

# High Precision Time Domain Reflectometry (TDR)

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# Introduction

High performance communications systems require a quality transmission path for electrical signals. For efficient signal flow and high signal integrity, the transmission path impedance should be kept as close to a constant, ideal value as possible. Time Domain Reflectometry (TDR) is a well-established technique for verifying the impedance and quality of signal paths in components, interconnects, and transmission lines.

As data rates increase and component geometries decrease, the precision and resolution of the basic TDR measurement system can be strained. This application note will review measurement system limitations and the sources of measurement errors. Practical techniques and useful methods to enhance precision will be reviewed.

Specific topics include:

- Techniques to remove the effects of fixturing (cabling and connections that obscure the analysis of the test component)
- A methodology for high-accuracy TDR testing of differential transmission systems
- Deriving one, two, or four port S-parameters for key insights into component performance and enhanced modeling accuracy

Techniques for achieving the highest possible accuracy and resolution in signal integrity impedance measurements



# Time domain reflectometry: measurement basics

When a signal is launched along a transmission path, ideally, none of that signal will be reflected back to the signal source and all the signal energy reaches its intended destination. This will be the case when the impedance of the entire transmission path and the line termination are equal to the output impedance of the signal source. However, if the signal ever encounters a change in impedance, some portion of the incident signal will be reflected.

A time-domain reflectometer (TDR) is a measurement tool used to measure the impedance profile of a component (device) under test (DUT). The concept is straightforward. Using a step generator and an oscilloscope, a fast pulse edge is launched into the DUT. Whenever there is an impedance discontinuity, a portion of the pulse will be sent back to the monitoring oscilloscope. The position of the discontinuity is determined by monitoring the time at which the reflected signal arrives back at the oscilloscope (along with the propagation velocity of the pulse within the DUT). The magnitude of the discontinuity can be determined from the size of the reflected pulse compared to the original pulse sent into the DUT. Thus this “echo technique” reveals at a glance any changes in impedance along the line. Analysis techniques exist to show the nature (resistive, inductive, or capacitive) of each discontinuity along the line and whether attenuation in a transmission system is from series losses or shunt losses. All of this information is immediately available from the oscilloscope’s display. Since the fast pulse step stimulus is broadband, TDR gives meaningful information concerning the broadband response of a transmission system as opposed to testing over the fixed range of frequencies employed by other reflectometer methods.

An example of the equipment configuration making up the TDR and some illustrative measurement results are shown in Figure 1.

For an extensive tutorial on the basics of TDR, please refer to Keysight Technologies, Inc. Application Note “Time Domain Reflectometry Theory.”

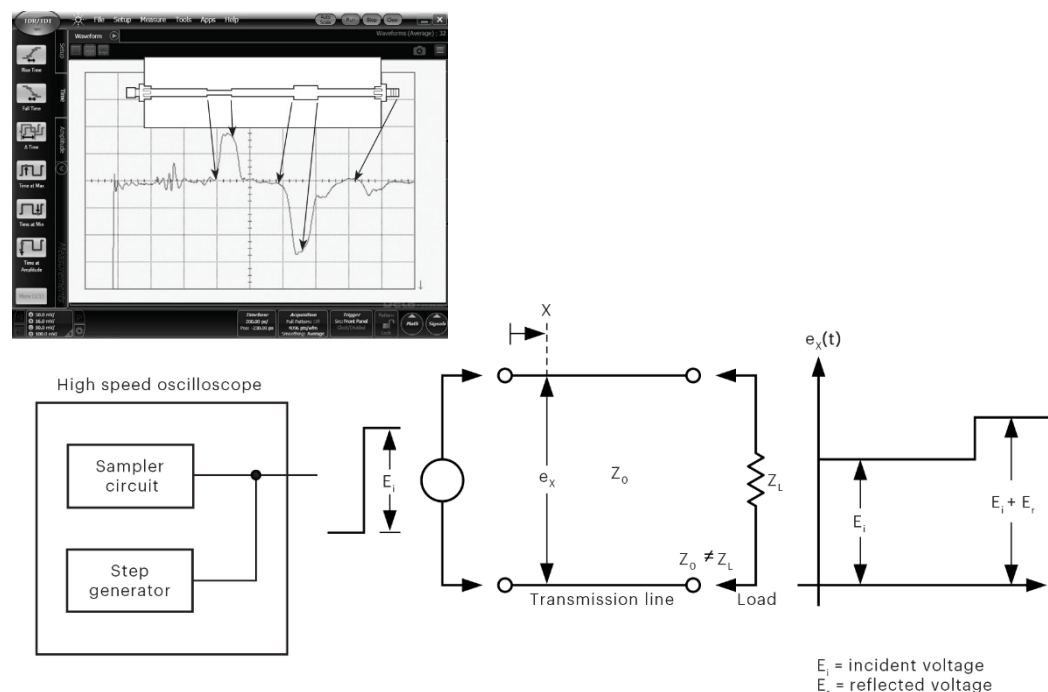


Figure 1. Basic TDR concepts

## TDR measurement limitations

Fundamental performance of the TDR system determines the measurement capabilities. Consider the following factors that dictate the overall performance of the TDR system:

### The step generator as an error source

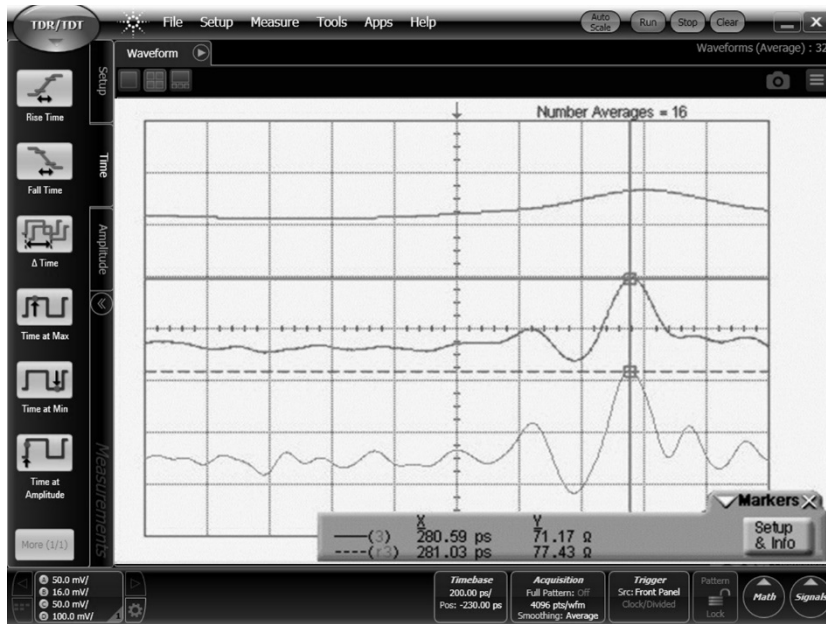
The shape of the step stimulus is important for accurate TDR/TDT measurements. The DUT responds not only to the step, but also to the aberrations on the step such as overshoot and nonflatness.

If the overshoot is substantial, the DUT's response can be more difficult to interpret. Impedance discontinuities are observed as changes in the reflected signal. Aberrations in the TDR step may be incorrectly interpreted as DUT imperfections. If the step is flat, guesswork is minimized. The risetime of the step is also extremely important. To determine how the DUT will actually respond, you should test it at edge speeds similar to those it will actually encounter.

