Application Note

USING TDR TO DEBUG SIGNAL INTEGRITY ISSUES

Products:

- ► R&S®RTO2000
- ► R&S®RTP
- ► R&S®ZNB

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Contents

1 Overview

Time Domain Reflectometry (TDR) has long been used as a tool for evaluation of boards, cables, and connectors. For signal integrity analysis, the TDR "measurement" has traditionally been done on one instrument (sampling oscilloscope or VNA) and the system-level "analysis" performed on another instrument (real-time oscilloscope). Integrating the TDR measurement and analysis into the same instrument not only saves time using a single instrument but offers a more intuitive approach to overall signal integrity analysis.

2 Introduction

From LAN to USB, from DDR4 to PCI Express, every digital design has three basic building blocks: transmitters, channels and receivers. The transmitter output may look clean on the screen of an oscilloscope, but high-speed signals degrade as they travel through the channel to the receiver. At the far end of the channel, the receiver has to properly detect data in the presence of noise and other types of interference.

Three issues are most likely to affect signal integrity. One is signal attenuation, and engineers often use equalization to fix this problem. Another issue is “outside” interference such as crosstalk or coupled noise from the power-distribution network (PDN). Third is “internal” interference from reflections due to impedance mismatches.

Impedance problems are often related to discontinuities in the channel. These may be present in connectors, printed circuit board (PCB) traces, solder pads, or any other element in the path between transmitter and receiver. Time-domain reflectometry (TDR) is a highly effective way to measure impedance effects and locate the mismatches.

Oscilloscopes and vector network analyzers are both capable of making informative TDR measurements. Each has important strengths and weaknesses relative to performance, measurement noise, and additional capabilities (e.g., protocol analysis, S-parameters).

In this white paper our focus is on the use of an oscilloscope to measure TDR and then identify and debug the effects of reflections due to impedance mismatches. We start with a review of TDR basics and then, with that foundation, shift to the matching of scope performance with SUT requirements. From there, the narrative outlines a suggested process for TDR measurements. The final section presents an overview of recommended solutions from Rohde & Schwarz.

3 The Basics of TDR

Developers often start with a device data sheet and a reference design. When the device is used in a circuit, reality is often different. The eye diagram in Figure 1 includes a test mask (red hexagon) that indicates a variety of mask failures: signal attenuation; narrowing due to jitter (lower eye); and reduced margin from power rail noise, crosstalk, or reflections.

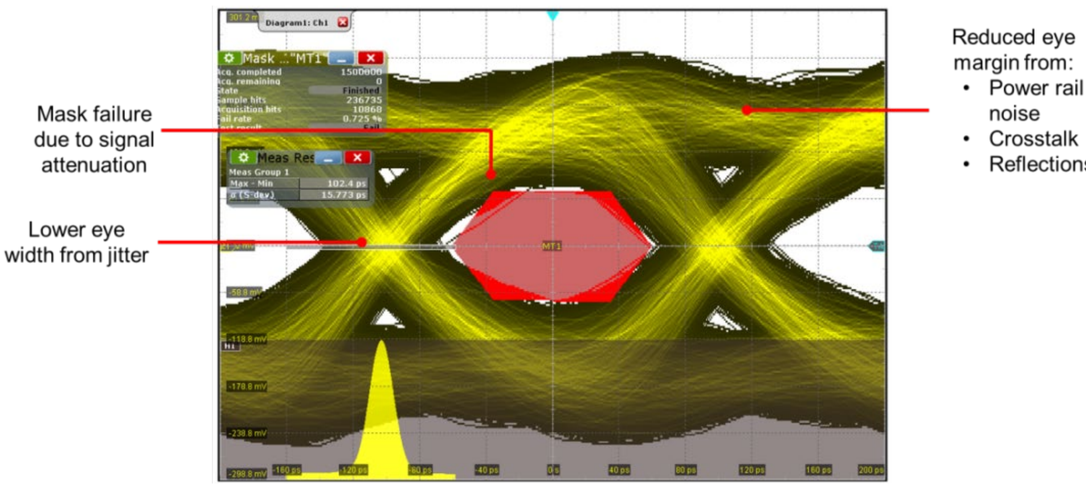


Figure 1: An eye diagram is an informative diagnostic tool when debugging and troubleshooting digital designs.

To help track down the underlying problems, TDR generates a step stimulus and measures the response in the time domain. The responses from the unknown or “black box” circuit are voltage reflections caused by impedance mismatches, including open circuits.

