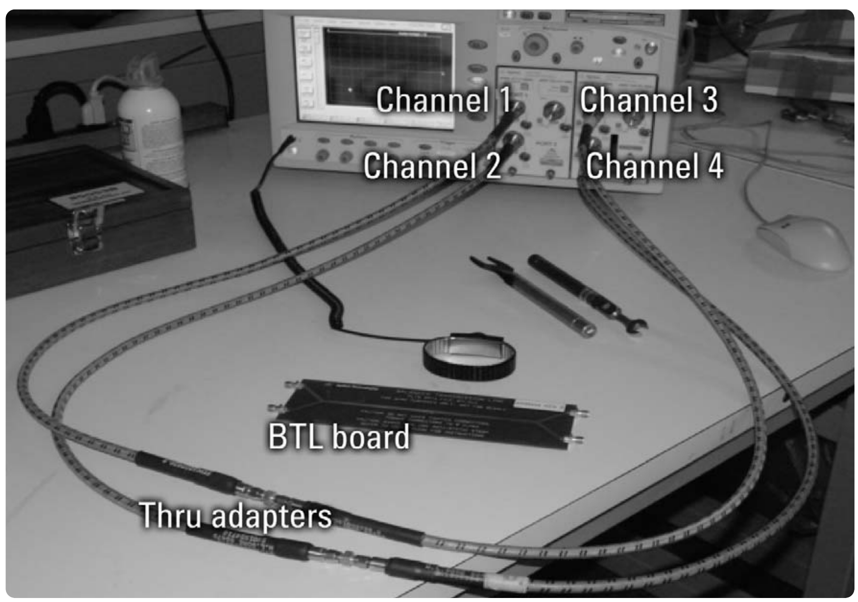


Figure 1. Typical measurement setup with Agilent TDR

Fundamental Differences between TDR and VNA Instruments

Time and frequency domains

In the case of the TDR, the measurement is done in the time domain by stimulating the DUT with a voltage step. There is a time delay for the step to travel through the DUT. This delay is related to the length of the DUT. Multiple reflections in the DUT will cause longer delays for the signal to propagate through the device. The size of these reflections can be determined from the magnitude variations.

Measurements with a PNA are done in the frequency domain. The device is characterized at each frequency of interest, one point at a time. The magnitude and phase shift is measured relative to the incident signal. The phase shift is related to the length of the DUT. The longer the DUT the larger the phase shift. Also, the higher the frequency the larger the phase shift.

A common measurement in the frequency domain is group delay. Group delay is computed from the phase by taking the derivative of the phase versus frequency. There is a duality between the time and frequency domains. All the frequencies from the device's characterization in the frequency domain are used to compute the time response.

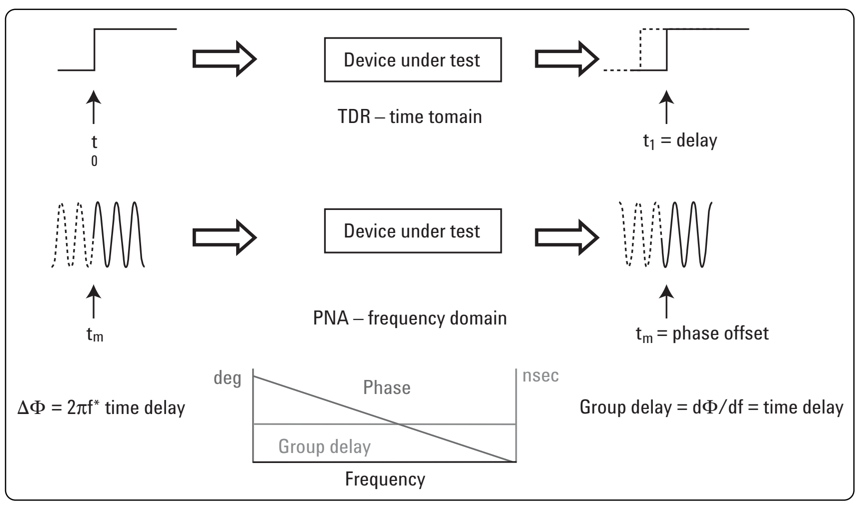


Figure 2. Time and frequency measurement domains

Measurements in the time and frequency domains are also related. A typical measurement in the time domain is a TDR measurement, which is the measure of the signals reflected from the device's input as a function of time. The equivalent in the frequency domain is the S-parameter, S_{11}, which is the input match or the input reflection coefficient. S-parameters are the ratio of the reflected wave (voltage) to the incident wave. Similarly, a TDR measurement shows the incident pulse and the reflected signals. The corresponding TDT measurement in the frequency domain is S_{21}, the ratio of the transmitted wave to the incident wave. More information on S-parameters is available[1]. Jitter in the time domain is related to phase shift in the frequency domain (Figure 3).

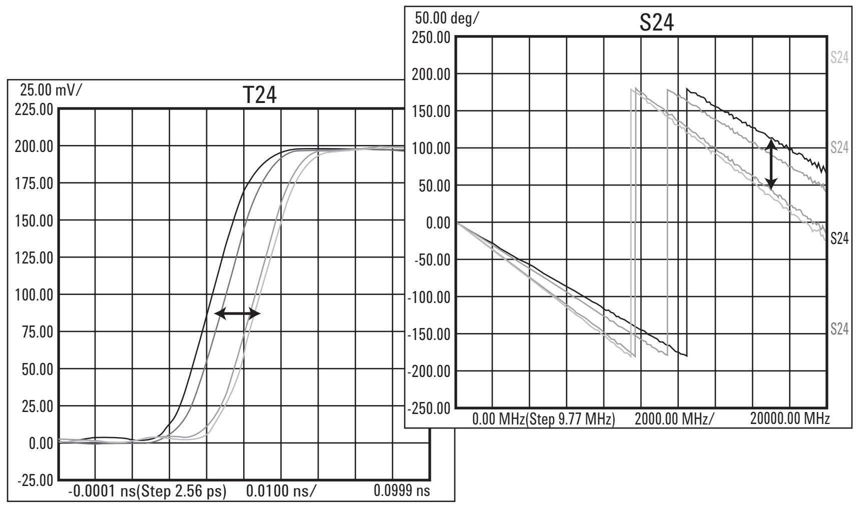


Figure 3. Jitter in the time domain is phase shift in the frequency domain

TDR and VNA sources

In the case of the TDR the source is a voltage step generator. The step generator puts out a voltage step with a rise time of 40 pico seconds. The frequency content of the step depends on the rise-time of the step and the power decreases the higher the frequency. This causes loss of dynamic range and accuracy for higher frequencies. The VNA source is a single tone frequency that is swept across a desired frequency range. The source power is typically leveled in a VNA and is constant over the entire frequency band, which doesn't cause loss of accuracy for higher frequencies. Figure 4 shows the sources in both domains.

TDR and VNA receiver bandwidths

The TDR has a broadband receiver with the choice of 12 or 18 GHz 3 dB bandwidths. The VNA has a selectable IF bandwidth. The bandwidth can be set from 1 Hz to 30 KHz (Figure 5). This narrow bandwidth significantly reduces the noise floor, to better than –110 dBm. Due to the wide band receiver of the TDR, the noise floor is higher, limiting the TDR's dynamic range to about 40 dB compared to the VNA's dynamic range of 100 dB. When also considering the source power roll-off at the higher frequencies of the TDR, the TDR signal to noise ratio above 10 GHz noticeably decreases.

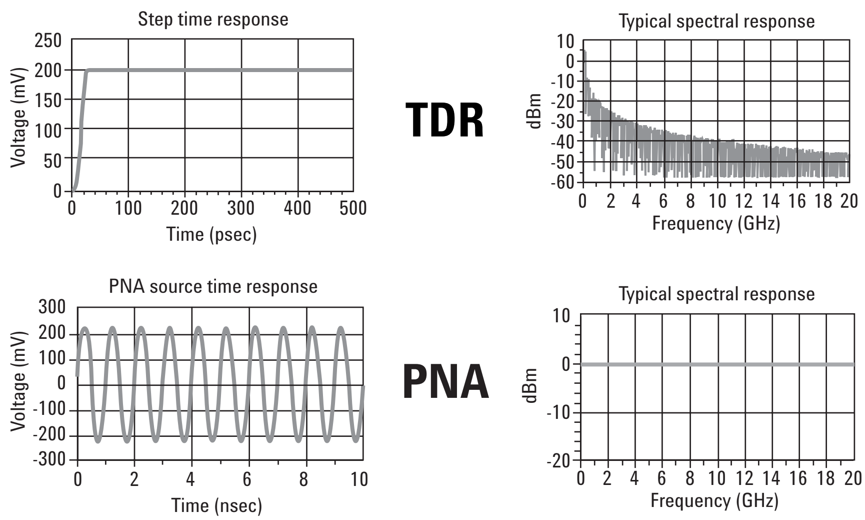


Figure 4. TDR and VNA sources

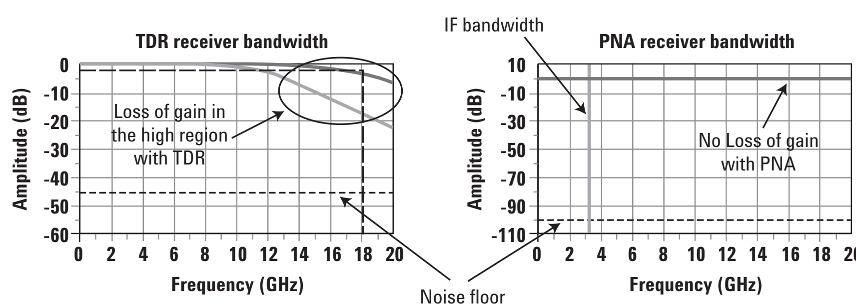


Figure 5. TDR and VNA receiver bandwidths

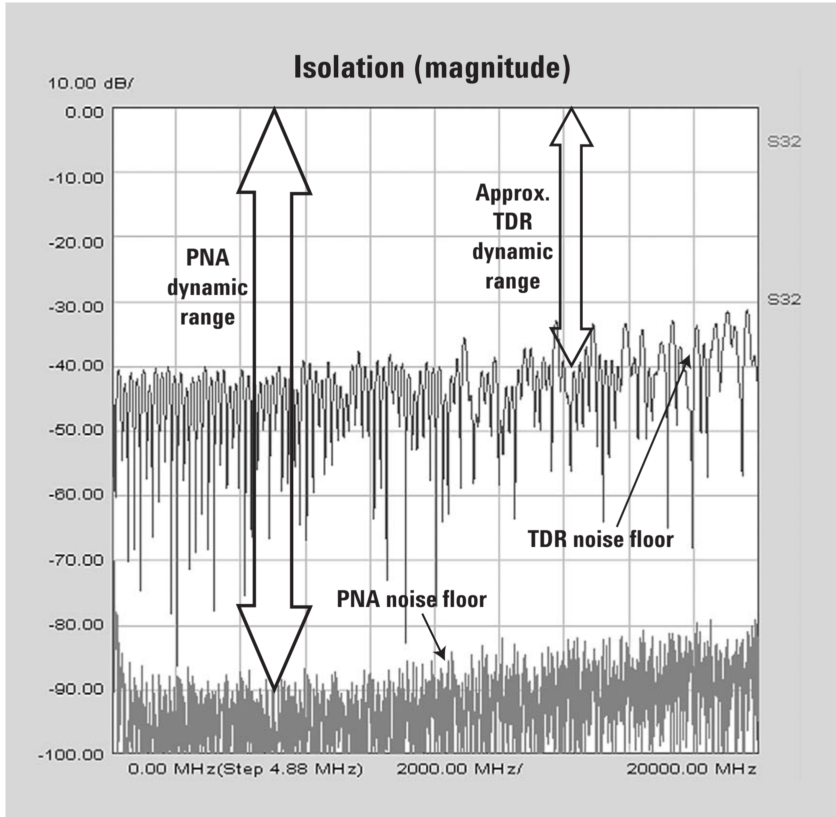


Figure 6. TDR and PNA dynamic range

Architectures and sources of error

Figure 7 shows a simplified block diagram of a four channel TDR. Each channel has a step generator that generates the stimulus to the device under test, a sampler, and an ADC to measure the signal.

For TDR measurements the ADC (e.g. Channel 1) samples the incident pulse and the reflected signals from the device under test (DUT). For TDT measurements, the signal is transmitted through the DUT and sampled by the ADC on channel 3. A common clock triggers each step generator. Jitter, timing, and drift will vary slightly between step generators.

Sources of error for the TDR can be divided into three areas. The first is errors do to the oscilloscope receiver channels. The second area is the step generator itself and thirdly the cables and connectors used to connect to the DUT.

- Oscilloscope
  - Finite bandwidth restricts it to a limited measurable rise-time
  - Small errors due to trigger coupling into the channels and channel crosstalk
  - Clock stability causes trigger jitter in the measurement
- Step generator
  - Shape of step stimulus (rise-time of the edge, aberrations on the step, overshoot, non-flatness)
- Cables & connectors
  - Introduce loss and reflections into the measurement system

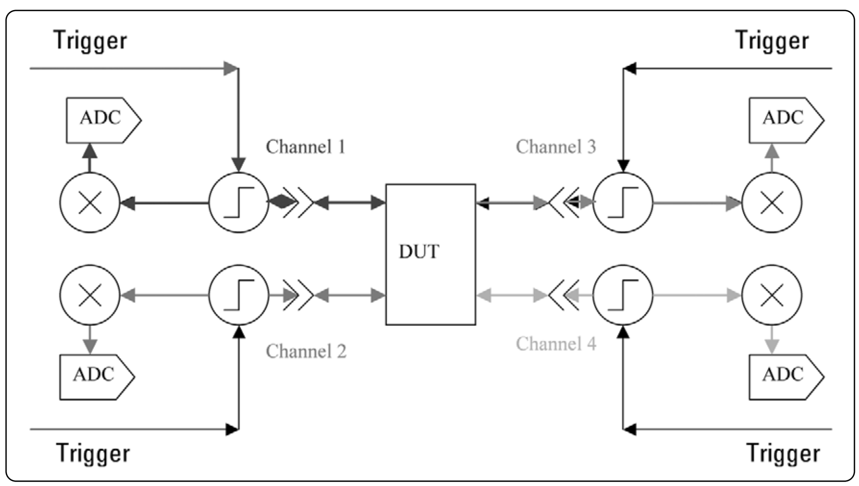


Figure 7. Simplified block diagram of a four channel TDR

The 4-port VNA has a single swept frequency source that is switched to each port (channel) to make a reflection and transmission measurement. The source (incident signal) is sampled by the reference receiver (R). The switches are set to route the incident signal through the directional coupler and to the desired test port. The directional coupler separates the reflected signal from incident signal and switches route the reflected signal to the "A" sampler. The S_{11} measurement is the ratio of A/R, which is equivalent to the TDR measurement in the time domain. Transmission measurements (e.g. S_{21} are the ratio of B/R and are equivalent to the TDT measurement. The source, reflected, and transmitted signals are appropriately routed to complete the set of 16 S-parameter measurements for a 4-port DUT. Figure 8 shows a typical VNA configuration for three receivers.