Edge speed is also critical when using TDR to locate the source of a discontinuity along a transmission line. Both the bandwidth of the oscilloscope and the risetime of the step source can limit measurement accuracy. The risetime of the overall measurement system is the combined risetimes of the oscilloscope and the step generator. It can be approximated by Equation 1.

Equation 1: 
$$t_{r_{\text{system}}} = \sqrt{t_{r_{\text{step}}}^2 + t_{r_{\text{scope}}}^2}$$

A real system has a finite risetime, which acts as a lowpass filter. If the measurement system is too slow, the true nature of the discontinuity may be disguised or may not even be visible. The TDR may actually be too fast and yield results that are not applicable to actual usage. (Typically, reflection performance changes with edgespeed because reflections are frequency dependent. This is easily observed with a return loss measurement on a network analyzer. When the amount of signal reflected is measured as a function of frequency, it is common to see that as frequency is increased, the magnitude of signal reflected back from a DUT increases.) Notice in Figure 2, a measurement of a 50 Ohm SMA to BNC adapter, that as the risetime of the step stimulus is decreased, the nature of the reflection from the DUT if used at high data rates becomes more apparent. At a 100 ps step speed, there is only one reflection seen at about 56 Ohms.



**Figure 2.** Reflections as a function of edge step-speed.

When the edgespeed is increased to 35 ps, more reflection sites are observed, with the dominant site at 71 Ohms. At a step speed of 20 ps, the impedance discontinuity increases to over 77 Ohms. In the case of the three measurements, the results obtained using a 20 ps risetime step stimulus do not apply for a connector that sees edges that are always slower than 100 ps in actual usage. Thus the connector might be acceptable for 100 ps edges but not for 20 ps edges. On the other hand, systems operating at or above 10 Gb/s will involve signals with risetimes perhaps below 30 ps. Components for 40 Gb/s transmission may see edges under 10 ps. Thus a TDR with a flexible edgespeed can be useful when components used at a variety of data rates need to be analyzed.

Signal integrity as well as failure analysis often requires the ability to locate and distinguish multiple, closely spaced reflection sites. A TDR can resolve two discontinuities if they are separated by roughly half the TDR rise time. High performance TDR system rise time (both step generator and oscilloscope) is <10 ps. In materials with dielectric constant near 1, this corresponds to a physical separation of about 1.5 mm. (See the section "Using very fast edgespeeds for accurate measurements of closely spaced reflections.") Typical printed circuit board material will have a dielectric constant of approximately 4. The measurable separation then becomes < 1 mm (This value will be larger if the signal fields are in air as well as the board dielectric). Note also that lower quality cables and connectors (discussed below) can also slow down the effective system risetime and degrade the two-event resolution.

## Cables and connectors cause loss and reflection

Cables and connectors between the step source, the DUT, and the oscilloscope can significantly affect measurement results. Impedance mismatches and imperfect connectors add reflections to the actual signal being measured. These can distort the signal and make it difficult to determine which reflections are from the DUT and which are from other sources.

In addition, cables are imperfect conductors that become less ideal as frequency increases. Cable losses, which increase at higher frequencies, increase the risetime of edges and cause the edges to droop as they approach their final value. Thus the issues surrounding the performance of the step generator discussed above are now present due to the cabling and can turn a very good step generator into an apparently bad one. Figure 3 illustrates how cables and connectors affect TDR/TDT measurements. The fastest waveform is the reflection of a step from a short circuit connected directly to the TDR. (Recall that the returned signal from a short circuit inverts the step generator output and that the signal must travel out and back through any cabling). The second fastest step is for a short circuit connected through 1 meter of high-quality cabling. The third is of a short circuit through 0.6 meters of inexpensive cable and SMA connectors. The important point here is that cabling can reduce the precision of a TDR measurement system.

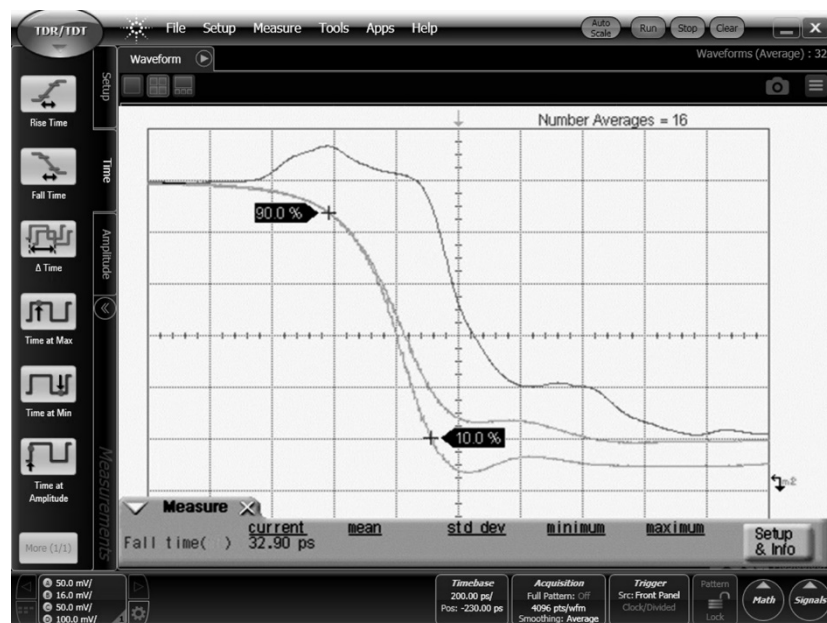


Figure 3. How cabling and connectors can degrade the TDR system.

## Techniques to minimize the effects of fixturing

Using a TDR with a remote head that can be connected to the DUT directly (no adapters or cabling required) will help to minimize systematic measurement errors but not eliminate them. If adapters, probes, or non-coaxial cables are required to reach the DUT, measurement results can become degraded through spurious reflections and systematic losses. Because these error mechanisms are stationary and systematic, there is an opportunity to use calibration techniques to significantly enhance measurement accuracy and minimize these error-producing effects.

One technique to remove systematic measurement errors is waveform subtraction. In this technique, an ideal DUT is connected to the system and the TDR waveform is recorded. When subsequent DUTs are tested, the recorded trace is subtracted from the current trace. Any differences indicate the deviation of the DUT from the ideal. Systematic errors are common to both traces and are effectively removed. This is a simple and convenient accuracy enhancement technique, but there are some significant limitations. First is the requirement of an ideal reference DUT. This may simply not exist or may be very difficult to achieve. Second, all results are relative. There is no simple way to see the absolute performance of the DUT. Finally, the step signal arriving at the DUT may become degraded. Even if this effect is common to both the reference and DUT measurement, it can severely limit the TDR performance.

Another calibration technique is built on the principle of characterizing the test system with precision standards or “known” devices. But rather than produce a reference trace for waveform subtraction, this technique is capable of altogether removing the systematic test system response from the DUT response. The process is commonly referred to as TDR calibration and is an easy and yet elegant and extremely powerful technique to achieve precision results with a TDR.

As powerful as the calibration technique is, the procedure to implement it is very simple and achieved in just a few basic steps. Calibration measurements, which characterize the test system, are made with all cables and connections in place but without the DUT. The first part of the calibration removes systematic errors due to trigger coupling, channel crosstalk, and reflections from cables and connectors by measuring the response with the DUT replaced by an ECal module or good quality calibration standards for a short, open, and load. The test system frequency response is derived from these measurements.