The stimulus is a fast step, and its rise time corresponds to an equivalent measurement bandwidth. If the channel has uniform impedance and is properly terminated, there will be no reflections. If reflections are detected, the amplitudes and polarities depend on the impedance at each discontinuity.

The round-trip time between transmitted step and received reflection is related to the distance between the transmitter and the fault. By calculating length along the channel, TDR pinpoints the discontinuities that are causing reflections. From this perspective, more resolution in the TDR measurement means greater precision in locating the cause of each reflection.

Within this process, four key parameters determine the accuracy of TDR: the quality of the stimulus (i.e., incident step signal); rise time and system bandwidth; and differential measurements.

TDR stimulus: The quality of the incident step pulse generated by the TDR instrument is especially important when measuring short traces. The step pulse must have a fast rise time, accurate amplitude and, to ensure quality measurements, minimal aberrations (e.g., overshoot, ring).

In addition, the stimulus generator should be as close as possible to the device under test (DUT). Reason: When making TDR measurements, every discontinuity in the channel also acts like a filter and reduces measurement resolution. Shorter cables and fewer connections minimize the number of discontinuities in the test setup itself.

Rise time and system bandwidth: The faster the rise time, the wider the bandwidth that can be analyzed. Rise time also determines the spatial resolution or smallest spacing between impedance discontinuities. System bandwidth is a function of source rise time and oscilloscope rise time.

The physical spacing of any two discontinuities determines how closely their reflections will occur in the TDR waveform. To distinguish neighboring faults, the intervening travel time must be less than half the rise time of the TDR pulse. A faster rise time will improve resolution and thereby make it easier to view wider-bandwidth artifacts and locate smaller discontinuities.

Differential measurements: Many of today's high-speed serial standards rely on differential transmission techniques, using complementary signals. Although more complex than a single-ended architecture, differential transmission is less susceptible to external influences such as crosstalk and induced noise, and it generates less of both.[1]

True differential measurements require a TDR instrument capable of launching simultaneous and complementary incident pulses. Also, because precise time alignment is very important, it is best to use skew-matched cables in the measurement setup.

The complementary pulses are sent down both sides of the differential pair and the reflections measured. Because the SUT receives a differential stimulus similar to what it sees in the end application, the measured results provide insights into the device's real-world response.

[1] This concept applies to TDR and time-domain transmission (TDT). TDT requires two channels, one connected to the transmit end of the electrical path and the other connected to the receive end. Consequently, differential TDT measurements require four measurement channels.

4 Matching Performance with Characteristics

Understanding what you *need to measure* as well as *how your system operates for that measurement* will help you understand the tradeoffs between TDR rise time and resolution. As a starting point, we need to be sure the performance of the oscilloscopes meets or exceeds the characteristics of the system under test (SUT).

For example, emitter-coupled logic (ECL) families have rise times in the range of 200 ps to 2 ns. As another, USB3 testing requires TDR with rise times of 50 ps (20 to 80%) or 75 ps (10 to 90%). In all cases, measurements require enough rise time to separate closely spaced discontinuities, but not so much bandwidth that the in-band noise affects measurement quality.

Let's look at oscilloscope performance relative to TDR measurements. In this application, scope rise time determines resolution, as defined by the following equation:

$$l = \frac{t_r \, c}{\sqrt[2]{\varepsilon_{eff}}}$$

- ► l is the minimum length and therefore the resolution of distance measurements
- ► t_r is the system rise time
- ► c is the speed of light in vacuum
- ► ε is the relative permittivity of the channel

System rise time, tr, is a root-sum-of-squares function of the pulse and oscilloscope rise times:

$$t_{r\,System} = \sqrt[2]{t_{r\,Pulse}^2 + t_{r\,Scope}^2}$$

Table 1 provides a quick summary of system rise time versus resolution, and Figure 2 shows an example measurement with resolution of 3.5 mm.

TDR system rise time	TDR resolution
10 ps	1 mm
20 ps	2 mm
30 ps	3 mm
100 ps	10 mm

Table 1: Faster system rise time equates to finer resolution in locating faults in the electrical path.