For a VNA there are random errors such as noise, switch and connector repeatability that are not corrected by calibration. There are also systematic errors that are corrected by calibration techniques. There leakage terms like directivity errors in each directional coupler and crosstalk between ports. The source and load presented by the VNA are not perfect and result in reflections due the mismatched impedances. Finally there are frequency response errors due to imperfect tracking of the receivers and signal paths. For a 2-port measurement there are twelve error terms and for a 4-port measurement there are 48 error terms that need to be corrected in the measurement. For the 2-port case the error terms are listed below in Figure 9. More information of VNA error terms and correction is available.[2]

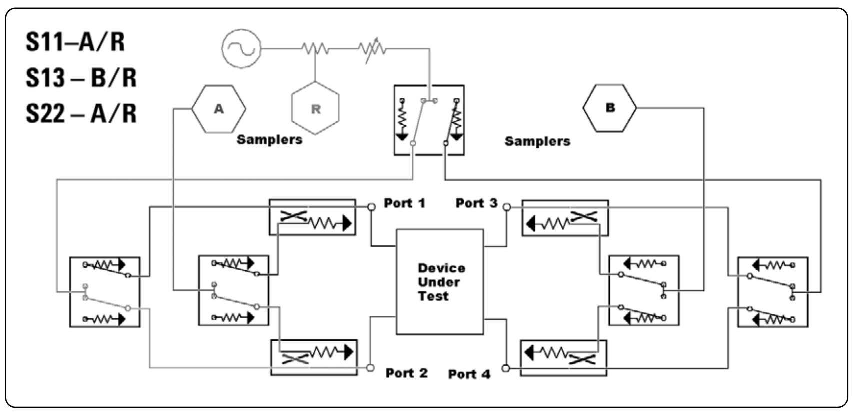


Figure 8. Simplified block diagram for a 4-port VNA

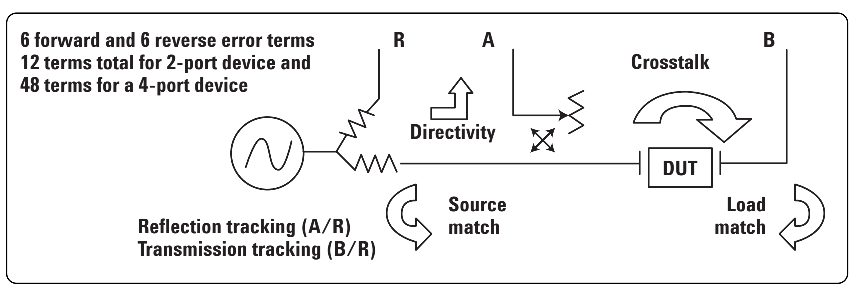


Figure 9. Systematic errors in a VNA

Overview of TDR and VNA calibrations

For a VNA one calibration does it all. It removes the systematic errors due to the instrument, test set, and cables used to connect to the DUT. All 48 error terms for a 4-port measurement are removed by connecting a short, open, and load to each port and connecting a thru between four or all six thru paths. Using extremely accurate calibration kits, this provides the most accurate measurements of S-parameters for linear devices. The S-parameter data taken in the frequency domain can be easily transformed into the time domain by using a Inverse Fourier Transform. All of the calibration is stored in a single file on the PC.

Calibrating a TDR for all the measurements for a 4-port device is more complicated. The process requires more than one calibration. First each of the modules need to be calibrated. This is referred to as a module or vertical channel calibration. All the test cables are disconnected from both modules and the calibration required placing a load on each channel at the directed time in the calibration process. This calibration calibrated the ADCs and timing in the modules. When completed the modules are calibrated to connectors on the front of the module. When this is completed the cables are re-connected to the modules and the second calibration begins.

There are two choices for this second tier calibration using Agilent TDRs. With Tektronics TDRs only the first one is possible. A reference plane calibration (RPC) is the quickest, but least accurate calibration. All that is required is to leave the test cables open and the PLTS software will find the end of the cables and set the measurement reference planes to that point. This is done for single-ended, differential, and common mode reflection measurements for channel. Thrus are then connected to each (six) of the thru paths. The RPC calibration removes the delay of the test cables by delaying the measurement time appropriately. Note this does not correct for the loss in the test cables or the overshoot and ringing of the step generators. For differential and common mode measurements any skew in the test cables and step generators is automatically removed. The reference plane is then set to the end of the “de-skewed” cables.

For Agilent TDRs a more accurate calibration can be used for the third calibration (part of the second tier). This process is called normalization. After the RPC calibration (leaving an open on each test channel) a normalization can begin. For single-ended TDR measurements a Short and Load are placed on each channel. The same is repeated for common mode calibration. For differential mode calibration the cross talk (or coupling) between stimulus channels is also removed. This requires the following steps to calibrate channels 1 & 2 and channels 3 & 4. First two shorts are places on channels 1 and 2. Then the short is removed from channel 1. Then a load is placed on channel 1 and finally the short on channel 2 is replaced with a load. The same is repeated for channels 3 and 4. The normalization process removes the cable loss, reflections due to source, and connector mismatch, and cleans up the shape of the step generator. More on this will be covered later in the presentation. To complete all of these normalization steps, 24 normalization and 24 setup files are created and stored on the hard drive in the TDR and 2 files are stored on the PC. These 50 files are recalled and used when measuring the DUT. The management of all of these files is automatically handled when using the PLTS software.

Note: For all of these calibrations for both the VNA and TDR it was assumed that a current factory calibration of the hardware was done.

The most accurate calibration is the VNA calibration, followed by the TDR normalization. Next is the reference plane calibration followed by a module calibration. The least accurate is to do an un-calibrated measurement. An un-calibrated measurement has none of the systematic errors removed and is only useful to get a quick idea of the general response of the DUT.

There is also a difference in the measurements made and the data that is computed between the TDR and VNA. For the VNA the 16 single-ended S-parameters for the 4-port DUT are measured in the frequency domain. From these 16 S-parameters 16 balanced (differential and common) S-parameters are computed[3]. The 16 single-ended and 16 balanced S-parameters are then used to compute the 32 time domain parameters using an Inverse Fourier Transform (IFFT). To get the differential of the common mode parameters, all of the single-ended parameters must be measured.

For the TDR, the 16 single-ended time domain parameters are measured. The four differential, four common and eight mode conversion parameters (another 16) are also measured. Using these 32 time domain measurements, the frequency domain measurements are computed using a Fourier Transform (FFT). Since each of the time domain measurements are measured independently and the FFT is done on each, the user only needs to measure the time domain parameters he is interested in. The frequency domain parameters for those parameters are then computed. This saves time in both calibration and measurement if not all of the parameters are needed. However it should be noted that having all of the measurement provides valuable information in troubleshooting unexpected results in the measurement of the DUT. The measurement and computation flow is shown in Figure 10.

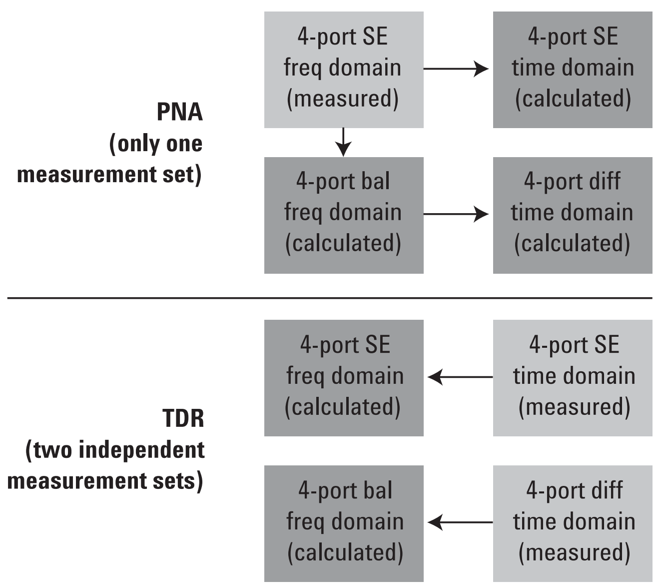


Figure 10. VNA and TDR measurement and computation flows

Summary of how VNA and TDR measurements differ

The first difference between the PNA and TDR is the measurement domain. The PNA measures the magnitude and phase of the signal in the frequency domain and the TDR measures in the time domain (voltage versus time).

The bandwidth of the measurement for the PNA is limited by the bandwidth of the instrument (20, 40, 50 GHz) or the user selected measurement range. For the TDR the bandwidth is dependent on the receiver bandwidth (usually fixed) and the rise-time of the source step.

How the instruments are calibrated, also differs significantly. For the PNA, a single calibration removes all the systematic errors. Depending on the calibration standards available the user can select between several calibrations types: SOLT, TRL, or LRM. For the TDR, there are multiple calibrations that can be made. First, each vertical channel needs to be calibrated by doing a module calibration. Second, a reference plan calibration (RPC) is performed to find the ends of the test cables to remove the phase shift (time delay) of the cables. Finally a normalization can be done to remove the cable loss and reflections due to source and receiver mismatches.

Finally the measurements that are made are different depending on the instrument used. The PNA measures 16 single-ended S-parameters and from them computes the 16 balanced parameters and then computes all 32 time parameters. The TDR measures both single-ended and differential time parameters and the single-ended and balanced frequency domain parameters are computed.

Measurement Criteria and Considerations

TDR measurement setting for device length

It is important to know your approximate device length and use this value to set your timebase appropriately. In general more time points around your device will help bring out small or closely spaced discontinuities and will improve reciprocity and other factors relating to over all measurement quality. In some extreme cases where the timebase is set to 5x or 10x the device length, and you are exporting the data (either time or frequency domain) to some other downstream tools (like TDA Systems- IConnect or HSPICE), those tools may have difficulty deciphering the characteristics of the device and ultimately using the data.

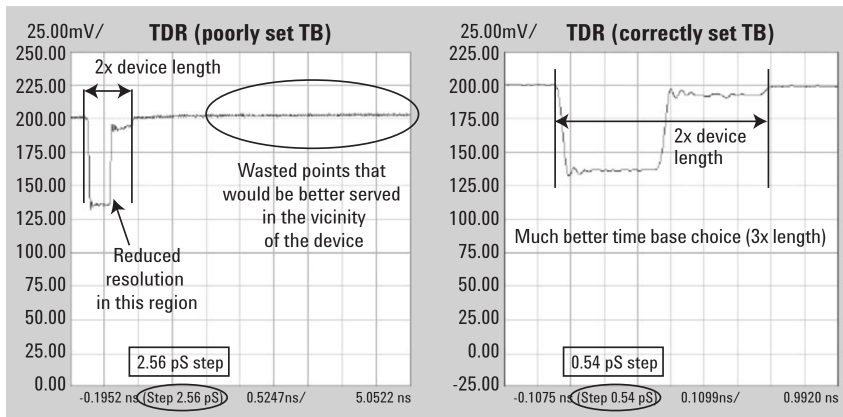


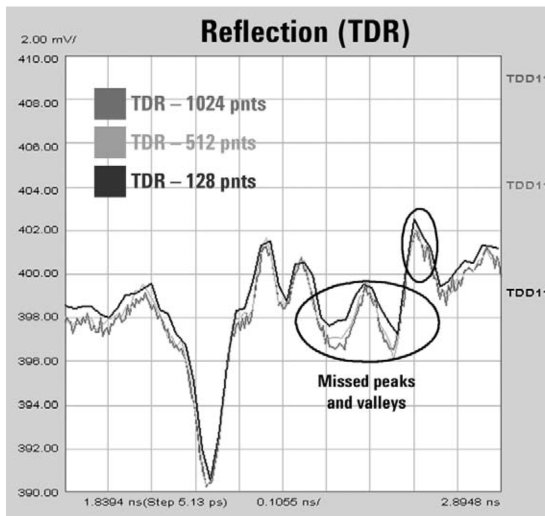
Figure 11. Example of a poorly chosen measurement range

TDR measurement settings for resolution

When considering the resolution you will require in your resulting measurement data, it is important to consider two main factors: spatial resolution (device complexity), and frequency domain resolution. Rise-time (if using normalization) and number of points are the main components that drive measurement resolution. While more complex devices don't generally support higher edge rates, it's necessary to normalize at a reasonably fast edge rate to distinguish closely spaced discontinuities like those associated with a PCB thru hole via or a package. Increasing the number of points helps with time domain resolution, helps detect resonances accurately in the frequency domain and only nominally increases the time to measure until you reach some of the higher settings (2048, 4096 points). In the example, note that the number of points had to be reduced significantly to exaggerate the effect, rarely would you need to drop the number of points below 1024. The top plot in Figure 12 shows this effect.

TDR Measurement setting dynamic range

Averaging has the effect of reducing noise on time domain signals (whether we are looking at volts or impedance) but it is more importantly a driver in lowering the noise floor (increasing the dynamic range) of the TDR measurement system. This can be important when measuring devices that have either a high loss (a 40 dB pad for example) or we are trying to measure very low signal levels such as mode conversion or crosstalk. In general set your noise floor so that it is at least 10 dB below the smallest signal you want to measure. If you are trying to measure signals that are 40 dB or smaller – you are much better off using a PNA measurement system. The bottom plot in Figure 12 shows the effect of averaging on noise floor.



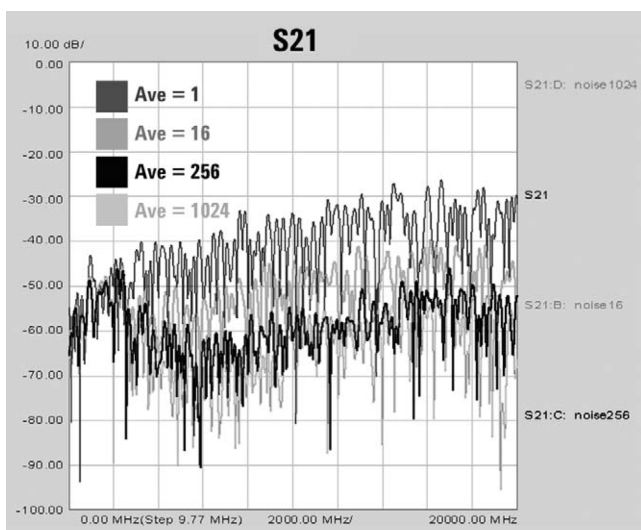


Figure 12. Example of poorly chosen spatial resolution for TDR measurement

Accuracy parameter definitions in time domain

Since accuracy can mean many different things to many people, let's define accuracy here as containing two components: peak-to-peak variation in the value (or noise; making it difficult to accurately determine what the nominal value is), and nominal deviation from the PNA value. A measurement that results in a lot of variation in amplitude but no nominal deviation from the PNA value would be as accurate as a very small peak-to-peak variation and almost no deviation from the PNA value. With that said the most accurate measurement is one with no variation and no deviation (uncorrectable error) from the PNA value. These two components provide a framework for discussing how normalizing at various rise-times affect accuracy. The dramatic increase in peak-to-peak variation (Figure 13) is mostly due to the fact that averages have been set relatively low at 16, at 1024 averages (which would take significantly longer for calibration & measurement) this peak-to-peak variation would probably be cut in half.

It's important to realize that normalizing at faster edge rates makes it increasingly difficult to actually measure impedances (or voltages if that's of interest). In order to accurately measure impedances, you need to trade off some amount of accuracy in the frequency domain or drive the number of averages up to minimize the increase in peak-to-peak variation as we go for normalizing at faster rise-times.

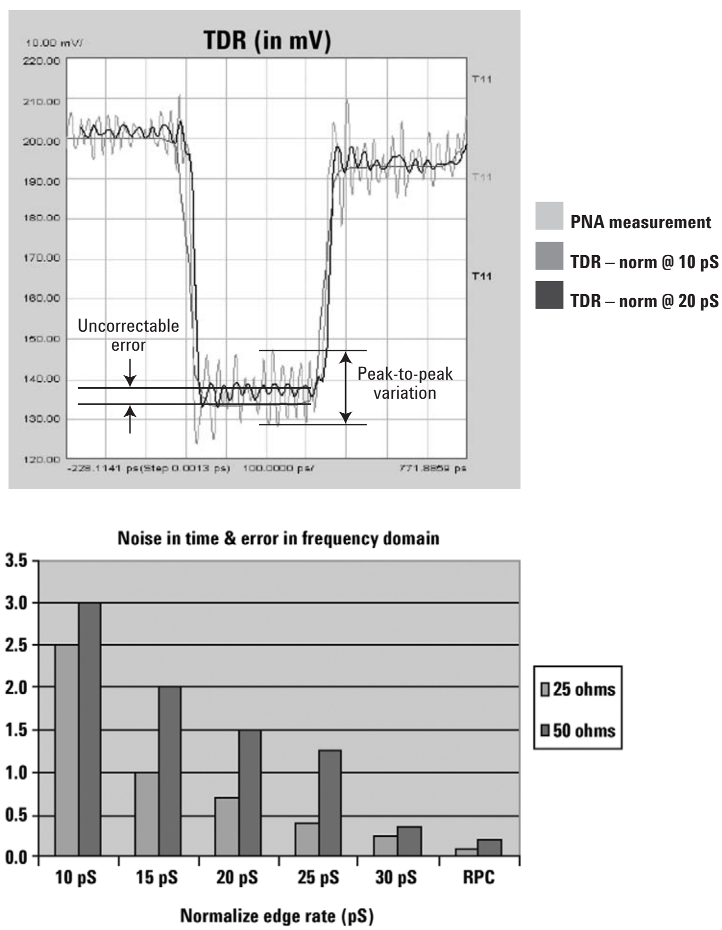


Figure 13. The increased noise to increased rise-time for normalized TDR measurements

Accuracy parameter definitions in frequency domain

We can also break accuracy in the frequency domain into these same two components and summarize our discussions at the end of this section in relation to the two domains and the two simplistic components of accuracy. Note in Figure 14 that while the increase in noise or peak-to-peak variation in moving from normalizing at 20 pS to normalizing at 10 pS is not as dramatic as in the time domain graphic in Figure 13, it is still noticeable.