Good quality ECal modules or calibration standards come with characterization data. A complete TDR calibration process uses that characterization data to determine expected measurement results (what the measurement results of each standard would be if measured with an ideal TDR system). Any difference between the actual measurement results of the standards and the expected measurement results are attributed to the test system and corrected with the digital filter. This is why it is very important to use good quality and well characterized calibration standards. If the digital filter is correcting for a poorly characterized or damaged calibration standard, it may actually add errors to the system.

## Generating the digital filter

The second part of the calibration generates a set of digital filters. This is done automatically without any input from the user. The digital filters compensate for the variation of the frequency response of the test system from the ideal. After TDR calibration is performed, if the standard used for the calibration is measured, the result should match the expected measurement results for that standard. The filter removes errors by attenuating or amplifying and phase-shifting components of the frequency response as necessary. Consider, for example, overshoot on the step stimulus. Without calibration, the frequency response of the DUT will include unwanted response to the overshoot. During calibration, the filter will phase-shift and attenuate the frequencies responsible for the overshoot and thus correct the DUT response to the overshoot. The filter works similarly to correct for cable losses due to attenuation of high frequencies.

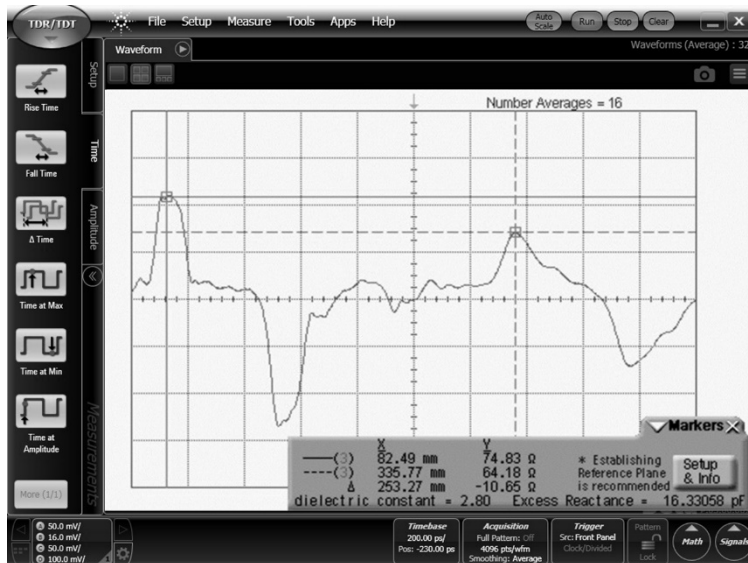
The digital filter generated through the calibration also adds the capability of adjusting the effective risetime of the TDR step generator. Thus the step of the Keysight TDR module can be slowed down or sped up to simulate fast or slow electrical signals. In the Keysight 86100, the user-specified risetime determines the bandwidth of the filter. Decreasing the bandwidth is accomplished by attenuating the frequencies that are beyond the bandwidth of interest. Increasing the bandwidth requires more consideration. To increase the bandwidth, the response beyond the initial  $-3$  dB frequency response needs to be amplified. While this is a valid step, it is important to realize that the system noise at these frequencies and at nearby higher frequencies is also amplified. The limit to which the risetime of real systems may be extended, is determined by the noise floor. In real systems, there is a point beyond which the amplitude of the frequency response data is below the noise floor. Any further increase in bandwidth only adds noise leading to a coarse measurement result. Because waveform averaging reduces the initial level of the noise floor, waveform averaging should be used when using calibration, particularly when decreasing the step generator risetime.

## Measurement examples

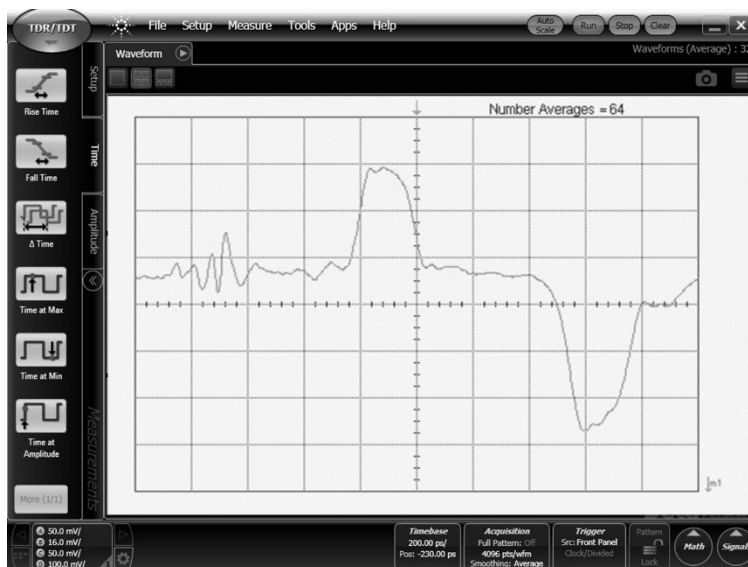
In the following measurement example, the simple PC board transmission line used in the example of Figure 4 (with both a high and low section of transmission line impedance) is measured. However, a duplicate section of transmission line is placed in series with the first. Ideally the measurement of the second section of line should be a duplicate of the first. However, the reflections and attenuation of the first section significantly degrade the measurement of the second, as shown below.

The digital filter generated through the calibration also adds the capability of adjusting the effective risetime of the TDR step generator. Thus the step of the Keysight TDR module can be slowed down or sped up to simulate fast or slow electrical signals. In the Keysight 86100, the user-specified risetime determines the bandwidth of the filter. Decreasing the bandwidth is accomplished by attenuating the frequencies that are beyond the bandwidth of interest. Increasing the bandwidth requires more consideration. To increase the bandwidth, the response beyond the initial  $-3$  dB frequency response needs to be amplified. While this is a valid step, it is important to realize that the system noise at these frequencies and at nearby higher frequencies is also amplified. The limit to which the risetime of real systems may be extended, is determined by the noise floor. In real systems, there is a point beyond which the amplitude of the frequency response data is below the noise floor. Any further increase in bandwidth only adds noise leading to a coarse measurement result. Because waveform averaging

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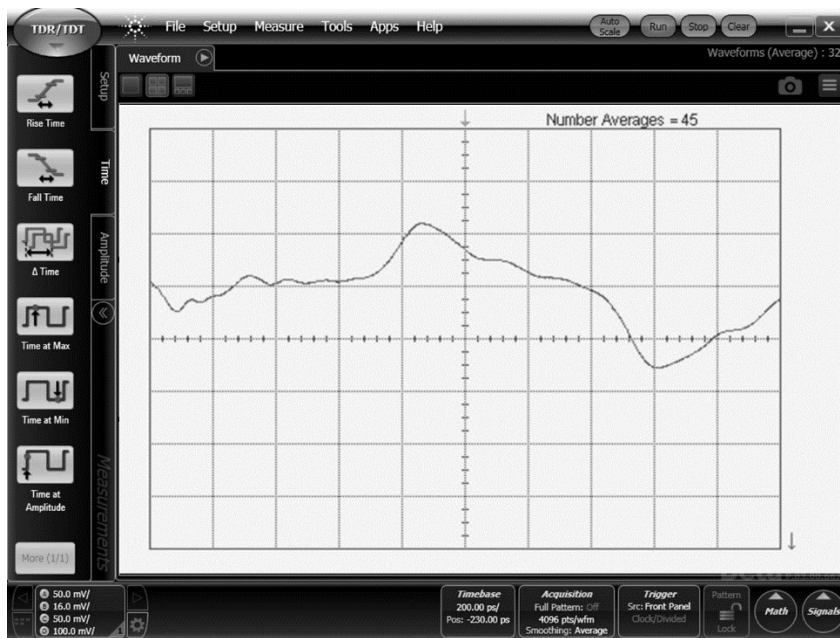