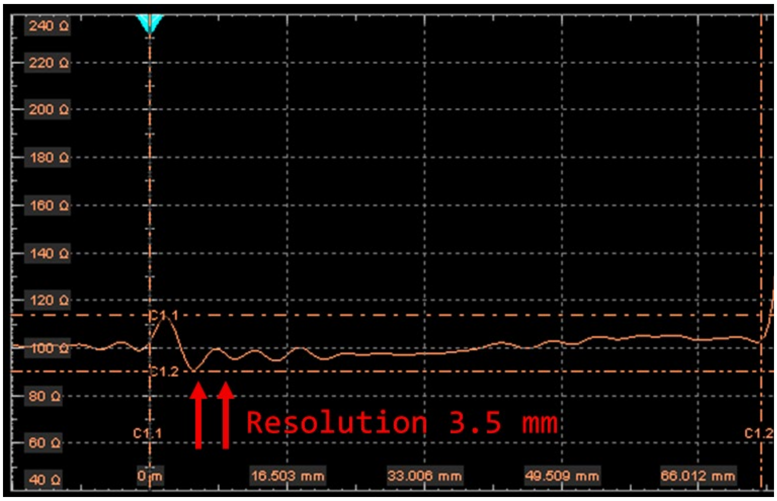


Figure 2: This TDR display has impedance on the vertical axis and distance on the horizontal axis.

Next, we need to consider the relationship between rise time and bandwidth as well as their individual effects. For example, a slow rise time will filter in-bound reflections and limit measurement resolution. In contrast, a fast rise time provides better resolution, making it easier to see more of the effects that disturb signal integrity: overshoot, noise, reflections, and so on.

There is also a crucial tradeoff: a faster rise time equates to a wider bandwidth, which increases the amount of noise in the measurement. Consequently, we have to make a judgement call: use a narrow bandwidth when excess noise is present or use a wide bandwidth when greater TDR resolution is needed (Figure 3).

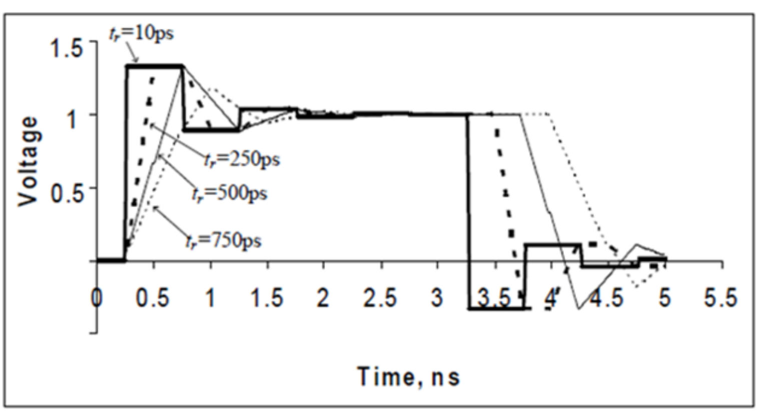


Figure 3: This conceptual diagram illustrates faster and slower rise times, hinting at the direct relationships with bandwidth and resolution (e.g., faster means wider/more, slower means narrower/less).

The final considerations are the coefficient of reflection and the calculated impedance. As described above, scopes rely on voltage waveforms to measure TDR, comparing incident and reflected signals. These are also used to calculate the reflection coefficient, rho (ρ):

$$\rho = \frac{V_{reflected}}{V_{incident}}$$

Rho is used in the calculation of impedance in a nonlinear equation:

$$Z(t) = \frac{1 + \rho(t)}{1 - \rho(t)} Z_0$$

We can check the behavior of this relationship by considering three general cases for the resulting impedance value and corresponding values for rho:

► A short circuit has zero impedance: Z = 0 and therefore $\rho = -1$

► An open circuit has infinite impedance: $Z = \infty$ and therefore $\rho = 1$

► All other cases: the equivalent impedance is Z0 and therefore $\rho = 0$

More Information

If you would like to take a deeper dive into the reflection theory, test methods, and more, please visit the IPC.org website (formerly the Institute for Printed Circuits). It offers detailed information around all things related to test methods for interconnects:

► *Temporal/spatial resolution*

► *Connector torque specifications*

► *Protection from electrostatic discharge (ESD)*

► *Proper measurement windowing*

► *Signal attenuation measurement methods*

► *And much more*

5 Best Practices and a Suggested Process

A few key ideas can help ensure useful, informative TDR measurements. When preparing to debug a design, two quick checks will help ensure the scope is ready for TDR. Then, a three-step process will help ensure informative results—and software built into Rohde & Schwarz oscilloscopes can guide you through each step.