The graph in Figure 14, shows how accuracy (percent of uncorrectable error) at a somewhat arbitrary point in the frequency domain is increased by increasing our edge rate (all dB values have been converted back into percentages to be plotted on the same graph as noise or peak-to-peak variation). While it may be a bit of a stretch to compare peak-to-peak variation in time domain against the opposite accuracy component in the frequency domain (uncorrectable error), these are the two factors that are impacted most in their respective domains with increasing rise-time.

Spatial resolution with VNA

When measuring balanced devices the same cautions apply. Spatial resolution actually becomes even more important when trying to design balanced devices. For example, discontinuities that are only slightly skewed in time in two legs of a differential pair may look like they occur coincident in time on a lower bandwidth instrument or at the wrong frequency range setting, or worse may not be seen at all. The reason this is important is that mis-matched discontinuities will directly contribute to mode conversion and a mis-balanced signal at the end of your channel. The choice of instrument or frequency range can be the difference between a design that works and one that does not, or a design that passes FCC and a design that radiates uncontrollably. Unlike other parameters that may allow you to change parameter settings after calibration, the calibration must be valid over the same frequency range as the measurements being taken.

Setting VNA source power for low loss devices

In general increasing source power on a VNA will only slightly increase the accuracy in your measurement. There is a danger however in setting the source power too high. Non-linearities in the receiver become a problem and distort your measurement data when source power is set too high. These settings may actually be within the range of capability of your instrument but will cause problems with the data.

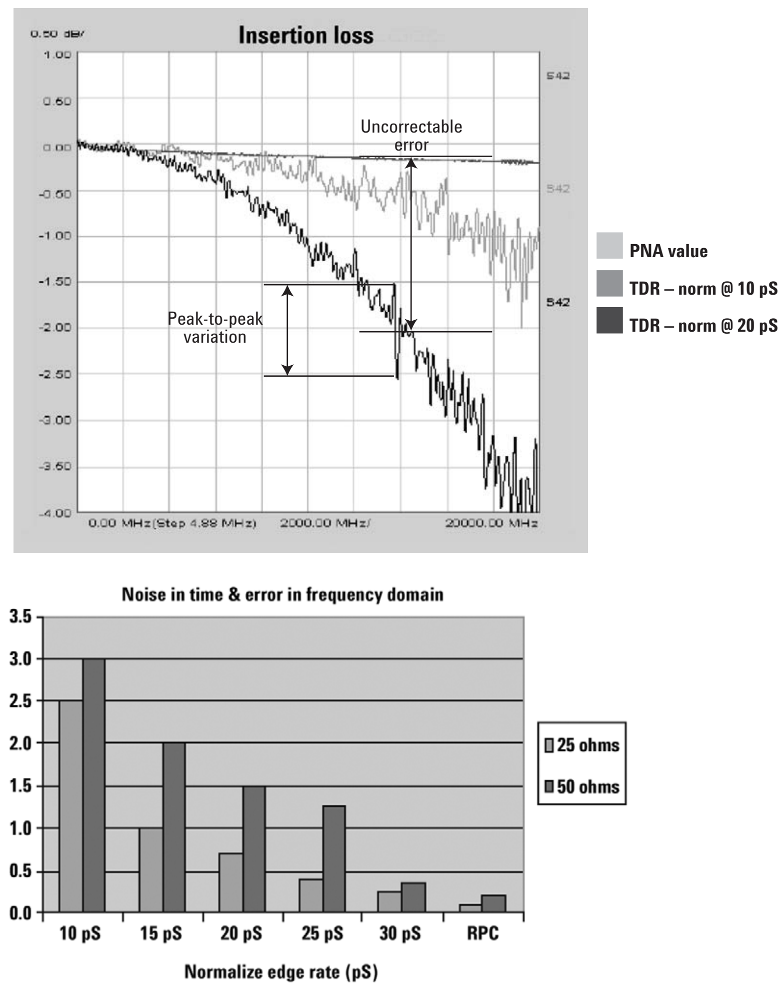
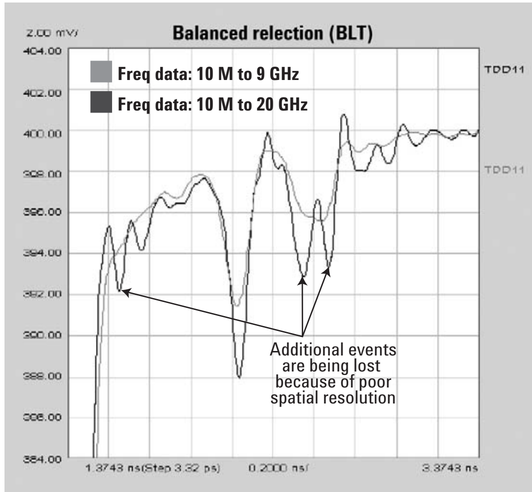


Figure 14. Error in the frequency domain due to rise-time selections



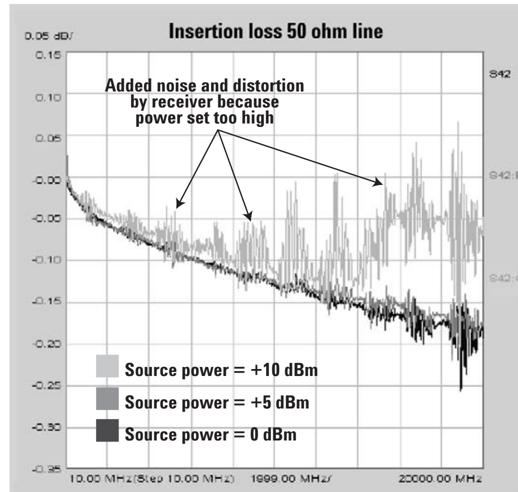


Figure 15. Effects of poor measurement settings – frequency range and source power

Setting VNA IF bandwidth and averaging

Dropping IF bandwidth can be an effective way to drop the noise floor (increase the dynamic range) of your measurement system. Narrow bandwidths allow us to be more precise in capturing the data we are actually interested in capturing with the noise from only a few frequencies to either side added in. Reducing the IF bandwidth has the same general effect as increasing averaging and can be used in conjunction with it, though there is a significant time to measure penalty when driving both and a point beyond which there are diminishing returns.

If low-level signals are of particular interest, increasing averaging will slightly improve dynamic range, or the ability to measure these signals accurately. Like the TDR, there is noticeable improvement in the dynamic range of the measurement as averaging is increased, provided IF bandwidth is not already set very low. The actual gain in dynamic range is less dramatic because the PNA has such a large dynamic range to begin with. Increasing averaging on the PNA is different than on the TDR – the PNA sweeps from Fstart to Fstop for each average, thus at a high number of averages it will seem like it will take a lot longer to do the same number of averages in comparison to a TDR depending on your IF bandwidth setting.

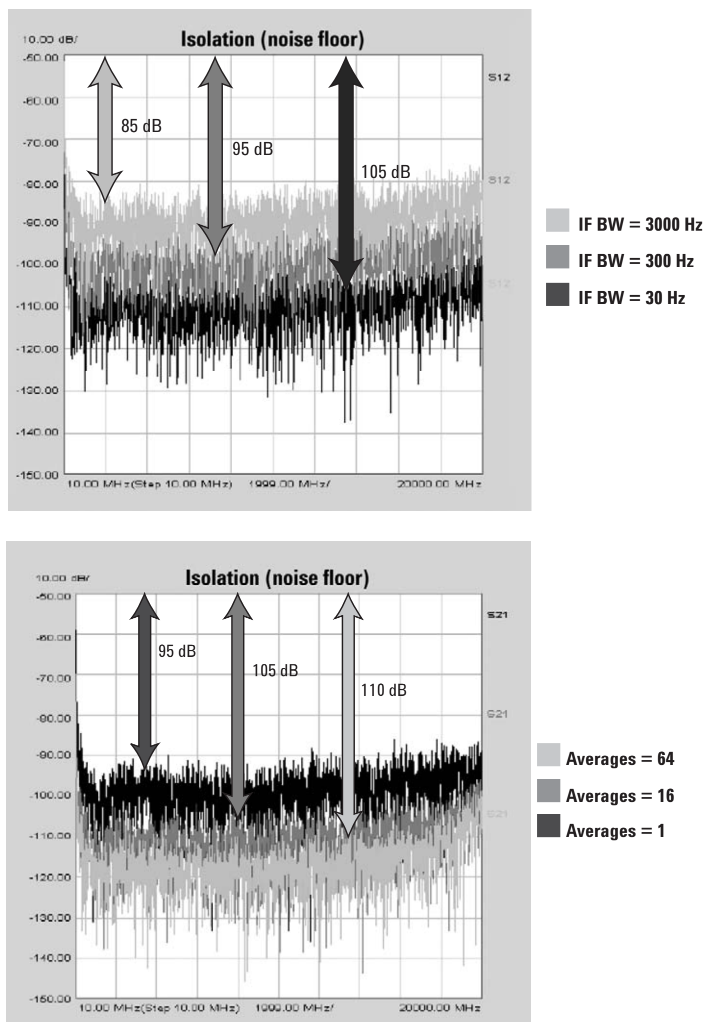


Figure 16. IF bandwidth and averaging effects on noise floor for PNA measurements

Summary

While a PNA impedance measurement can be as accurate as a few tenths of a percent, with a TDR and careful selection of normalization edge rates and averaging, within 1% accuracy should be attainable for single-ended low-loss devices. Note that while faster rise-times will get you better frequency domain accuracy and better spatial resolution, it does not necessarily mean you will get a more accurate measurement if you are trying to measure voltage or impedance.

Calibration and Normalization

In general with the TDR the more accurate a measurement that is needed, the longer it will take to actually perform the calibration. Unlike the PNA, calibration is only required for the specific measurements needed. The calibration wizard in PLTS only requires the error terms for the selected measurements, thereby somewhat reducing the time to calibrate. The levels of calibration range from not performing calibration (factory calibration assumed) to performing the maximum calibration, which includes performing normalization. While module calibration with a reference plane calibration will take out the delay of cabling & fixtures (and de-skew for differential measurements) it will not correct for the loss associated with the cables. Normalization removes the loss of cables, removes reflections due to mismatch of the source, and improves pulse edge. This essentially provides a way to very the rise-time being presented to the DUT and can be faster than the rise-time of the step generator. Normalization is always done in conjunction with a module and reference plane calibration and takes longer to complete.

Comparing TDR calibration methods with a VNA calibration

Figure 17 shows the measurement and through adapter with the different levels of calibration available with a TDR and with a VNA. The TDR results are noticeably less accurate than the measurement obtained with a PNA instrument. The data shows that normalization at faster edge rates get closer to PNA measurement accuracies but will never equal it (even with extremely fast rise-times which are achievable with an Agilent TDR and Picosecond Pulse Lab's accelerator). When looking at phase, the offset seen from the PNA measurement to the TDR measurement with a 30 pS rise-time is not due to the slower rise-time, it is a result of the drift of the step generator. This phase correlation (as with the 20 pS edge) will overlay or not overlay depending on when the measurement was taken.

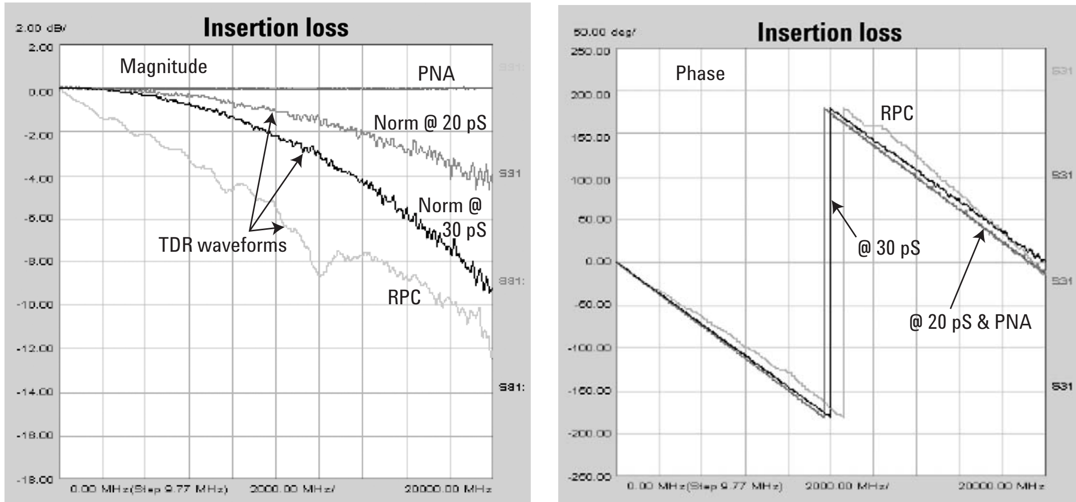


Figure 17. Comparing different calibration types

Normalizing at faster rise-times gives better accuracy overall and is especially important for accurate measurement data in the higher frequency region. The roll-off in response due to going to slower rise-times is consistent and predictable because of the stable nature of the filters used in the TDR during the normalization process. There are limits to how fast a rise-time is acceptable by the TDR instrumentation based on what your timebase and number of points settings are, as well as a real minimum. While normalizing at faster rise-times results in more accurate S-parameter data, it also tends to increase the noise when looking at the data in the time domain, sometimes making reading of mV or impedance values more difficult.

Figure 18 illustrates the increase in noise that can be seen when moving to normalizing at faster rise-times. This increase in noise can only be partially compensated for by adjusting other parameters such as averaging. If reading impedance or voltage values in the time domain and accuracy in the high band of the frequency range of interest, then 20 pS seems to be a good tradeoff between time and frequency domain accuracy.

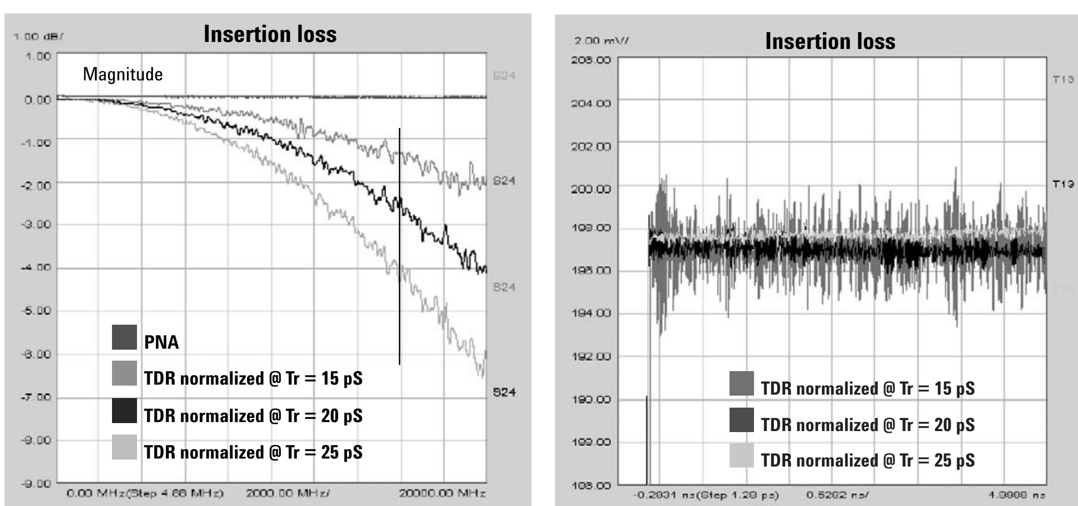


Figure 18. Rise-time effects on frequency response and noise

The reason for this increase in noise is because of the difference in the bandwidths of the filters used in the normalization process. The basic system response has a predictable cutoff frequency represented by fc in the left plot of Figure 19. Through the process of normalization filters are used that accentuate the frequencies more than the basic system response. While this provides a faster edge by allowing some of the higher frequency components of the edge to pass, it also allows some of the high frequency noise to pass through the filter effectively raising the noise floor of the whole system (right plot).