**Figure 4.** TDR measurement of two multiple impedance transmission lines in series



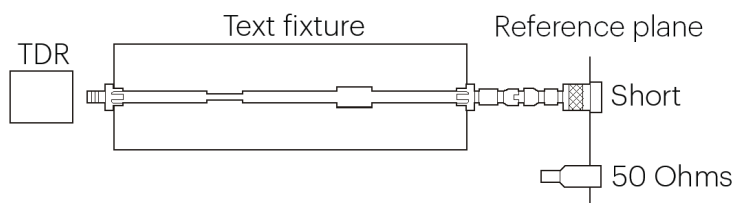
**Figure 5.** View of the first PC board

The above two figures show first the measurement of the first section of line, while the second figure shows the measurement of the second section of transmission line. Note how the second section, although identical to the first, has measurement results that are significantly attenuated and smeared compared to the first. This then shows how the cabling and fixturing leading up to a DUT can significantly alter the TDR results.



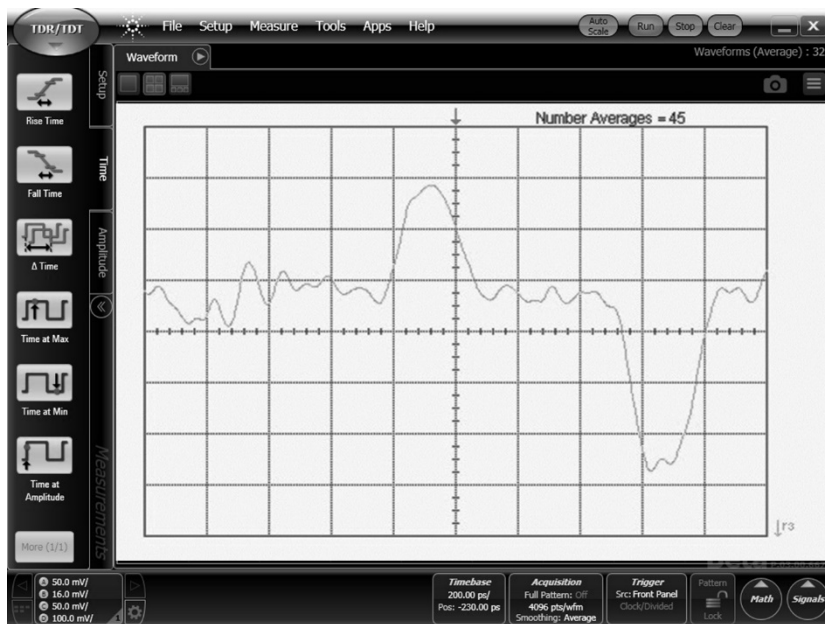
**Figure 6.** View of the second PC board.

Calibration can significantly improve the measurement results. Breaking the connection between the two transmission line sections, a short and load termination can be placed at the output of the first section of line. This then becomes the measurement reference plane. The calibration procedure will then correct measurement errors generated before this point.



**Figure 7.** Setup for calibration

With the calibration complete, the measurement results for the second board are seen. Note that the effects of the first board are removed in two ways. First, the reflections of the first transmission line are effectively removed from the result. Second, the effects of the first transmission line upon the measurement of the second line are also removed. The measurement results of the second line now are in excellent agreement with the direct measurement of the line seen in Figure 1.



**Figure 8.** Calibration removes the effects of the test fixture

The calibration provides significant improvement in the measurement of components where the DUT is not a coaxial component. A good example is probing on a circuit board. Using a TDR requires some form of fixturing to go from the coaxial system of the TDR to the non-coaxial DUT. The adapters and fixtures to allow this will mask the true performance of the non-coaxial DUT. However, the problem is significantly reduced through calibration. This is achieved when a short and load termination can be measured in the native environment of the DUT. For example, probing calibration standards are used to remove the effects of a probing system.

A second benefit of the calibration is the ability to effectively speed up or slow down the edgespeed of the TDR step. This was discussed above on page 4 where it was shown that the TDR edgespeed should be similar to the edgespeeds components will encounter in actual usage. The TDR results then are directly applicable to how the component will be used.

The calibration then provides a convenient method to examine the impedance performance of components for a variety of signaling rates. For further details on TDR calibration, please refer to Keysight Application Note 5988-2490EN “Improving TDR/TDT Measurements Using Normalization”.

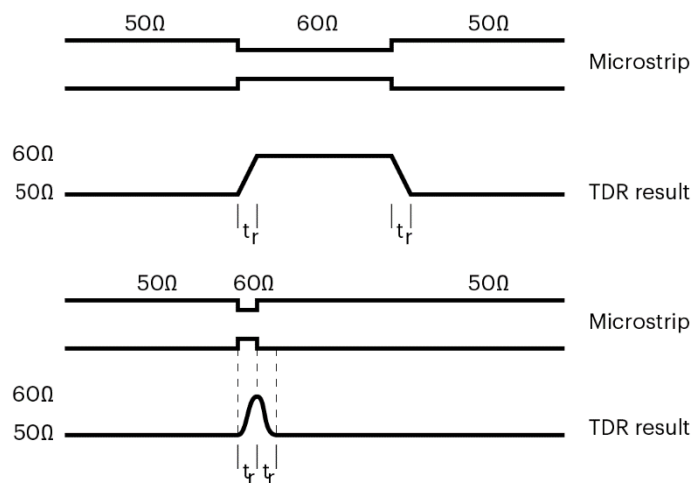
In summary, the key benefits of this calibration process are:

- Removal of reflections within the test system and connections to the DUT
- Removal of imperfections (overshoot and ringing) in the step generator pulse
- Control of the step generator edgespeed
- Compensation for loss/attenuation in test system cabling

# Using Very Fast Edgespeeds for Accurate Measurements of Closely Spaced Reflections

In TDR measurements, as the physical separation between reflection sites diminishes, eventually the two reflections appear as one. The limitation in the TDR system to see closely spaced reflections is fundamentally tied to the risetime of the step generator and the bandwidth of the oscilloscope. As discussed earlier, a general rule is that reflections must be separated in time by at least half the TDR system risetime to be resolved as two distinct reflections. To get an intuitive feel for this consider a basic microstrip transmission line where the impedance changes from 50 Ohms to 60 Ohms and then back to 50 Ohms. Since there are two locations on the line where the impedance changes, there will be two reflection sites. How narrow can the 60 Ohm section be before the two impedance transitions can no longer be observed individually? The TDR trace will be at the 50 Ohm level until the transition to 60 Ohms is encountered. Since the impedance becomes higher, the reflected voltage will be in phase and add to the 50 Ohm level. The time required to reach the full 60 Ohm voltage level is simply the risetime of the step generator. The TDR response will stay at the 60 Ohm level until the transition to 50 Ohms occurs. The time required to make the full transition back to the 50 Ohm level (after the transition is initially encountered) is once again the risetime of the TDR system.