5.1 Two best practices

Experienced users rely on two best practices when preparing to debug a design. One is to review the configuration settings that affect distance measurements, and this requires an impedance check followed by measurement of a known length. The other involves optimization of averaging settings to reduce noise and ensure convergence on the mean value of the measured impedance.

The impedance check requires two measurements: an open circuit and a known termination. Figure 4 shows two example measurements of an 85-ohm differential-coupled trace on a PCI Express PCB. On the left, the measurement shows an infinite response or open circuit; on the right, the far end has been properly terminated and the screen trace shows the expected impedance values.

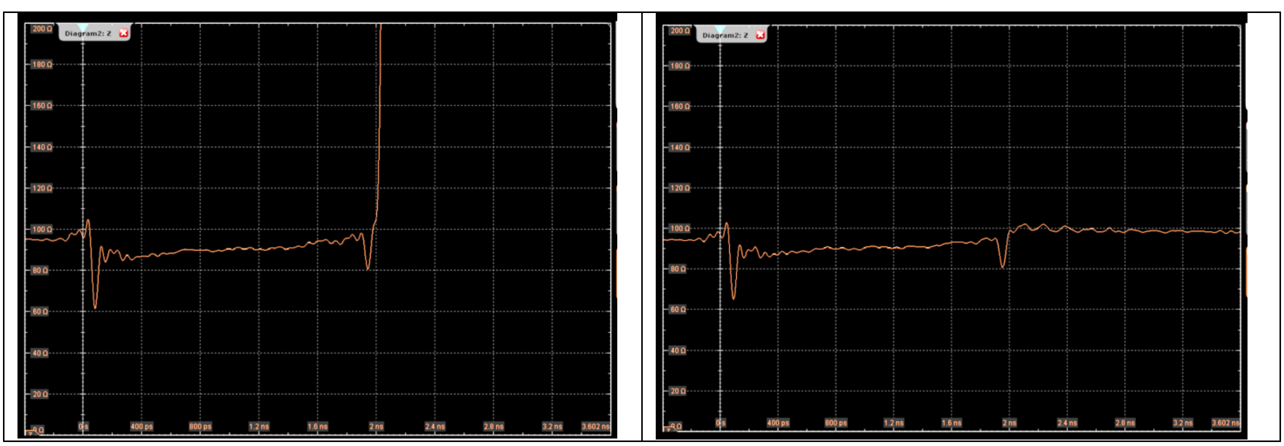
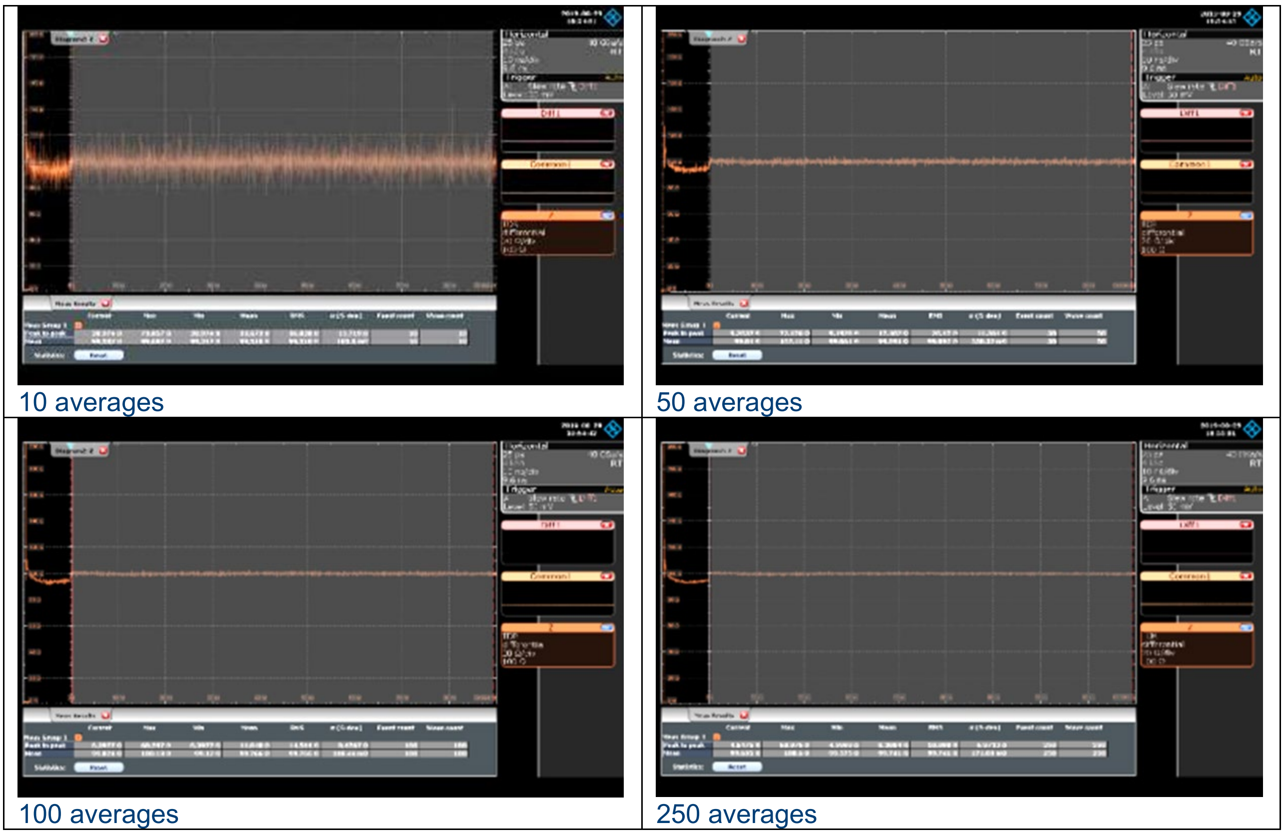