Summary of a good TDR calibration

- The real advantage of calibration (and more particularly normalization) is that you can remove unwanted effects of cables and connectors leading up to your device.
- Magnitude and phase (S-parameters) of thrus will show error as a function of frequency.
- Faster rise-times will result in higher accuracy (in magnitude) but there are factors in going too fast or in increasing the number of points.
- A good calibration at a reasonable rise-time will show acceptable noise in the time domain.
- Checking reciprocity is a way to verify a good calibration has been performed.

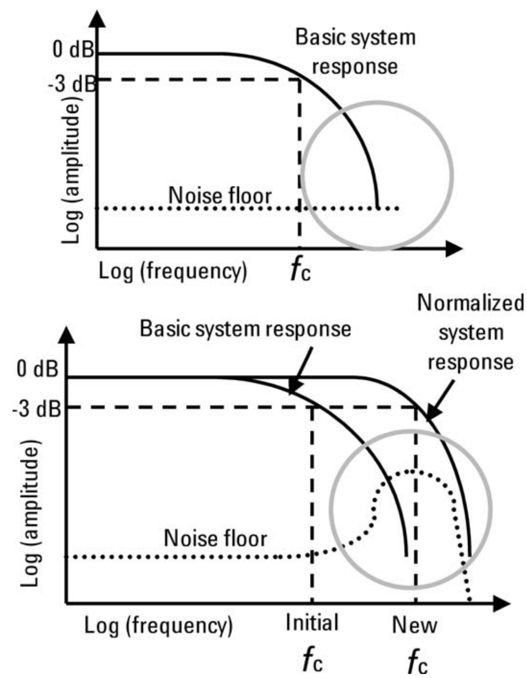


Figure 19. TDR bandwidth and noise floor changes due to normalization

Measurement Accuracies: Reciprocity, Repeatability, Drift

In order to help gain insight into the various levels of accuracy available with the TDR and PNA instruments it's not only important to understand calibration but also reciprocity, repeatability and drift. Understanding these attributes of measurements will help determine which instrument should be used based on accuracy needs.

In its simplest sense reciprocity maintains that for a passive linear device under test, insertion loss (magnitude and phase) going in one direction should equal the magnitude and phase looking in the opposite direction. It follows that this is not only a requirement for single-ended (SE) devices (Figure 20) but for balanced devices as a well. Instrument architectures play a large part in reciprocity since in some cases there is a single source and triggers when coming from the different directions (PNA) and in some cases there are different sources (TDR). This is important because it is not only a measure of the quality of the data but some tools when importing S-parameter data require a minimum amount of reciprocity in order for their internal algorithms to operate and converge properly.

Magnitude and phase reciprocity of a TDR and VNA

Through adapters can also be used to see how good reciprocity is. In TDR measurements of thru adapters we can visually see differences between the S_{13} and S_{31} magnitudes, while the general roll off is the same, the noise is clearly different for the two paths. The blue trace in Figure 21 shows the error between the two traces, which can be as high as 1 dB different for the two reciprocal paths. The phase reciprocity (or delay through the adapters) appears to be much better. In this case, exported data out of PLTS for this TDR measurement may not pass the reciprocity checkers requirements. In general, reciprocity gets better when normalizing at faster edge rates.

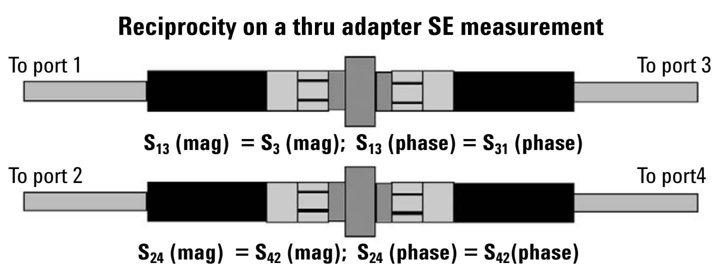


Figure 20. Reciprocity definition for thru adapter measurement

- *Good reciprocity for both magnitude and phase is difficult with TDR*

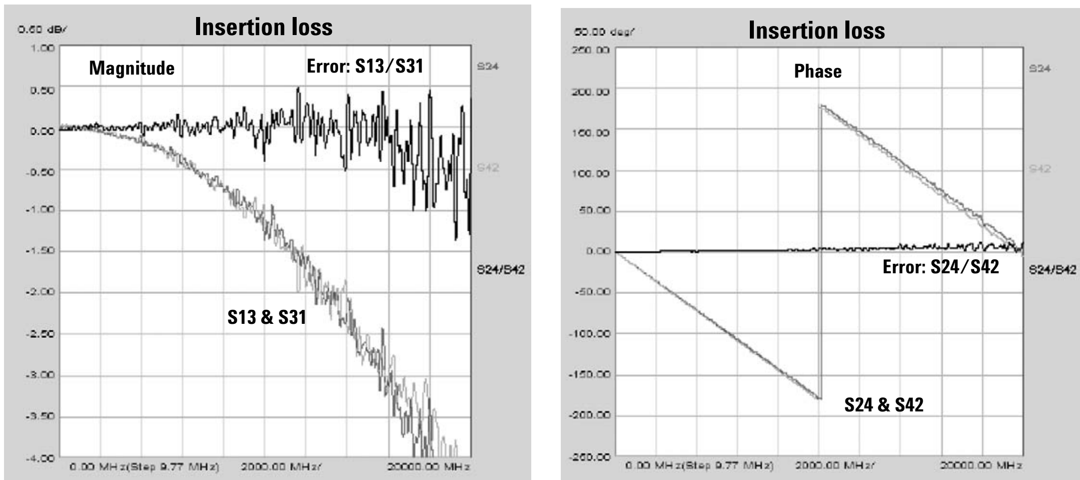


Figure 21. TDR measurement reciprocity of thru adapter

By contrast, the reciprocity of a PNA measurement with a SOLT calibration is significantly better (Figure 22). It's difficult to see the difference between the two traces for phase and even for magnitude, the traces virtually overlay (as compared to the TDR traces in Figure 21). From several dozen cases inspected, almost all PNA files where we export data into other tools pass the internal reciprocity checkers and lead to successful import.

- *Excellent reciprocity for both magnitude and phase achieved with the PNA*

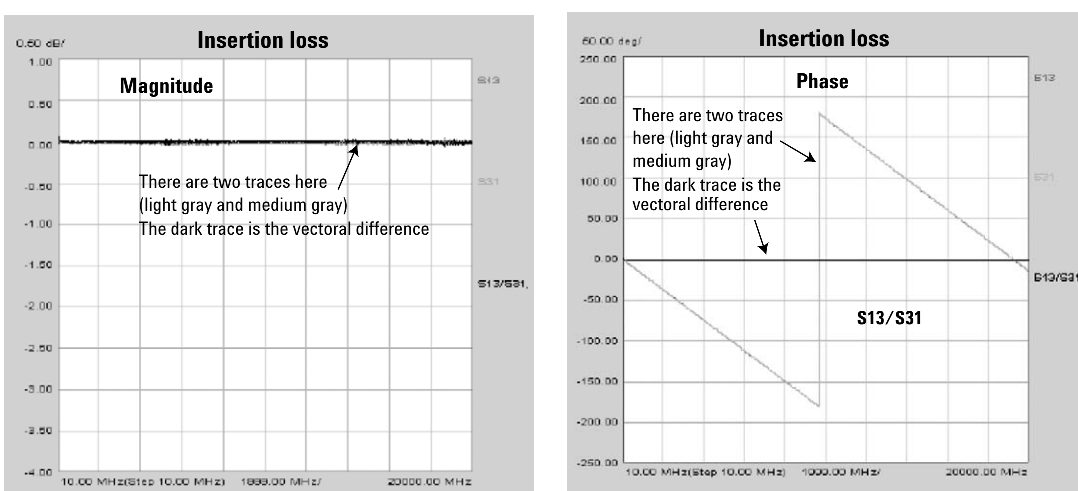


Figure 22. PNA measurement reciprocity of thru adapter

After observing reciprocity of a nearly ideal thru adapter, it is good to check reciprocity when connected to more typical signal integrity device. Using the convenient QuickMath function associated with PLTS, it is very easy to get a vector difference between measurements flowing through a device in two different directions. In Figure 23, using the BTL board, you can see that correlation in phase gets worse at higher frequencies because phase (delay error) is additive. From a magnitude perspective there is decent agreement between SDD12 and SDD21 especially in the frequency range the device was designed to operate over which is below 16 GHz.

Again, measuring the same device with a VNA after performing a SOLT calibration there is excellent agreement in both magnitude and phase when viewing the insertion loss as measured through the device by going in two different directions. Comparing the error in reciprocity for this case study example between TDR measurements and PNA measurements, we can see that the error for the TDR measurements is approximately a factor of 10 higher for TDR (see Figure 24).

- *TDR reciprocity: ± 25 degrees phase ± 4 dB magnitude*

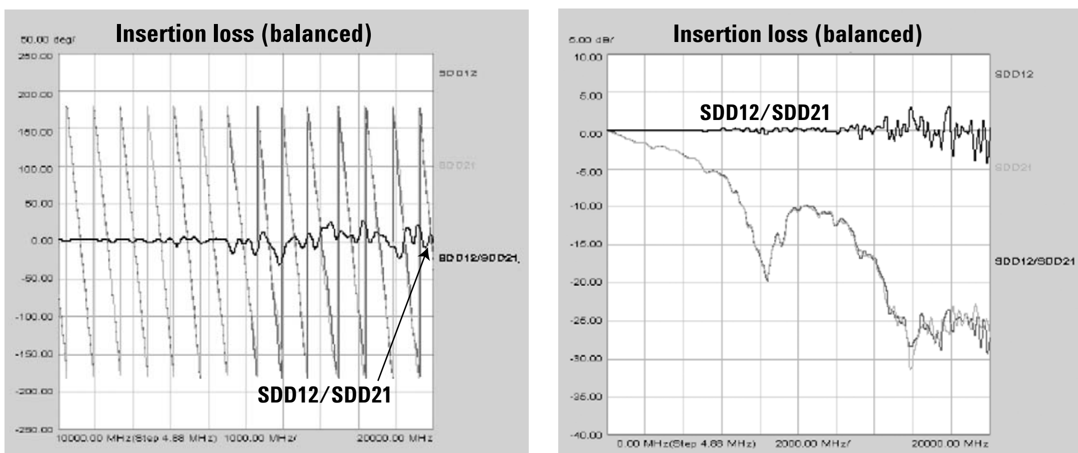


Figure 23. Differential reciprocity of BTL board measured with a TDR

- *PNA reciprocity: ± 2 deg phase ± 0.25 dB magnitude*

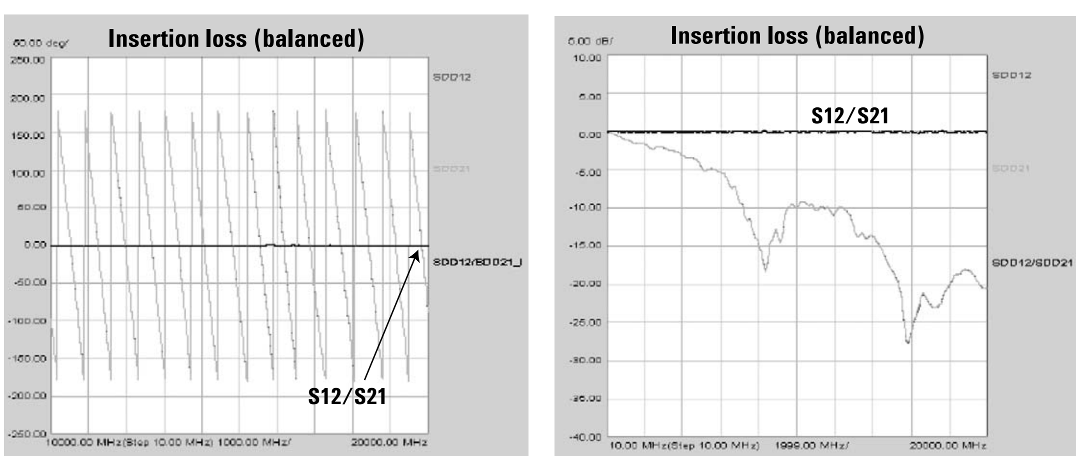


Figure 24. Differential reciprocity of BTL board measured with a PNA

In understanding why reciprocity and repeatability are so much worse with the TDR in comparison to the PNA it's important to understand some of the architecture of the two different systems. The TDR has four different sources and trigger jitter that may not be the same at the different the sources, this makes near-zero reciprocity (as we get with the PNA) almost impossible. The TDR also has four receivers that will tend to exhibit very small differences in their behavior. The PNA on the other hand, has very few sources and receivers that are switched to the different ports with tighter controls as to the fidelity of the signals coming out of each of the ports, and being received. Two different measurement approaches, two different architectures, two different levels of accuracy in our measurements.

Looking more closely at the delay (or phase) associated with an edge that comes out of the different ports in a single-ended test measurement for example. For example, we can see that signals out of the two different ports do not arrive at the DUT at the same time (Figure 25). For this case the normalized reference planes have been set to the end of the cable, taken out the delay and loss associated with it, but because some time has elapsed (even a few minutes) trigger jitter and source drift affect the two different ports differently. The two plots show how bad this drift can actually get. When phase reciprocity with TDR measurements line up exactly (like with a VNA) – this is actually just by chance.

- *Measurement is 7 mm zero-length thru*

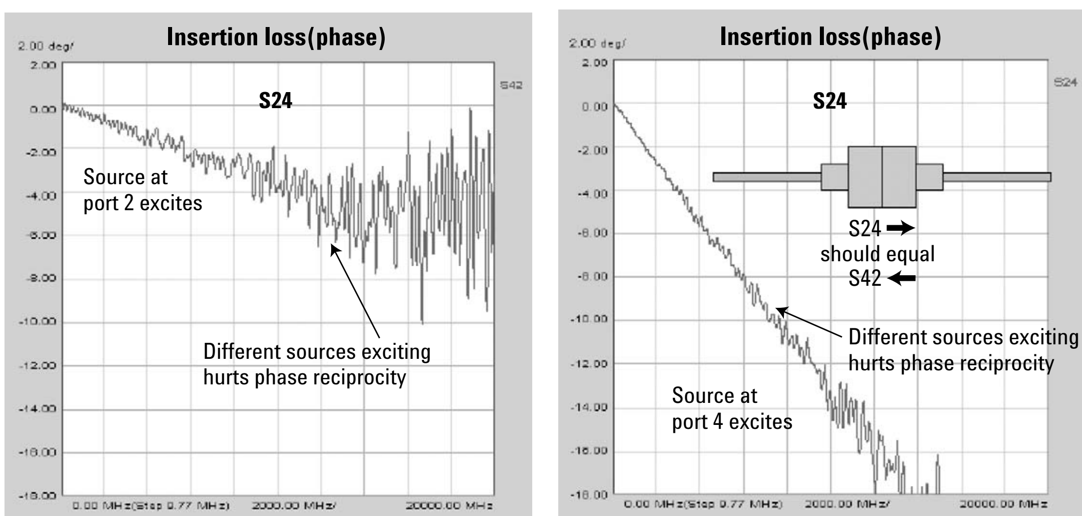


Figure 25. Reciprocity differences due to two different sources in TDR

Magnitude and phase repeatability of a TDR and VNA

Having different sources at the different ports also affects the repeatability of our measurements even though we perform a normalization immediately preceding our measurement the next day. The two single-ended (SE) measurements shown are an example of the difference that can be seen in the day-to-drift of two channels. The fact that the TDR has these various sources drifting at different rates and triggered by slightly different circuitry hurts the ability to get very good reciprocity within a measurement, and repeatability from day-to-day or week-to-week.