As the section of 60 Ohm line gets shorter, the transition from 50 Ohms to 60 Ohms will become close to the transition from 60 to 50. When the beginning of the voltage transition for the 60 to 50 Ohm section is at approximately the same time as the end of the voltage transition for the 50 to 60 Ohm section, the minimum measurable spacing for two reflection sites has been achieved. If the reflection sites become closer, the TDR waveform will not have sufficient time to reach full amplitude and the measurement of the magnitude of the impedances will be in error.



**Figure 9.** Determining two-event resolution

Thus on the TDR display, the “time” between the two reflection sites can be noted as the time difference between the foot of the first edge (due to the 50 to 60 Ohm transition) and the foot of the second edge (due to the 60 to 50 Ohm transition, and in this case a falling edge). This time is essentially the risetime of the TDR system. However, it is important to note that the time displayed on the TDR is indicative of roundtrip reflections or in other words how long it takes for the pulse to get to and return from reflection sites. Thus the time separation noted above is the roundtrip time. The minimum one-way distance between reflection sites is then half of the system risetime. The minimum physical distance is given by the propagation velocity in the media and TDR system risetime:

Equation 2: 
$$\frac{c \cdot t_{rise}}{2\sqrt{\epsilon}}$$

where epsilon is the dielectric constant of the transmission system and c is the speed of light in a vacuum.

The effective system bandwidth and step speed can be increased through the calibration as discussed above. Thus the two-event resolution of the TDR system is improved through calibration.

## Performing Precision TDR Measurements for Differential Transmission Systems

As systems increase in speed, differential transmission techniques are used to maintain signal integrity. Differential transmission uses two transmission lines carrying complementary data signals. Characterizing the quality of a differential transmission line for impedance values and discontinuities requires a technique to stimulate both legs of the transmission media. Also, when the two transmission lines are electromagnetically coupled with each other, analysis of the impedance properties of the system requires some modification compared to a single-ended line.

The most obvious technique for testing a differential transmission line or component is to have a TDR system with complementary step generators. That is, while one step generator produces a positive going step into the “positive” side of the system, a second step generator produces a negative going step into the “negative” side of the system. Differential impedance measurements are made by comparing the reflected differential voltage with the incident differential voltage. (Differential voltage being defined as the voltage across the two input terminals of the DUT and differential impedance being the differential voltage divided by the current through the system. Note that if the system is balanced, the current into one side of the line is the same as the current out of the other side).

Precision differential TDR measurements place some critical restrictions on the TDR system. Any asymmetries in the two legs of the measurement system may potentially lead to imbalances or errors in resulting measurements. Asymmetry in a differential system is one of the leading causes of mode conversion from differential to common mode or vice versa. Error sources include:

- Timing skew between the two step generators
- Timing skew between the two oscilloscope receivers
- Differences in the step pulses in the two generators, either in amplitude or in overall shape
- Differences in the response of the two oscilloscope receivers

Carefully designed hardware provides the foundation for an accurate measurement solution. In addition, the calibration process discussed earlier, with all of its capabilities to remove systematic error producing effects, has been extended for use with differential TDR. The end result is the highest precision in differential TDR measurements.

The 86100 TDR system has skew capability at both the step generators and receiver. It is important to understand how each is implemented and what the effects will be on the measurement results. When examining a differential transmission system, it is critical to maintain a precise alignment of the stimulus pulses. The time at which the first step generator produces a pulse can be adjusted to occur either later or earlier than the pulse from the other step generator of the TDR module.

The receiver of the TDR can also be adjusted to sample data at a variable time relative to the step generator trigger event (which is used to determine when the signals are sampled). Thus the signal returning to one channel of the differential TDR can be effectively shifted in time relative to the other channel by adjusting the time at which it is acquired by the TDR. This then effectively allows the returned signals to be aligned if any system skew must be eliminated.

For example, if there are unequal lengths of cable between the two step generators and the DUT, the two steps would arrive at different times at the plane of the DUT. Also, the reflected signals from the DUT would be misaligned as they return to the TDR receiver through the unequal lengths of cable. A procedure is built into the 86100 TDR system to remove the effects of skew due to path length leading to the DUT. One part ensures that the steps are aligned at the reference plane (to balance the stimulus to the DUT) while the other part removes the misalignment of returning signals to the TDR.

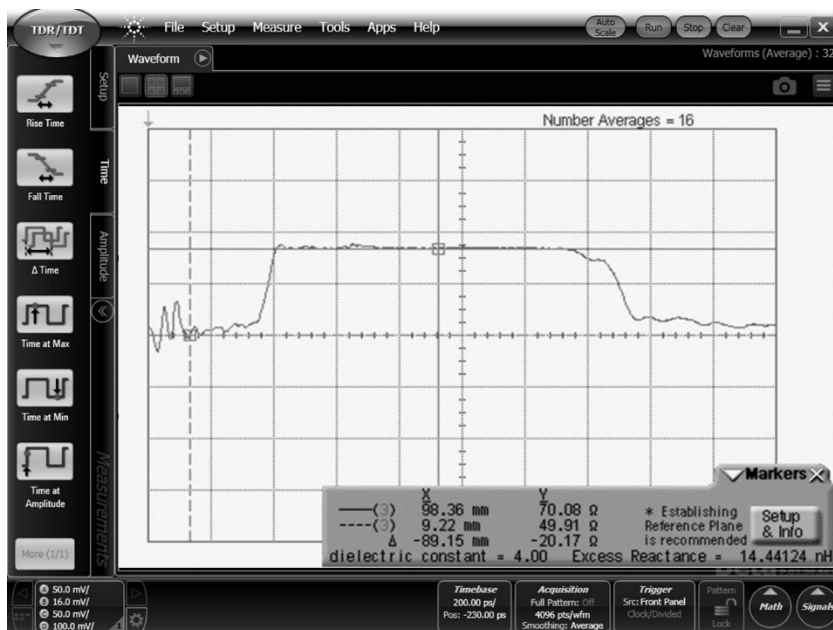
It is important to recognize the differences between a differential measurement and simply taking the difference between two single-ended measurements. The basic single ended measurement stimulates the input and examines what returns at that input port. The differential measurement stimulates both ports and examines what returns to both ports. The critical difference is that through coupling of the differential transmission lines, the stimulus on one port may result in signals being reflected back to both ports. Also, the characteristic impedance of the transmission line will be affected by a differential stimulus and the associated coupling.

An example of a single ended measurement of a differential transmission line is shown below. The two lines of this basic differential circuit initially have a single ended impedance of 50 Ohms. The lines are physically separate, thus there is minimal coupling in this region. The two lines then come together and the two trace widths are reduced (which would cause an increased single ended impedance). The lines are then increased in width and are spread apart.