Figure 4: These traces show an open circuit (infinite Z) response on the left and a properly terminated response (85 Ω) on the right. The actual distance can be calculated using the time (~1.9 ps) and the relative permittivity.

It's worth noting the screen annotation in Figure 4: the vertical axis is impedance (ohms) and the horizontal axis is time (picoseconds). This is the default for most oscilloscopes; however, the horizontal axis can be switched to distance based on the relative permittivity value for the transmission channel. Of course, you may not know the relative permittivity for your design. If this is the case, a quick check with an open or terminated structure can help you determine the value.

With regard to averaging, digital averaging in the time domain is equivalent to intermediate-frequency (IF) filtering in the frequency domain. Because TDR signals are periodic, averaging can reduce random noise and thus improve measurement accuracy and repeatability.

One way to check the effect of averaging is to consider the mean value versus the peak-to-peak spread. Figure 5 shows the results of an experiment that progresses from 10 to 250 averages, and the traces illustrate the expected effect: there is an inverse-square relationship between the number of averages and the resulting reduction in noise.



10 averages | 50 averages | 100 averages | 250 averages

Figure 5: In this example, the most striking improvement occurred after increasing from 10 to 50 averages.

Table 2 compares the mean value and the peak-to-peak spread after 10, 50, 100 and 250 averages. Statistics suggest the mean value will converge after about 50 averages, and the data bear this out.

Averages	Mean value	Peak-to-peak (absolute)	Percent error
10	99.5 Ω	20.9 Ω	10.5%
50	99.8 Ω	9.2 Ω	4.6%
100	99.8 Ω	6.4 Ω	3.2%
250	99.6 Ω	4.6 Ω	2.3%

Table 2: Increasing the number of averages will reduce the absolute peak-to-peak value, but the mean value is likely to converge after about 50 averages.

5.2 A suggested process

A simple three-step process will help you achieve informative results. The steps are calibrate, measure and analyze.

Step 1, Calibrate: The first step is to choose the necessary configuration: TDR or TDT; single-ended or differential. As a common example, let's look at differential TDR. The calibration process requires three measurements: *short, open, and match* (with termination; Figure 6). For each, the measurement sequence is to (1) transmit a known reference from the initial launch point, (2) measure the reflection and (3 back-calculate the variance.