- *Zero-length Thru 2 consecutive days with a new calibration*

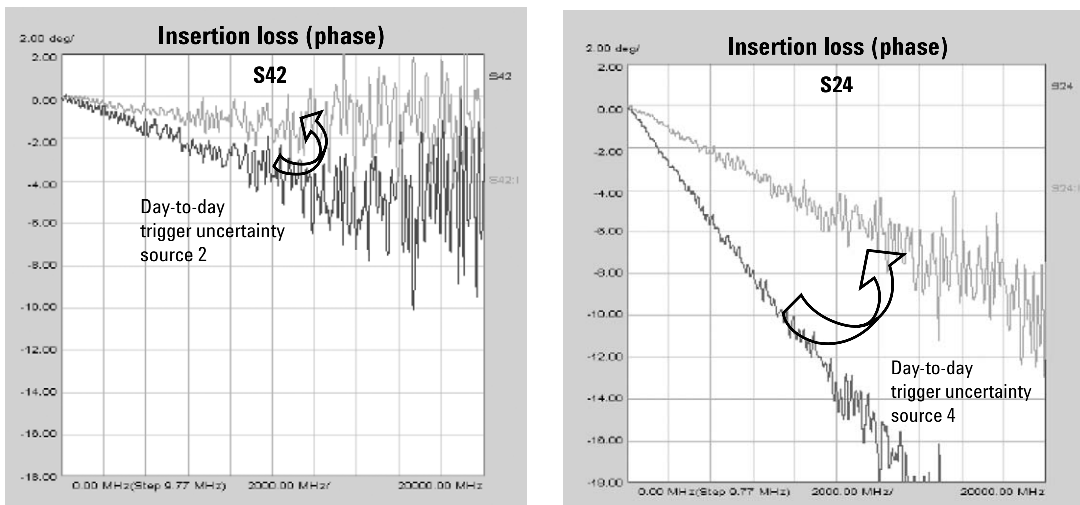


Figure 26. Reciprocity drift over a 24-hour period for TDR

By contrast, a PNA measurement strategy exhibits not only very good reciprocity, but also excellent repeatability from day-to-day or week-to-week mostly because of its superior architecture. With fewer sources and fewer receivers, it follows that there are fewer areas to introduce errors.

• *Zero-length Thru on different days with new calibrations*

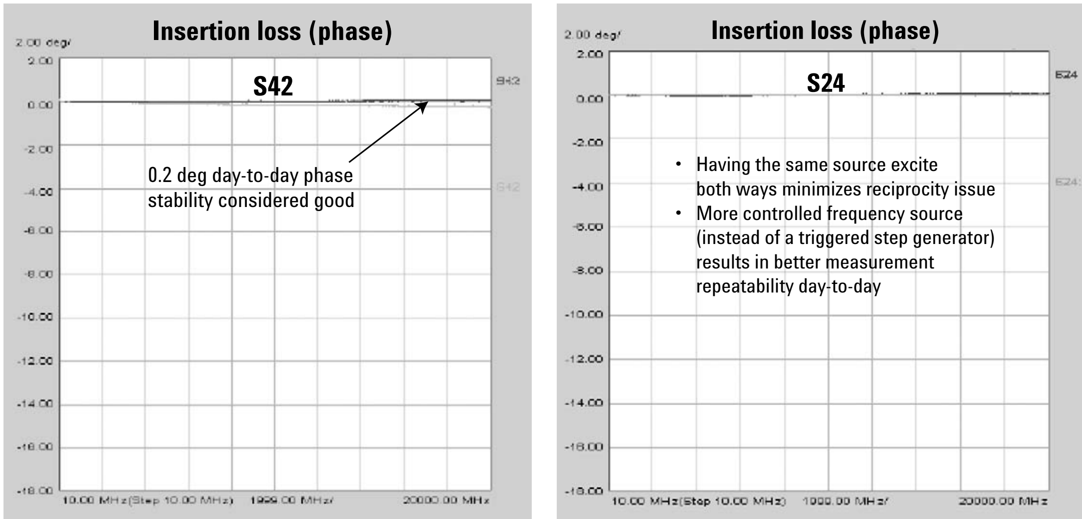
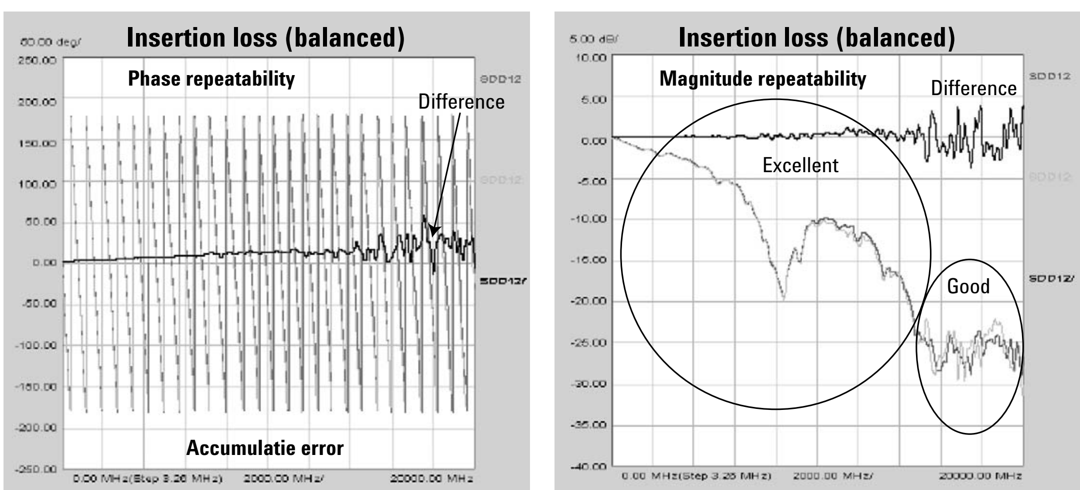


Figure 27. Reciprocity drift over a 24-hour period for PNA

Looking at more typical DUTs (like the BTL board), we see that the same trends generally hold true. Phase repeatability is okay, but there is an accumulative error as we go out farther in frequency. In terms of magnitude repeatability, we get fairly good agreement between measurements taken on different days as long as we stay within a reasonable frequency range. When we start to go beyond, what the device can reliably operate (in this case 15 GHz), there is upwards of 3 to 4 dB of error. Below this frequency range however, there is < 1.5 dB of error.

• *TDR repeatability: ± 60 degrees phase ± 4 dB magnitude*

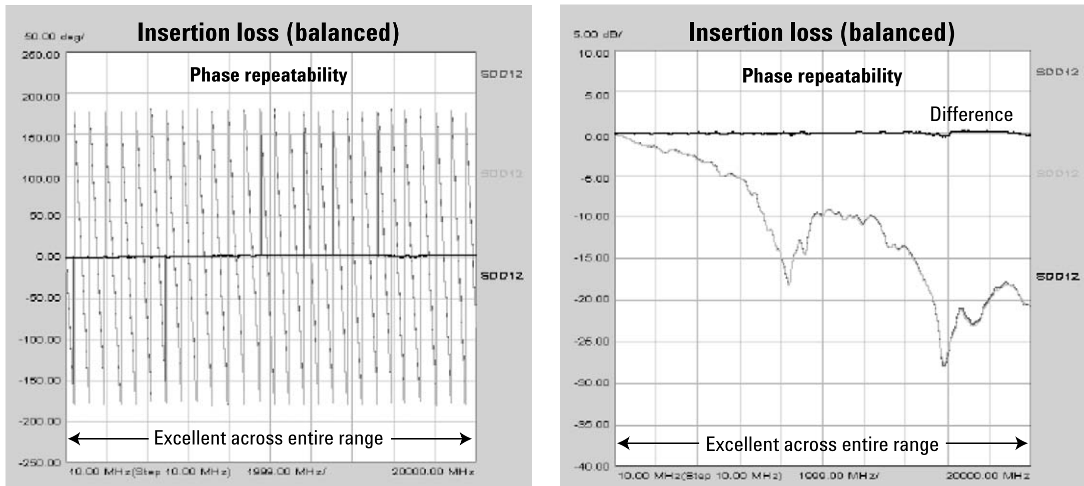


• *2 measurements normalized at 20 pS (with new calibration) five days apart*

Figure 28. TDR measurement repeatability

The PNA instrument phase stability is excellent across the entire range and magnitude repeatability is also excellent with < 0.5 dB of difference between measurements performed on different days.

- *PNA repeatability: ± 2 deg phase   ± 0.5 dB magnitude*



- *2 PNA measurements also five days apart*

Figure 29. PNA measurement repeatability

Another important point to mention is the TDR source and trigger drift (differences between measurements taken initially and those taken later in the day without re-calibrating). The shifts in the time delay exactly correspond to the shifts in phase, proving there is a linear relationship between the two. The other important thing that this illustrates is that source and trigger drift are bounded. Instead of drifting unbounded, the TDR channel sources will tend to drift away from an initial result and drift back in a somewhat predictable fashion. In this example we are showing that drift is bounded within a range of about 13 pS, or half of the 25 pS rise-time. This drift is fixed and is not dependent on rise-time.

- *Thru adapter over a 12-hour period at 4-hour intervals with the same calibration*

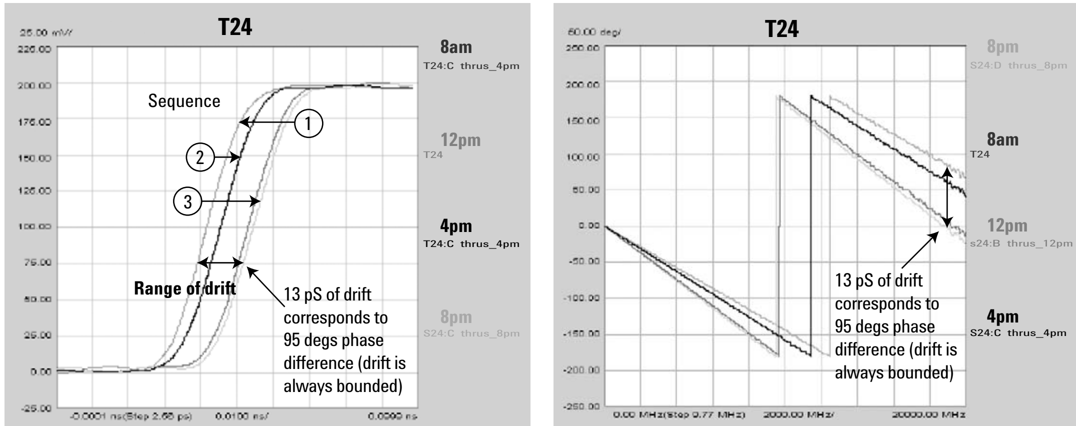


Figure 30. Jitter drift (phase drift) of TDR source

Figure 30 shows a summary comparison of TDR and PNA approximate reciprocity, repeatability and drift. This data is taken from measuring the same BTL board so it may or may not be indicative of the overall results that a user would experience with a significantly different device. As we can see, the PNA not only has the capability to collect more accurate measurements as we have seen previously but it also exhibits more consistent and stable results over time. Most of this as we have pointed out, is due to the differences in the actual instrument architectures.

	Reciprocity	**Repeatability**	**Drift**
TDR*	2 to 4 dB dependent on calibration ± 25 degrees	3 to 6 dB dependent on calibration ± 60 degrees	Magnitude within noise of instrument 210 deg @ 20 GHz
PNA	0.25 dB magnitude ± 2 degrees	+/- 0.5 dB for magnitude ± 2 degrees	Magnitude within noise of instrument < 5 degrees

* TDR values may seem larger than expected. It should be noted that these values are at the high end of the frequency range.

Figure 31. Summary of reciprocity, repeatability, and drift

Measurement Comparisons

Devices that will be measured and compared include single-ended (2-port) verification standards and two balanced (differential) structures built in FR4. The single-ended devices are taken from the Agilent 85053B 3.5 mm verification kit. These devices include a 50 ohm air line, mismatched air line, 20 dB, and 40 dB attenuators. These devices were chosen for several reasons. First their characteristics are very well known and come with measured data that is traceable to NIST.

After understanding the differences found in the single-ended devices, more complicated differential devices will be compared. Differential devices include the standard balanced transmission line (BTL) demo board that is shipped with all PLTS systems and a typical signal integrity device – a backplane and paddle cards.

The instruments used for these measurements were described in section one and include the Agilent Digital Communications Analyzer (DCA) with two 54754A differential TDR modules, a Tektronix CSA8000 mainframe with two 80E04 differential TDR modules, and an Agilent E8362B PNA Series Network Analyzer with a N4419B test set. The measurements were taken with 2000 points, covering a frequency range of 20 GHz and a timebase of 5 ns. High quality phase stable 1 Meter Gore cables were used with all the instruments.

Single-ended comparisons of TDR and PNA measurements

The 50 ohm air line is a device whose performance is traceable to the National Institute of Standards and Technology (NIST). These devices are easily characterized and their performance is known and published. This is an almost perfect device. The insertion loss is extremely low (~ 0 dB) and it has excellent match (> 50 dB). The device is ideal to investigate the accuracy and flatness of insertion loss measurements as well as the measurement noise floor for reflection measurements. A picture of the device is shown in Figure 32.

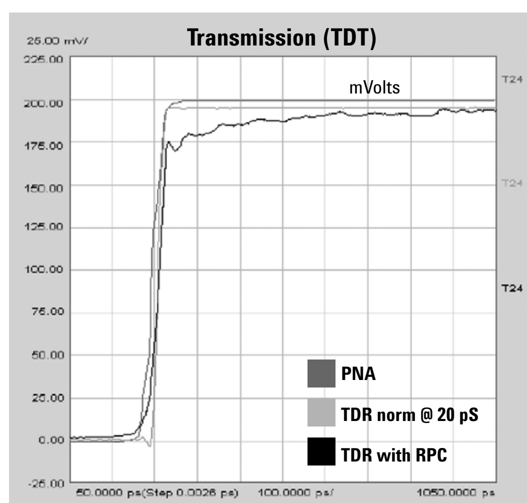


Figure 32. Precision air line transmission line

Figure 32 also compares the time domain forward transmission (TDT) for PNA and TDR measurements. Assuming the PNA data is the most accurate, we see that with normalization the TDR data is very close to the PNA. The un-normalized or reference plane calibration (RPC) data is noticeably lower. The rise-time is slower and the step takes a long time to reach its final value. The main problem with the RPC data is the low power in the step signal for high frequencies. There is also loss due to the test cables and variations caused by reflections caused by source match. For the normalized data there is a small error in the level of the 200 mV step.

The voltage shift (small error in the normalized data) is corrected using PLTS version 2.5 or later and a new version of the instrument firmware (4.0 or greater) where the "correction" factors can be read to correct the level of the step. An example of this correction is in the next device that will be measured is shown in Figure 33.

Switching to the frequency domain, the PNA measurement in Figure 33 indicates that that there is very little loss (~ 0.2 dB @ 20 GHz) for this air line. The RPC data shows 12 dB of loss at 20 GHz. This is due to the test port cable losses, mismatch losses, and primarily the loss of power in the step source for higher frequencies. The smooth roll-off of the normalized measurement is due to the digital filter used to set the rise-time of the step. Note, normalization corrects for the problems identified in the RPC measurement. Both normalized and RPC phase measurements correlate well with the PNA. The RPC is worse than the normalized measurement. There is a small error of about 20 degrees at 20 GHz out of a total of 1800 degrees. That is about 1%. Note: this is a very good measurement with the TDR. There are times where the phase error is larger due to source jitter and drift.

A typical question is: How much does my test cable effect the uncorrected RPC measurement? Comparing this RPC measurement (with 1 M Gore cables) to one done with just six inches of semi-rigid cable connecting the air line, it was determined the 1 meter test cables only contributed about 1 dB of loss to the measurement at 20 GHz.