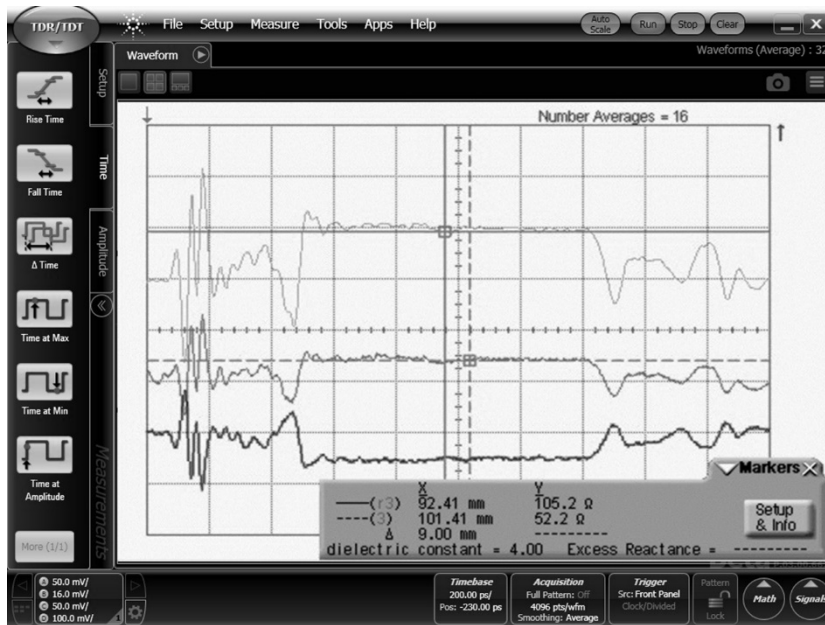
**Figure 10.** Differential line model

If each leg is tested individually (driven single ended), the TDR results are seen as a 50 Ohm line, then a 70 Ohm section, and a 50 Ohm section before being terminated in a 50 Ohm load. The result is the same for each leg.



**Figure 11.** Differential trace measured single-ended

In the differential measurement, the TDR system combines the results from both ports when stimulated by both steps. Thus the signal on each leg will be a combination of signal from both step generators. The result is that the differential impedance is close to 100 Ohms, which was the intent of the transmission line design. The odd-mode impedance (one leg of the transmission line to ground when driven differentially) is close to 50 Ohms.



**Figure 12.** Differential TDR showing differential (upper trace) and odd-mode impedances (middle and lower traces) of the differential transmission line

The final steps to measurement error reduction involve de-embedding of fixturing and removing any residual aberrations in the pulses from the step generators. This is achieved with the calibration process referred to earlier. The procedure for differential measurements is similar to that used for single ended TDR, except that the procedure is performed twice (once for each channel). Calibration also allows for pulse risetime adjustments to simulate faster or slower data signals.

The benefits of the differential calibration are shown in the example below where imperfect fixturing and cabling obscure the true results from the DUT. The first step is to remove any skew in the system prior to the DUT. First, the reflected signal from the DUT measurement plane (open circuit or short circuited) is examined (Figure 13). Half of the skew is removed through shifting forward the output launch time of the “late” step generator. The remaining half is removed by delaying the time at which the late signal is measured, effectively allowing it to catch up to the early signal. Note again that these corrections are made not for skew in the DUT, but in the system leading up to the DUT.

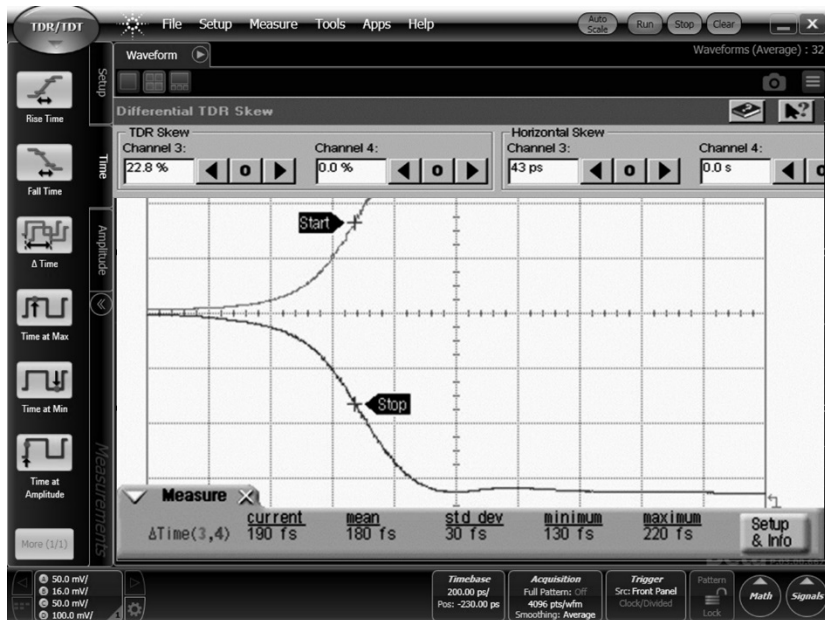
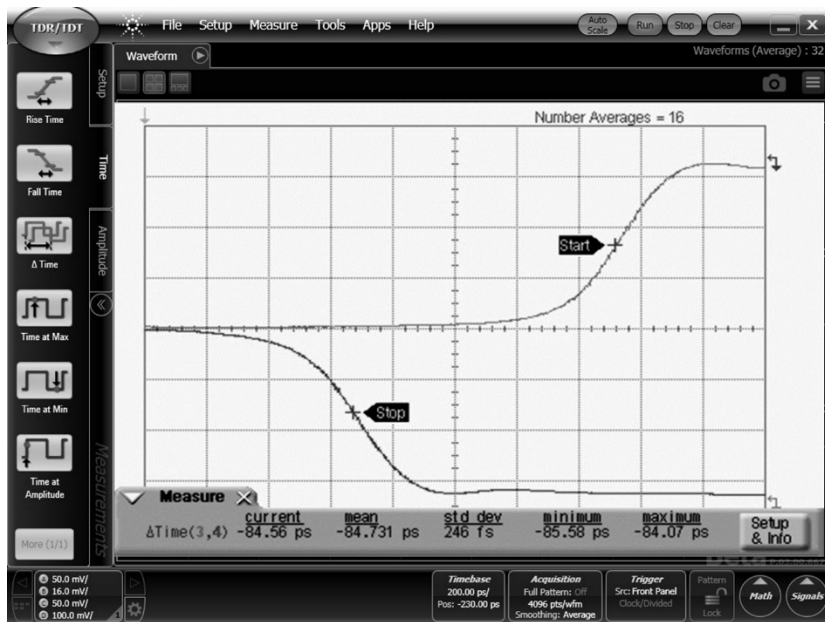