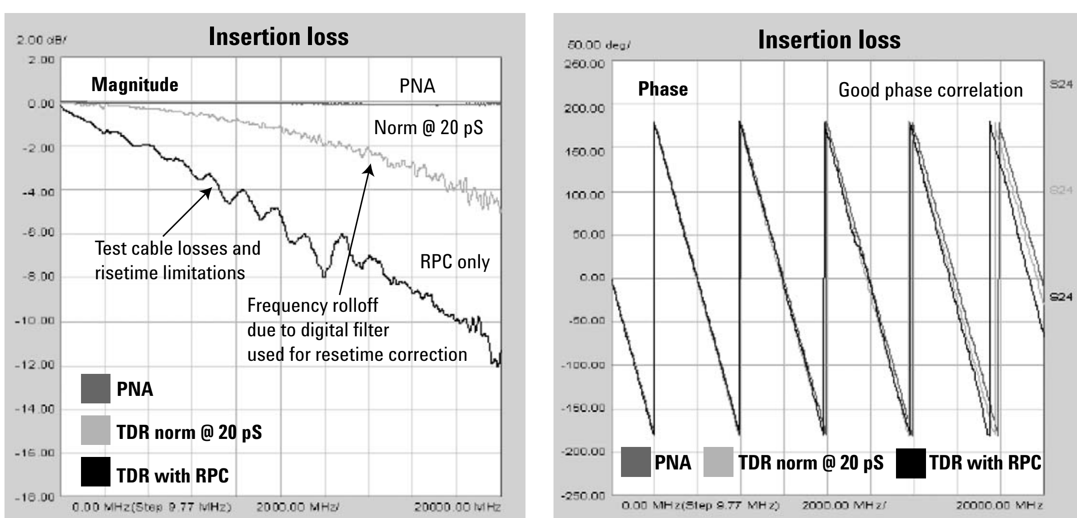


Figure 33. Insertion loss of air line example

Figure 34 shows the return loss for the air line in both the time and frequency domains. In the time domain plot, impedance is displayed showing the PNA measurement as a clean trace about 50 ohms. The normalized trace is noisy but follows the PNA data very closely. The RPC data is off about 1 ohm.

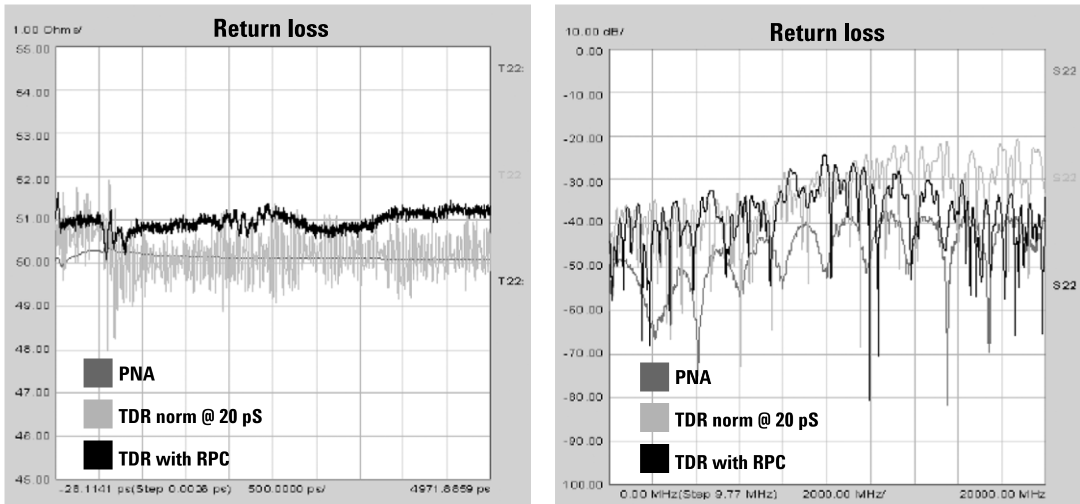


Figure 34. Return loss of air line example

In the frequency domain, return loss is plotted in dB. The return loss of this device is very good. The PNA measurement shows that it varies from –65 dB to as high as –38 dB. Although the trace has some noise, the return loss is easily determined. For the TDR, both the normalized and RPC measurements show the noise floor of the TDR. The noise floor limits the measurement range of the TDR for this measurement. However, most devices for signal integrity applications have return losses much higher than this air line.

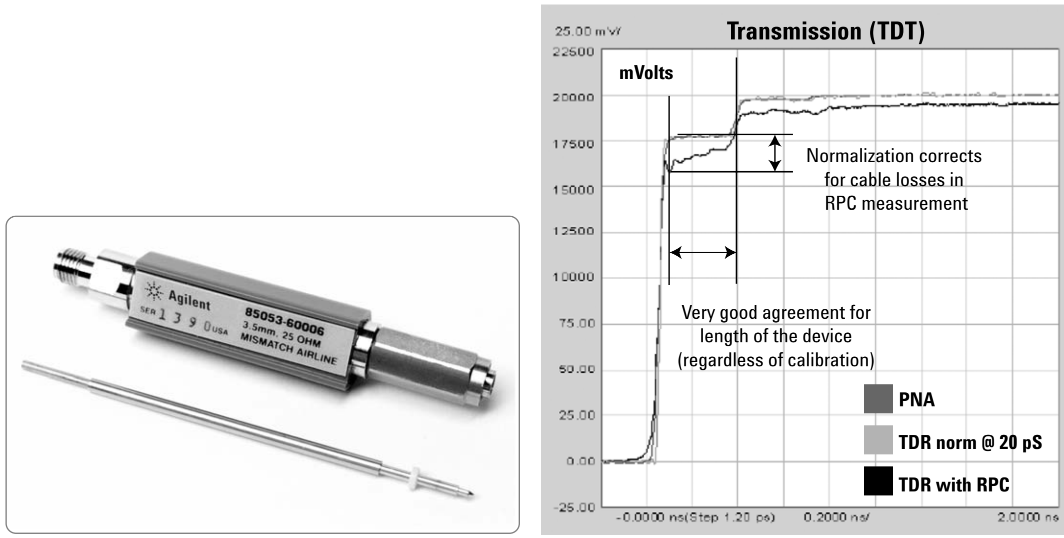


Figure 35. A 25 ohm mismatched air line with TDT measurement

The next single-ended device to compare is a mismatched line (Figure 35), also from the 85053B verification kit. It is similar in construction to the air line, except the center conductor has a step in diameter. This step in diameter changes the characteristic impedance to 25 ohms. This device is basically a 25 ohm transmission line with a short section of a 50 transmission line on each side. This device is well characterized and its measurements are traceable to NIST. The interesting characteristics of this device are the impedance step is very accurate and causes well-defined resonance pattern for reflection measurements and a known variation for transmission. Other than the mismatch it is also a very loss device. The distance to the step and the impedance are well controlled.

Figure 35 also shows a plot of the TDT response of the mismatched line. The PNA data is the most accurate. The trace is normalized TDR data and has very good agreement with the PNA data. It just has more “noise” than the other trace. This data has the correction talked about previously. The black trace is the RPC data from the TDR. The rise-time for the RPC data is slower and there are significant differences in amplitude from the normalized data and PNA data. However, all three measurements predict the location of the stepped impedance accurately. This shows the time references for the instruments are all accurate and calibration techniques accurately remove delays associated with cables to precisely set the measurement reference plane.

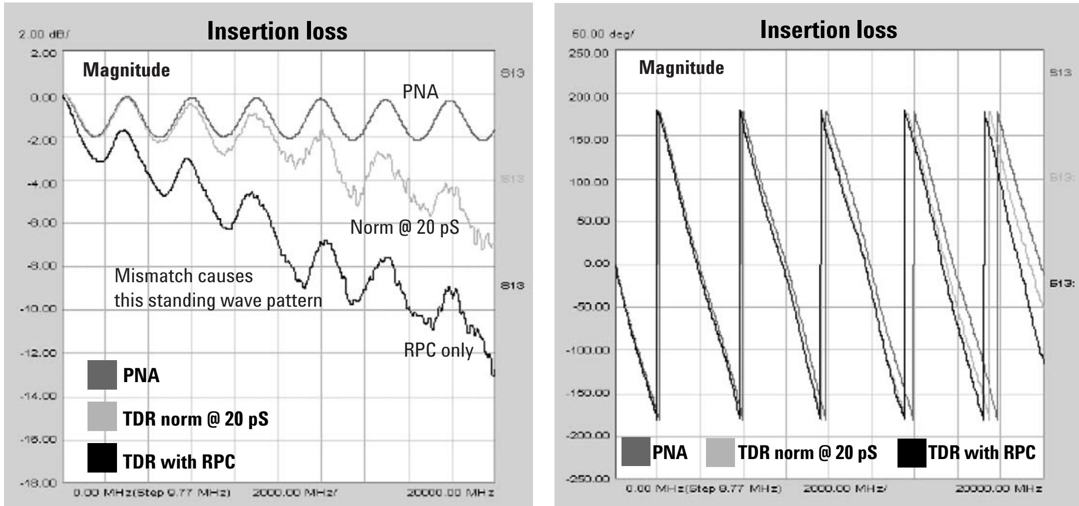
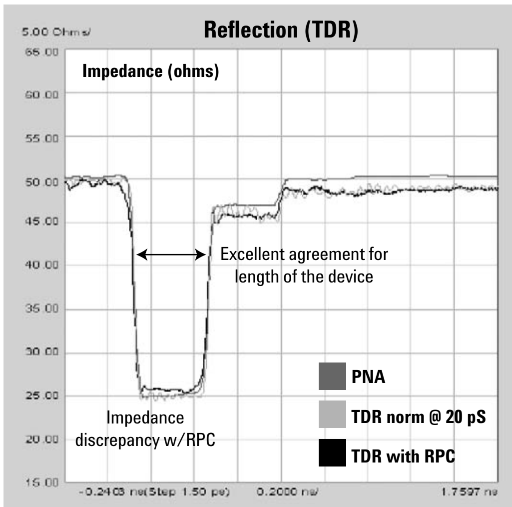


Figure 36. Magnitude and phase versus frequency for 25 ohm mismatched line

The insertion loss shows the typical “sinusoidal” variation of the mismatched air line. The variation is from 0 dB to –2 dB of insertion loss. The normalized TDR magnitude data correlates well only for the first couple divisions. Then the roll off due to the normalization filter causes the loss to increase. Also note that even with just 2 dB of loss the TDR data has noticeably more noise as frequency increases. The RPC data has the general variations but the loss is significantly pessimistic. At 20 GHz it is showing an additional 12 dB of loss. The phase is reasonable but gets more inaccurate at higher frequencies with the RPC data being the worst.

The TDR response (Figure 37) of the mismatched line again shows good agreement for the positions in time for the steps in impedance. The normalized TDR data agrees with the PNA data through the mismatch area of the line (again more noise). However the agreement for the reflected step and rest of the line has an offset. The RPC data missed the 25 ohm impedance of the step by a couple ohms.



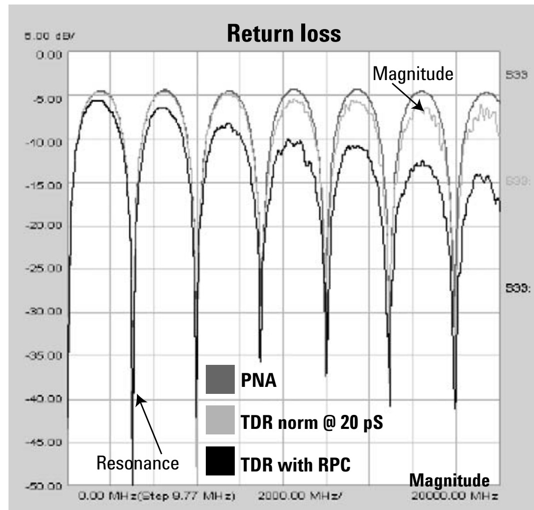


Figure 37. TDR and return loss measurements of the 25 ohm mismatched line

The return loss (Figure 37) shows the PNA correctly measured the resonances of the mismatched line and the 4 to 5 dB peaks. The normalized data again does well for the first three divisions and then starts to show more loss. The RPC data catches the resonances but shows 10 dB too much loss at 20 GHz.

The next device to consider is a 20 dB attenuator. Its loss is nearly flat across the frequency range and provides a very good match across the frequency range. From the data shown in Figure 38, The PNA accurately measures the magnitude and phase of the attenuator. The normalized TDR data matches well for the first few divisions of the plot but again rolls off at higher frequencies and has noticeably more noise. The RPC data has about 12 dB of error at 20 GHz. Notice the phase measurement. For both TDR measurements the 20 dB of loss causes the phase to quickly become noisier.

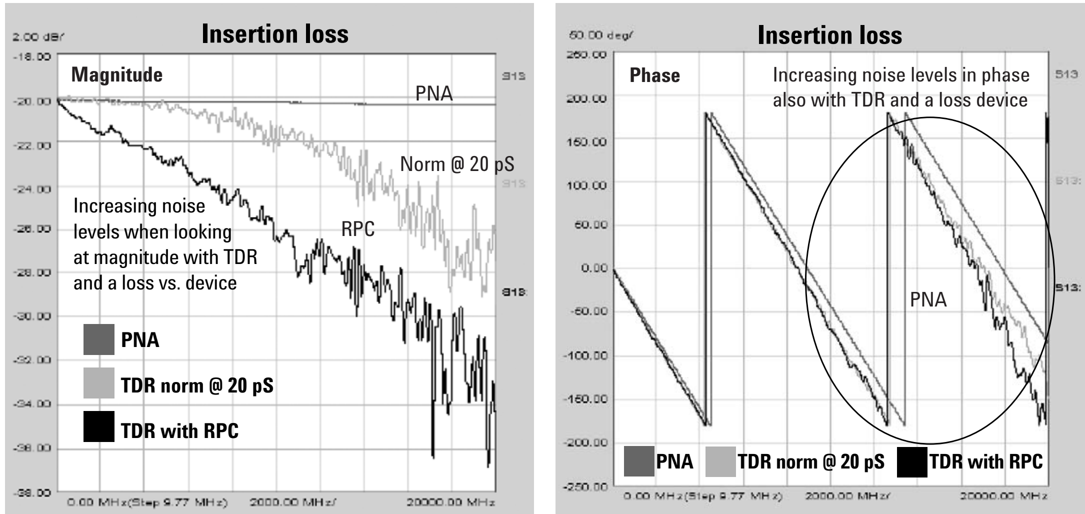


Figure 38. A 20 dB attenuator with insertion loss versus frequency

Measuring the return loss (Figure 39) of the attenuator is a challenge for the TDR. The good match of the attenuator puts the measurement at the noise floor of the TDR measurement. The PNA is able to accurately measure the magnitude and phase of the attenuator. Notice there is now a small amount of noise in the PNA measurement as higher loss devices are measured. The TDR measurements are so noisy that it is hard to tell what the actual data should be. The lower signal levels make the phase measurement meaningless.

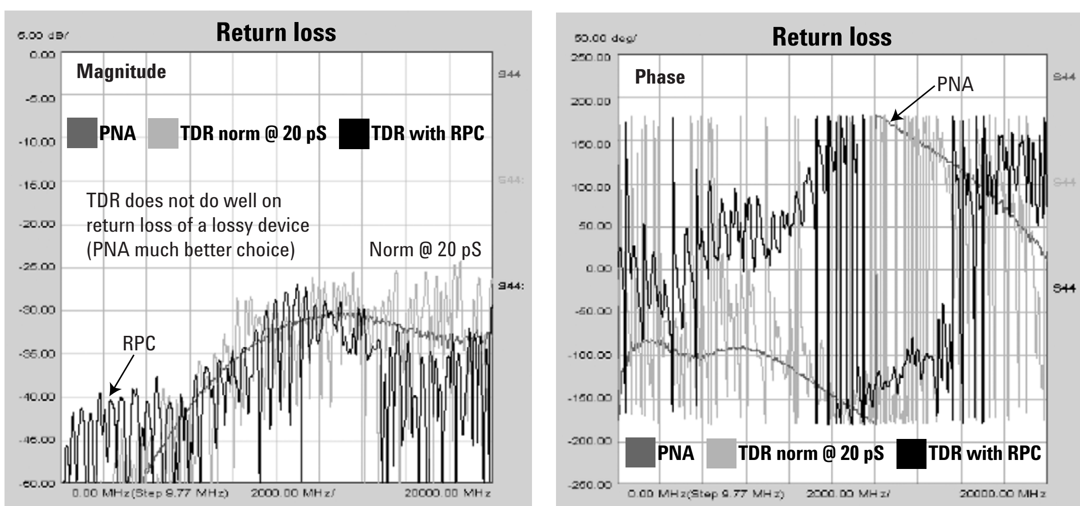


Figure 39. Return loss of a 20 dB attenuator

To summarize the results from the single-ended measurements, the following four points can be made.

- With normalization, the TDR (with PLTS) can be an effective strategy for measuring impedance and obtaining frequency domain characteristics of moderate loss devices.
- High loss devices (20 dB or greater) are difficult to accurately characterize in the frequency domain with only TDR information. 40 dB of loss measurements are not very useful.
- Currently whether you require accurate time or frequency domain data plays a large part in determining the optimum edge rate for normalization (faster edge rates give more accuracy in the frequency domain, but also more noise in the time domain waveforms).
- Reference plane calibration should only be used for estimating the length of a device and getting an idea of the response of the device.

Balanced (differential) comparisons of TDR & PNA measurements

Two balanced devices will be considered. The first is the balanced transmission line demo board that is included with the Physical Layer Test System (PLTS). It is a coupled microstrip transmission line on FR4. The line has a step width (impedance) change in the middle of the line and then returns to 100 ohms balanced. It is in the picture (Figure 1). The other device is a sample backplane with two line cards with SMA connectors for measuring the backplane.

Studying the results of the single-ended measurements, will give insight into what is happening to the more complicated balances devices. The same trends seen in the single-ended measurements will be seen here.

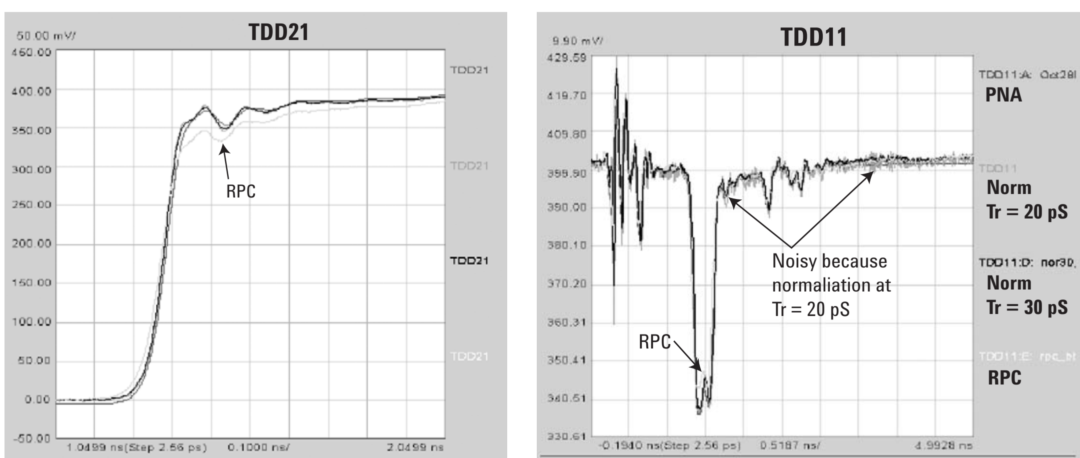
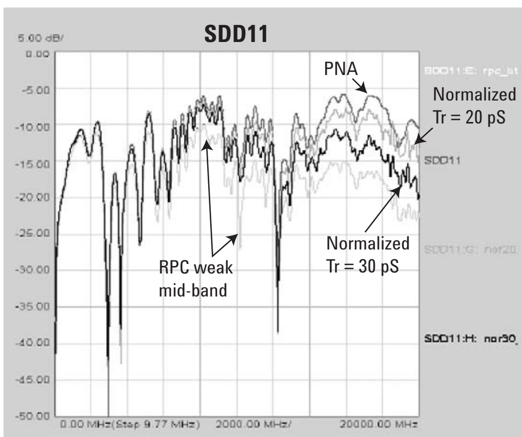


Figure 40. Differential TDT and TDR responses of the BTL board

In both the differential TDR and TDT measurements there is good agreement between the PNA (most accurate) and the normalized TDR measurements. Again the TDR measurements has noticeably more noise than the PNA measurement but still goes a good job of measuring the time domain response of the device. The RPC data again misses the value of the step in voltage (impedance) for the TDR measurement and predicts too much loss for the TDT measurement.

Figure 41 shows the return loss in the frequency domain for the PNA data, 20 pS, and 30 pS normalized TDR data. The 20 pS data comes closest to matching the PNA data. There is very good agreement in the lower third of the frequency range good agreement in the mid band; and OK agreement in the high band. The 30 ps data is less accurate and the RPC data is only good for the lower band and then predicts too much loss.

The phase agrees well for the lower band but starts deviating mid-band and continues to deviate and get noisier at higher frequencies. The RPC data has a problem around 12 GHz where the resonance is and there is a larger phase error.



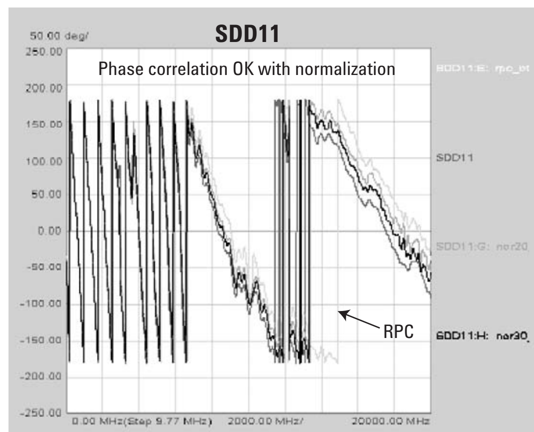


Figure 41. Differential return loss for BTL board

Just looking at the PNA data and the 20 pS normalized data, the difference can be seen in the top trace in Figure 42. This trace is the vectoral difference (division) of the two traces and can be broken into three bands. Below 11 GHz the error is less than 1 dB. From 11 GHz to 18 GHz there is about 2 to 4 dB of error and above 18 GHz there is > 5 dB of error.

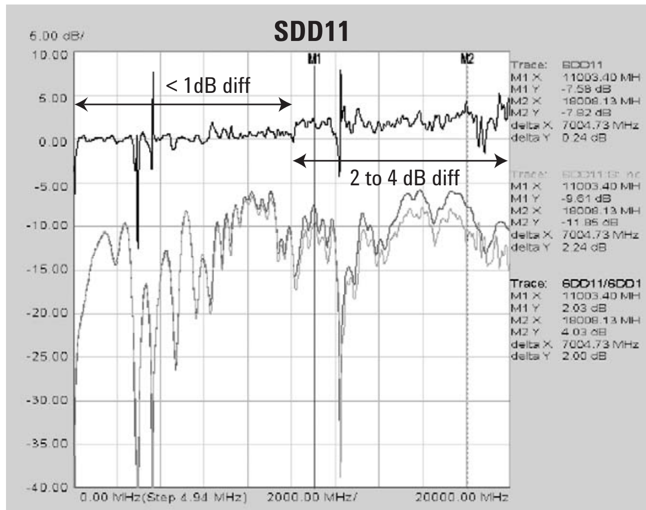


Figure 42. Differential return loss errors in normalized TDR data versus frequency

Figure 43 shows the insertion loss for the BTL board. The trace colors are the same as Figure 41. Again for this measurement the normalized TDR data at 20 ps is the closest to the PNA data. The RPC data shows the loss to be about 12 db lower. The phase is good at the low frequency ranges and deviates more as frequency gets higher.

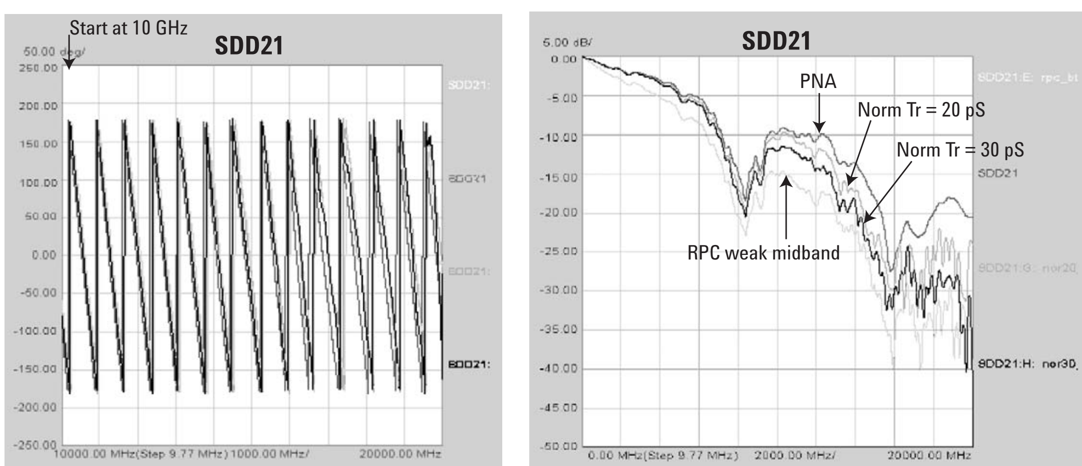


Figure 43. Differential insertion loss for BTL board

In Figure 44, the top trace is the error assuming the PNA data is the most accurate. The error in the low band (below 11 GHz) is less than 2 dB and above 14 GHz the error is greater than 4 dB.

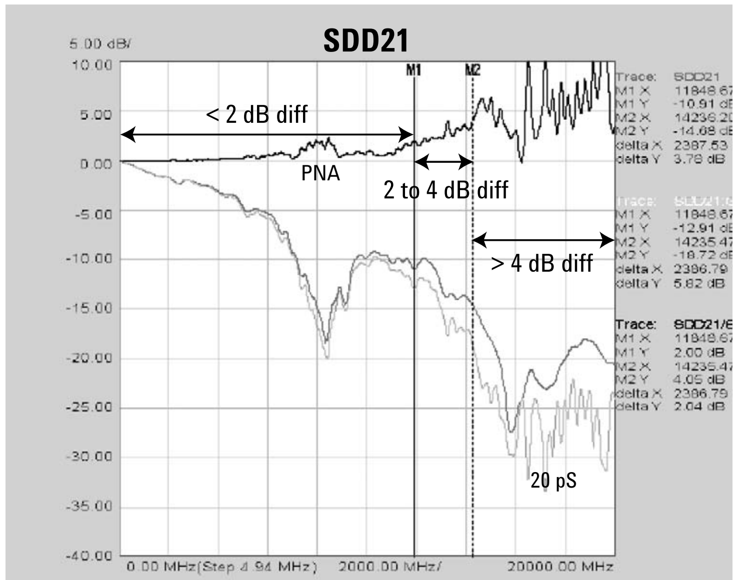
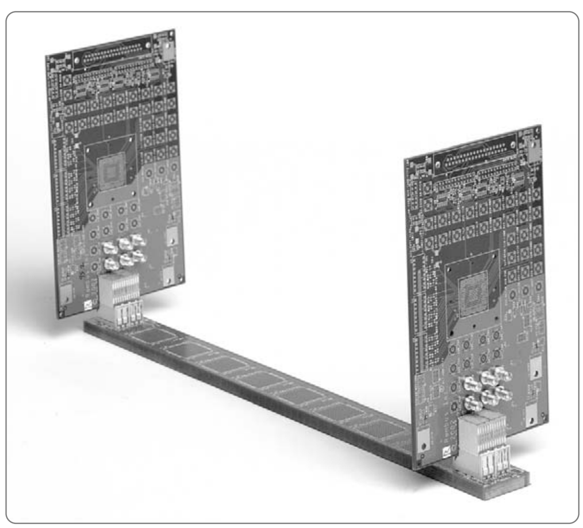


Figure 44. Errors in differential insertion loss TDR measurements

The next example is a typical backplane example with differential line (paddle) cards to measure the backplane. This is a typical example than many designers are using to characterize backplanes. There are SMA connectors on the paddle cards to connect to the TDR or PNA. The measurement reference plane is the end of the test cables. Therefore the measurement includes the SMA connectors, traces on the paddle cards, the large differential connectors and the backplane itself. A picture of the device is in Figure 45.



Device characteristics:

- **Typical device for integrity problems**
- **SMA connectors on daughter cards**
- **Backplane with differential connectors**

Figure 45. Typical backplane example device

In Figure 46 there is fairly good correlation between the measurements. The normalized data indicated a little more loss and the RPC data slightly more. Overall, there is a pretty good agreement.

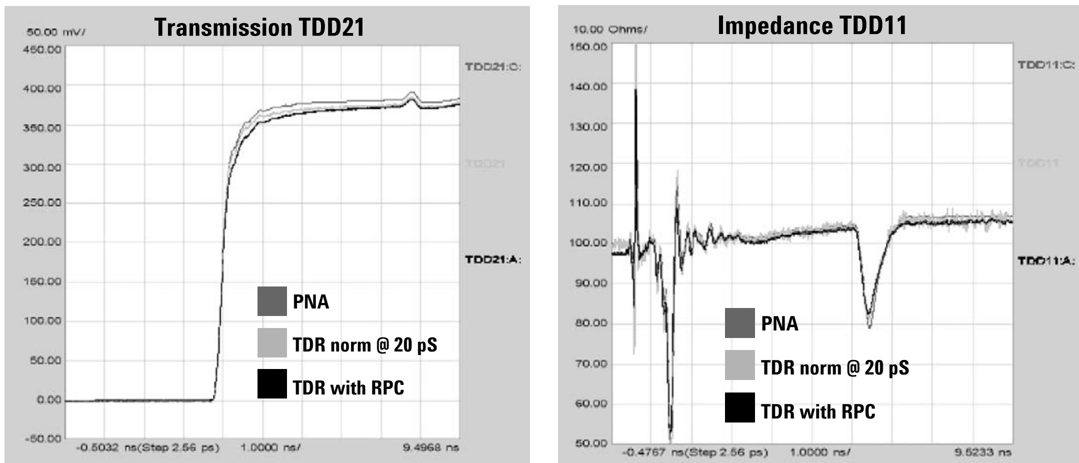


Figure 46. TDT and TDR measurements of example backplane

The differential return loss (Figure 47) shows the normalized trace is a good fit in the lower frequency band and an acceptable fit at higher frequencies. The RPC data is 10 dB. This is too optimistic at the higher frequencies, which could mislead the designer into thinking it is better than it really is.

The insertion loss compares well for the lower third of the frequency range, with the normalized data still looking good mid-band and the RPC data starting to be too pessimistic. At the higher frequencies both the normalized and RPC data are in the noise floor of the TDR.