Figure 13. Before and after skew adjust

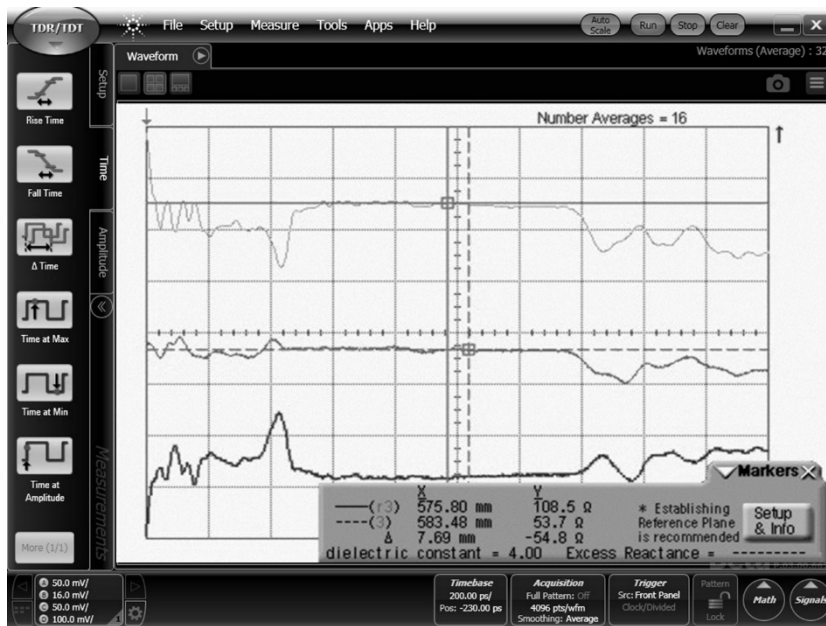


Figure 14. Differential and odd mode impedance results with fixturing error

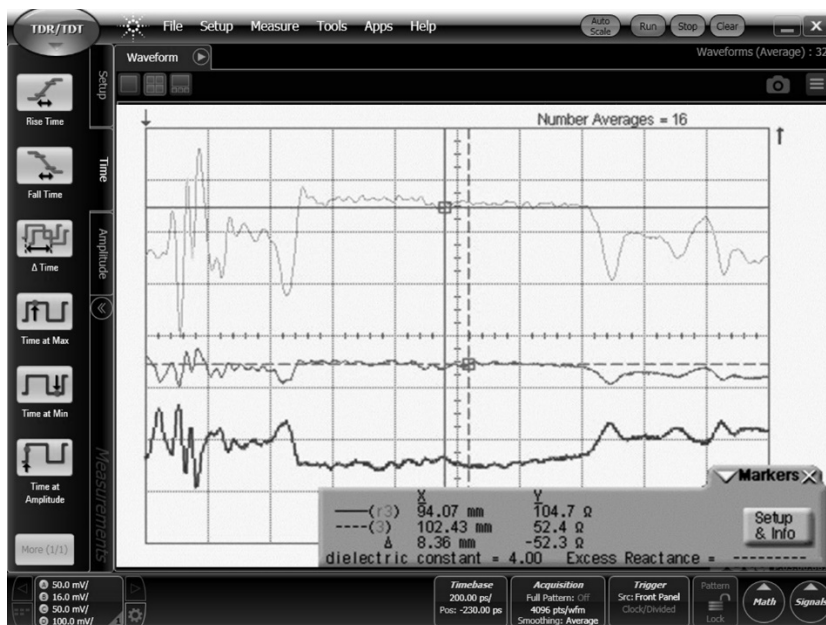


Figure 15. Differential and odd mode impedance results with fixturing errors removed

Even with a precise alignment of the step generators and receivers, the fixturing leading to the DUT may degrade both the stimuli and DUT responses. As an example, this has been intentionally done through adding additional cabling and loss between the TDR and the DUT. The resultant measurement errors are shown in Figure 14. Compare the differential (upper) and odd-mode (middle and lower traces) results of Figure 14 to the same measurement (with no fixturing) of Figure 12. Rather than seeing a differential impedance of 105 Ohms, and odd mode impedance of 52 Ohms, the readings have increased to 109 and 54 Ohms.

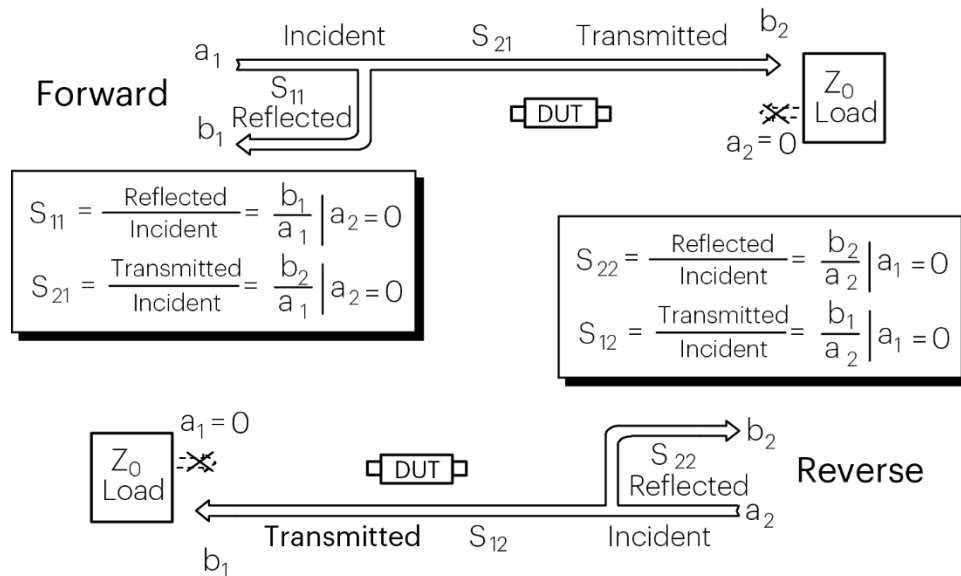
When the measurement including the fixturing and loss is repeated, but the measurement errors removed with calibration, the measurement results are in excellent agreement with those taken when no fixturing was physically in place (Figures 12 and 15).

The calibrated measurement system provides the highest precision differential TDR measurement result, even when error-producing mechanisms are present. The calibration process and measurement techniques are equally valid for common-mode measurements, where the two step generators have the same polarity outputs, based on calibration standards (load and short) being provided to perform the calibration. Measurements of DUTs that require a transition from the coaxial cabling of the TDR system to a non-coaxial cable type (such as probing on a circuit board) benefit significantly from this, as long as a load and short termination of the appropriate type is provided.

## Deriving ‘S’- Parameters from Traditional TDR Results

Important insights into component behavior can be achieved through frequency domain analysis in addition to characterization in the time domain. For example, a common measurement is to determine the amount of signal that is reflected back from a component over a specific range of frequencies, perhaps from the kilohertz range through the gigahertz range. The frequency response results often yield important insight into why components behave specific ways. Resonances are easily detected and general performance can be directly associated with specific circuit behavior. Advanced component models can be facilitated through frequency domain measurements. Such measurements are commonly called ‘S’ (scattering) parameters and have been used in RF and microwave design for decades.

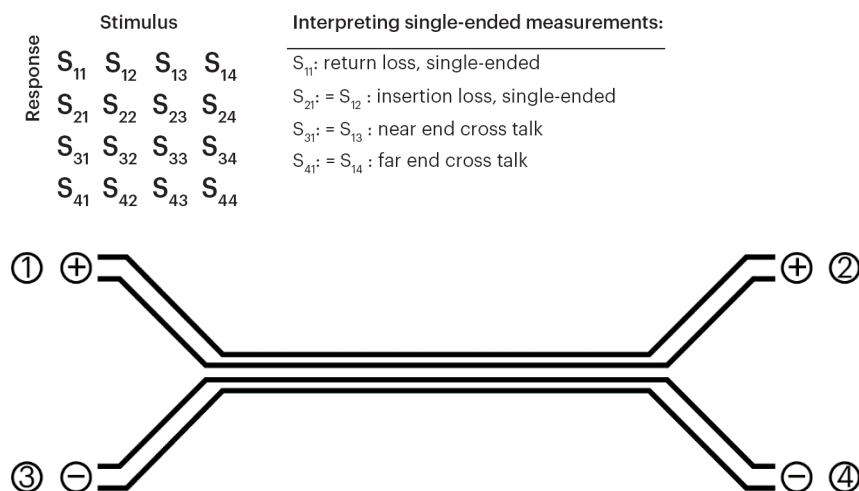
The common instrument used to obtain S parameters is the network analyzer where a sinusoidal signal generator is varied in frequency over the range of interest. A receiver, tuned to the frequency of the signal generator is used to monitor the signal (reflected or transmitted) from the DUT. Components can be one-port (input or output only) or two-port (input and output). For the case of the two-port component, we are concerned with transmission and reflection at each port. Thus for a two-port component there are two pairs of reflection and transmission measurements and thus four S-parameters.



**Figure 16.** Signal model for S-parameters on a two-port device

## Measuring differential components and channels

A differential component with just a positive and negative input and output adds two ports to the above example and four more S-parameters. However, differential channels can couple to their complementary channels, doubling the 8 S-parameters to 16. Note that the stimulus and response for these measurements are still effectively single-ended. That is, only one port is stimulated and one measured to construct each of the S-parameters. The S parameter notation is  $S_{\text{out/in}}$ . Thus  $S_{21}$  is the signal seen at port 2 with a stimulus at port 1. In the following example for a differential circuit, one differential port pair is noted by ports 1 and 3, the other differential port pair by ports 2 and 4. The 16 possible measurement configurations and some physical interpretations are shown below.



**Figure 17.** Single-ended S-parameters for a 2-port differential device

Finally, a differential circuit can be driven in either differential or common mode, and the response be measured in a differential or common mode. Thus the full S-parameter set for a two-port differential component, including single-ended, differential, common, and mixed mode configurations has 32 unique S-parameters.

It is important to interpret what the various differential and common mode measurement configurations provide. The differential S parameter notation is slightly different than the single ended notation. It still follows an S “out-in” format. However, port 1 includes both the positive and negative legs of the differential input, as also does port 2.



**Figure 18.** Differential S-parameter model

Thus  $S_{DD11}$  indicates the reflected differential signal when stimulated differentially. Similarly,  $S_{DD21}$  indicates the differential output (at differential port 2) when a differential signal is input to differential port 1. Thus there are four basic quadrants to the 16 element differential S-parameter matrix, as displayed in Figure 19. The upper left quadrant is a measurement of differential transmission and reflection for a device with two differential ports (typically differential in and differential out) when stimulated with differential signals. Similarly, the lower right quadrant gives common transmission and reflection performance when the two port device is stimulated with common mode signals.

The mixed mode parameters (combinations of differential and common mode stimulus or response) provide important information about how conversion from one mode to the other may occur which in turn provides insight into how components and channels may radiate or be susceptible to radiated signals. For example, the lower left quadrant indicates how differential input signals are converted to common mode signals.  $S_{CD21}$  would be a measure of how a differential input to port 1 is observed as a common mode signal at port 2 (see Figure 20). Common mode signals are more likely to cause radiated emissions than a differential signal, hence the  $S_{CD}$  quadrant is useful in solving such problems. The upper right quadrant ( $S_{DC}$ ) indicates how common signals are converted to differential signals. Differential systems are intended to reduce susceptibility to spurious signals by rejecting anything that is common to both legs of the differential system. But if spurious common mode signals are converted to differential signals, they no longer are rejected. Hence the  $S_{DC}$  quadrant measurements are useful in solving problems of susceptibility to spurious signals. For example,  $S_{DC21}$  indicates how a signal that is common mode at port one is converted to a differential signal and observed at port 2.

Response		Stimulus			
		Differential signal		Common signal	
		Port 1	Port 2	Port 1	Port 2
Differential signal	Port 2	$S_{DD11}$	$S_{DD12}$	$S_{DC11}$	$S_{DC12}$
	Port 1	$S_{DD21}$	$S_{DD22}$	$S_{DC21}$	$S_{DC22}$
Common signal	Port 2	$S_{CD11}$	$S_{CD12}$	$S_{CC11}$	$S_{CC12}$
	Port 1	$S_{CD21}$	$S_{CD22}$	$S_{CC21}$	$S_{CC22}$

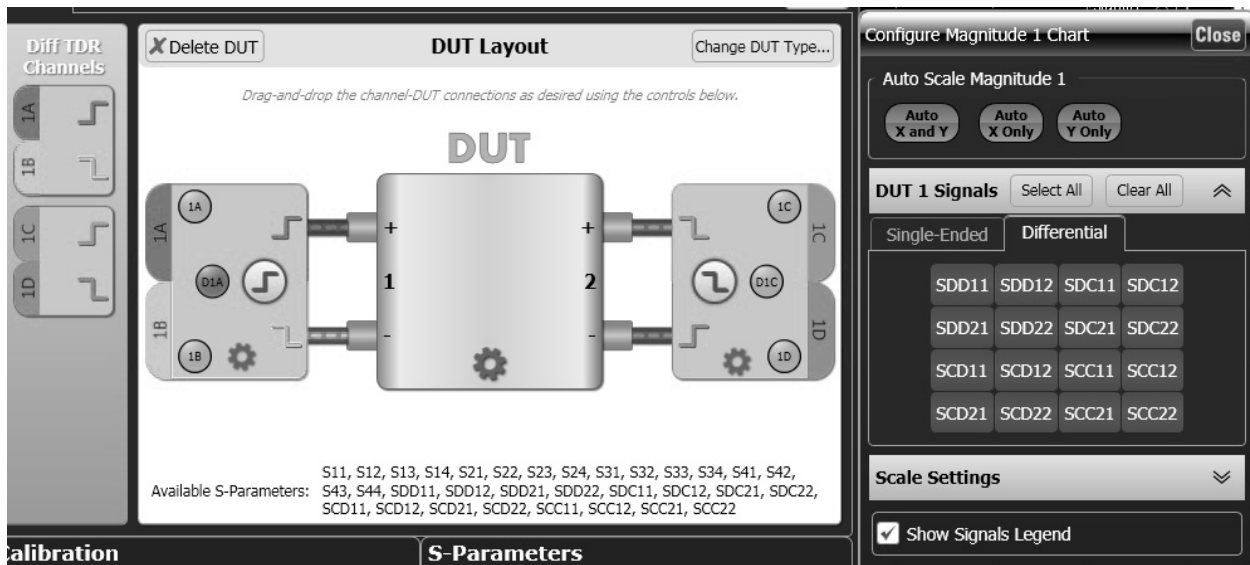
**Figure 19.** Mixed mode S-parameters



**Figure 20.** Mixed mode S parameters:  $S_{CD21}$

Although the network analyzer is directly suited to generate the frequency domain S-parameters, the 86100 TDR can be configured to produce frequency-domain S parameter results in addition to conventional TDR measurements. Depending upon the instrument configuration, the full set or a subset of the 32 differential S-parameters can be achieved. Full and thorough characterization of a component is now possible in both the frequency and time domains with a single instrument.

The 86100 TDR system with Option 202, "S-Parameter and Time Domain Characterization" provides S-parameter measurement results directly on the instrument display.



**Figure 21.** TDR Setup Screen for the 86100 TDR showing a differential DUT and the available differential S-Parameters



**Figure 22.** Live on-board frequency domain results on the 86100 TDR showing all 32 S-Parameters for a 2-port differential DUT

## References

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