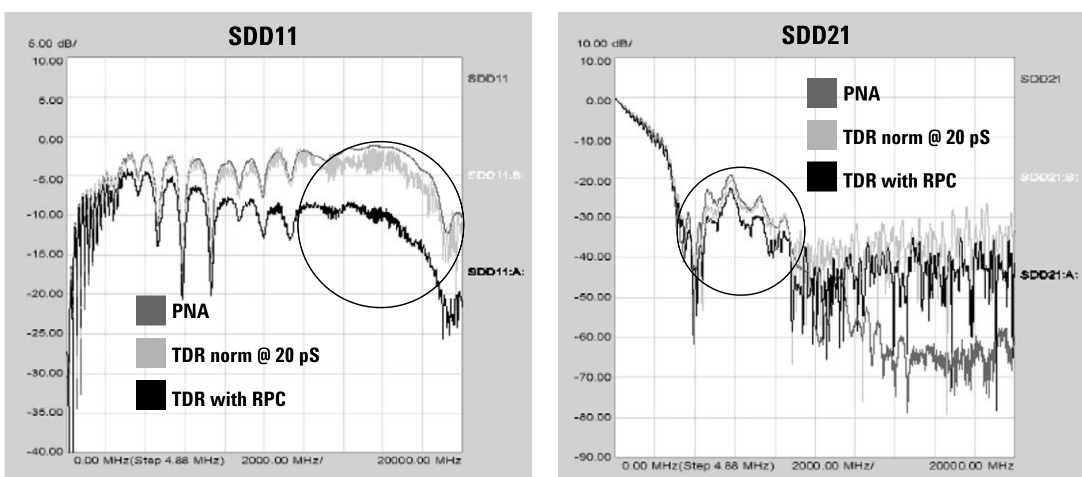


Figure 47. Differential return and insertion loss of example backplane

Figure 48 shows eye diagrams based on the PNA data and TDR data for both normalized at 20 pS and RPC. Since this backplane was designed for XAUI applications running at 3.125 G bits/second, the eye diagrams were generated using a PRBS pattern of 2^11 at 3.125 GB. Comparing the PNA and TDR normalized eye diagrams there is very little difference in eye height and eye width. However, the TDR data from a RPC has an eye height 35 mV lower and an eye width 18 pS narrower. If the S parameters were used as a model or a model was generated from them, the model from the RPC data would be 35 mV too pessimistic and design margin would be used up needlessly.

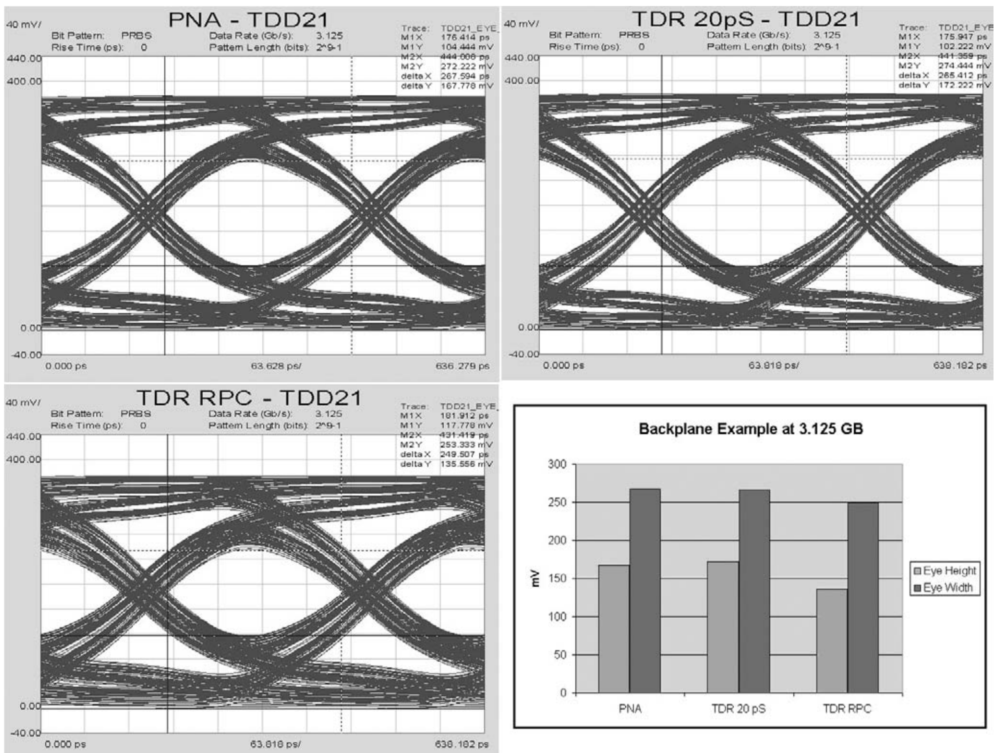


Figure 48. Eye diagrams of backplane example at 3.125 GB

Case Study

While we discuss at length the importance of calibration and normalization, it is not always obvious how important they are in impacting real things that matter like product reliability, speed of a channel, design margins, and time-to market. This is an example of how important selecting the right instrument and/or calibration (normalization) method can impact some of these important metrics.

In this example we will be taking a very simple design because it will clearly illustrate what effect calibration can have on your design speed and design margins. More complicated serial structures like daughter cards plugged into back planes through connectors will probably show similar trends but may contain a lot more resonances.

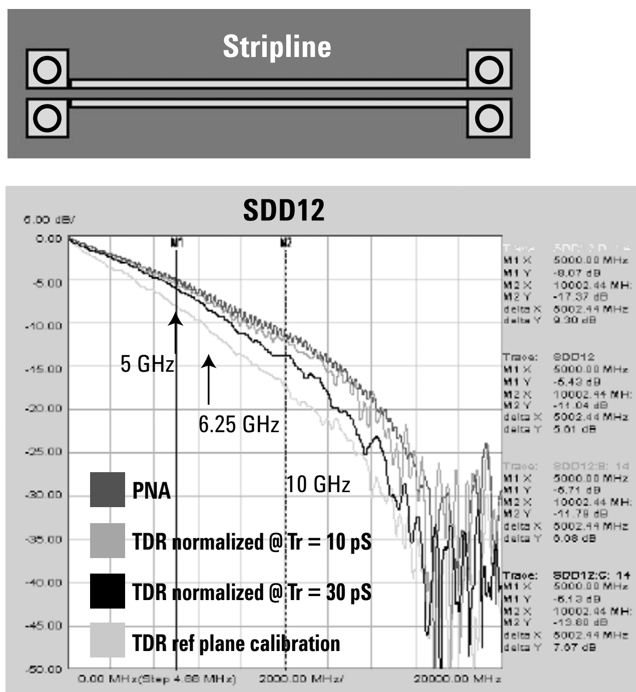


Figure 49. Differential insertion loss of a buried stripline

In this example we'll be looking at a few frequencies of interest and comparing reference plane calibration, and normalization at two different edge rates, to a PNA measurement (considered to be excellent in terms of accuracy).

- Case Study: Simple channel consisting of two SMA connectors to 14" buried diff pair to SMA connectors
- Frequencies of interest are 5 GHz and 6.25 GHz which correspond to 10 and 12.5 Gb/s
- This data shows only 1 to 2 dB difference between the normalized values, more in the case of reference plane calibration (RPC)

Using the four calibration setups described earlier and taking the S-parameter measurements for differential insertion loss in the previous figure, PLTS is able to create eye diagrams that are generated using a worse case bit pattern at a moderate 10 GB/sec bit rate. Lets assume our critical eye dimensions are the maximum opening at 1/3 of a bit width and the "keep out" region needs to be at least 65mV tall (at the end of our channel) in order for our system to operate properly. We can see that most of the calibration and normalization methods pass our criteria the reference plane calibration method does not. If we were to rely on quick data collected with the easy to perform RPC, we would be severely underestimating the performance of this channel.

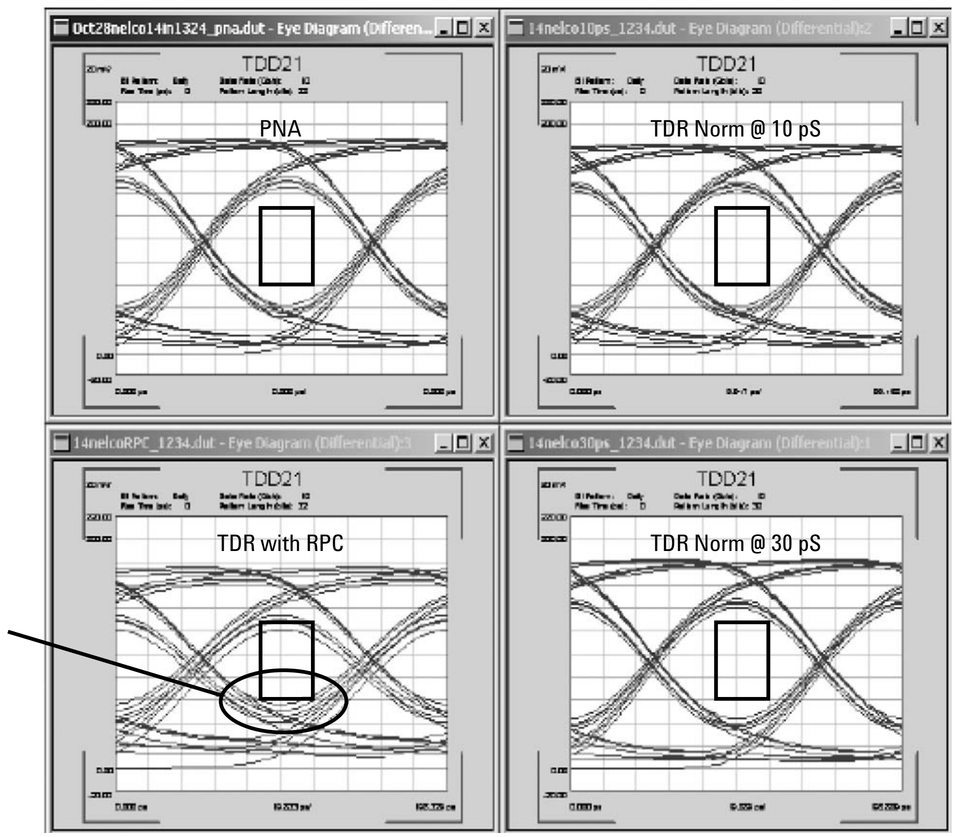


Figure 50. Eye diagrams using 10 Gb/s data rates and various calibration methods

Lets say our goal is to determine the fastest that we can reliably operate this particular channel. By taking the same DUT files created from the measurements, PLTS allows us to successively increase the data rate and collect information about the eye opening very easily. Plotting this information gives us keen insight as to what we might determine to be the maximum operating data rate given a looser 50 mV requirement. We can see that normalizing at 10 pS with an Agilent TDR, while it does have its risks, we can get nearly the same accuracy as a PNA until we get into higher bit rates. This is predictable from how the S-parameter curves slope off with the different calibration & normalization schemes; there are greater differences between PNA and TDR measurements (regardless of normalization edge rate) at higher frequencies.

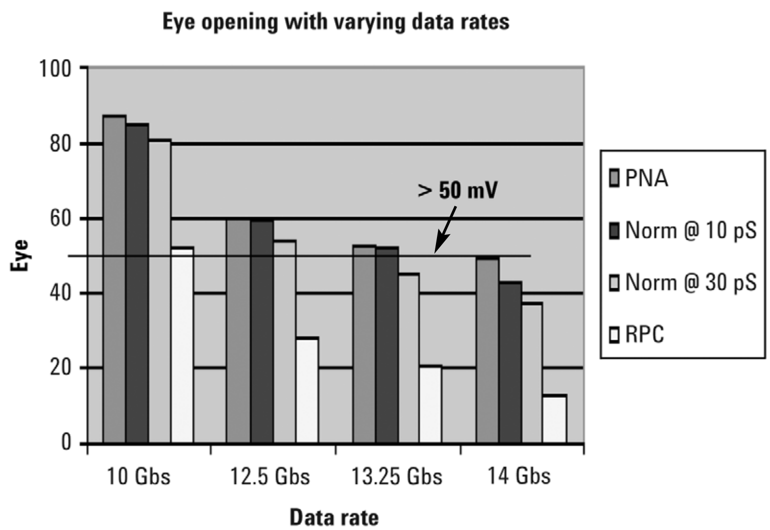


Figure 51. Comparison of eye openings versus data rates

By looking at the data this way, and within a particular normalization scheme, there is a relationship between dB loss and the eye opening at our frequencies of interest. Once minimum eye height is established, we can get a better understanding of the perceived maximum data that each calibration/normalization process will allow. The real maximum data is probably much closer to the PNA measurement given that it exhibits the lowest introduced loss into the structure during the measurement. By doing comparisons of the different normalization methods with the PNA we can get further insight into bandwidth we are leaving on the table by using a less than adequate normalization scheme. Furthermore, in the S-domain the data shows really only a few dB of difference between the different techniques yet this can directly result to 10 to 40% of unused bandwidth we are leaving on the table.

Normalization method	Max data rate (left on the table)	As a %
PNA with SOLT calibration	14 Gb/s	0.0 %
TDR with 10 pS normalization	13.5 Gb/s (0.5 Gb/s unused BW)	3.6 %
TDR with 30 pS normalization	12.5 Gb/s (1.5 Gb/s unused BW)	10.7 %
TDR with RPC (or Tektronix)	10.0 Gb/s (4 Gb/s unused BW)	40 %

Once design criteria (like the 50 mV minimum eye opening) have been established there is a short way to determine roughly how much bandwidth we can get out of a particular calibration or normalization process. By using several calibration methods once, and plotting the maximum operating frequency for the same structure, we can establish a dB value that corresponds to these maximum data rates. The value in this is for future designs you may not need to go through and do a full eye analysis to get an idea of the what different calibration schemes will yield in terms of maximum data rates. This can help in choosing the correct calibration technique and avoid leaving unused bandwidth on the table.

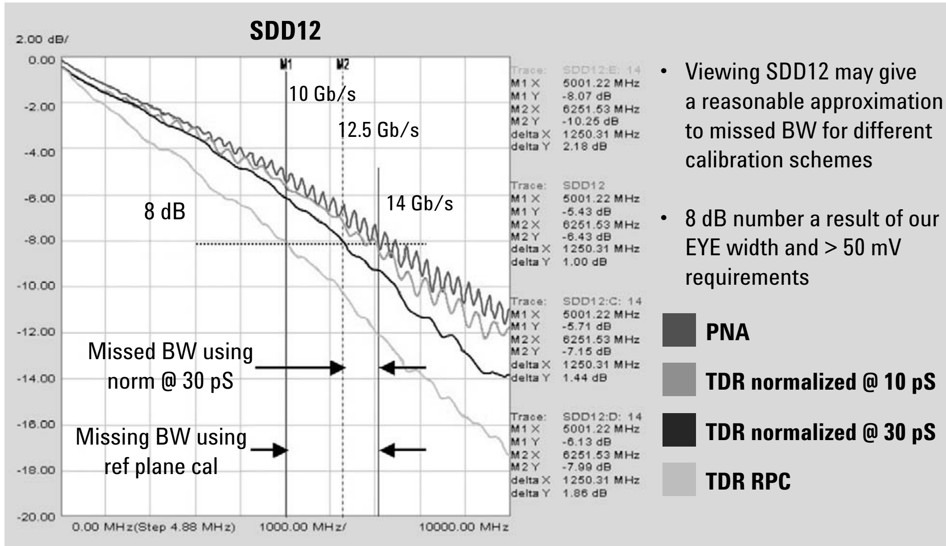


Figure 52. Differential insertion loss of buried stripline example

To summarize the case study:

- Different calibration methods yield significantly different amounts of error (discrepancy from PNA)
- Understanding these discrepancies can help build a case for certain calibration strategies
- Correct strategies help designers avoid leaving significant bandwidth on the table (or allow for better margins and higher reliability)
- Once criteria are established for the eye width, required eye opening, etc. maximum insertion loss targets can assist in estimating maximum data rates of structures or missed BW when evaluating calibration methods

Summary

The TDR has long been used in signal integrity labs for characterizing passive structures. The vector network analyzer (VNA) is becoming more popular in labs as data rates increase and digital standards require frequency domain characterization. Models can be developed from either TDR or VNA data. The VNA clearly provides the most accurate data in both time and frequency domains. Models using S-parameters directly will be the most accurate when measured by a VNA. The Agilent TDR 86100 with normalization gives time domain data very close to that derived from a 20 GHz VNA. To get this close correlation a fast rise time needs to be selected after normalization. This leads to noisier data in the time domain than that from the VNA. Frequency domain data derived from TDR data rolls off at higher frequencies. The roll off is dependent on the risetime selected. This roll off leads to error that can be interpreted as pessimistic insertion loss data and optimistic return loss data for frequencies greater then 10 to12 GHz. Without TDR normalization, the data rolls off much quicker and is much less useful, except at very low frequencies (data rates). Eye diagrams based on S-parameter data are comparably for PNA and normalized data. However, the eye diagram derived from a TDR with only RPC calibration data showing a more closed eye opening (error). As data rates cross the 6.25 GB rate and continue to increase, the accuracy provided by VNA data will be required for accurate designs and validation.

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