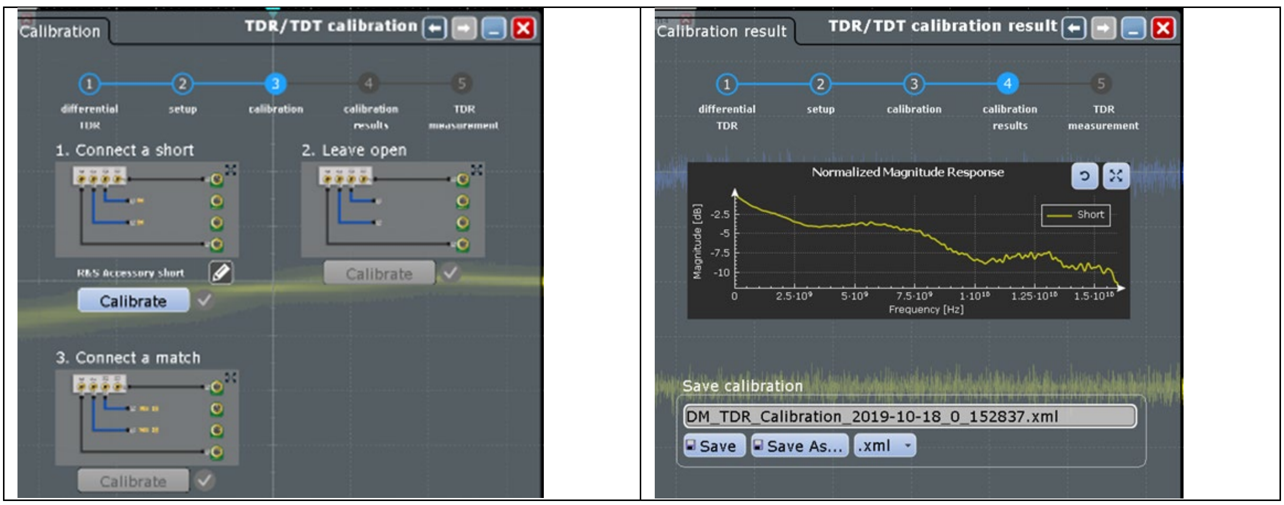


Figure 6: In this example, a software wizard guided the calibration process (left) and saved results such as the frequency-dependent loss curve (right).

When the calibration measurements are complete, the oscilloscope software saves the results—cable loss, launch delay, low-frequency leveling, etc.—for use with the actual TDR measurements. In most cases, the entire process takes about 15 seconds to complete.

Step 2, Measure: In R&S scopes with the pulse-source option, the resident software includes a measurement "control console" that presents the relevant user-selectable attributes (Figure 7, left). The resulting measurement display can be configured to show impedance, reflection coefficient, and more (Figure 7, right).

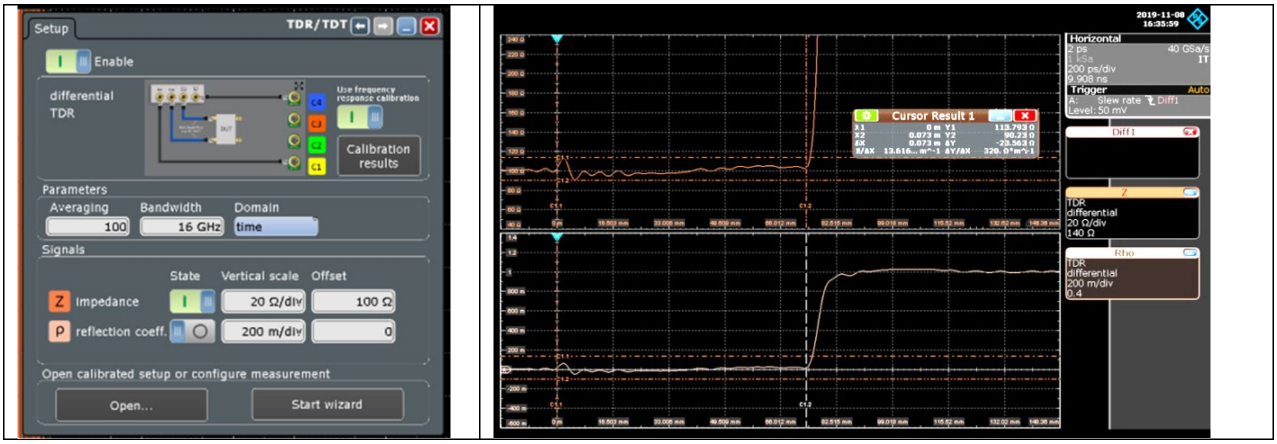


Figure 7: Through words, numbers and diagrams, the control console (left) simplifies TDR differential measurements. The example screen (right) shows impedance (upper trace) and reflection coefficient (lower) versus distance (in millimeters).

Step 3, Analyze: As a real-world example, let's look at a 10 Gbps link with skew-matched traces. In Figure 8, the highlights show two trouble spots on the PCB: an etching problem on the left and a discontinuity on the right. Visually, it appears that each is roughly the same distance from its associated PCB pad.

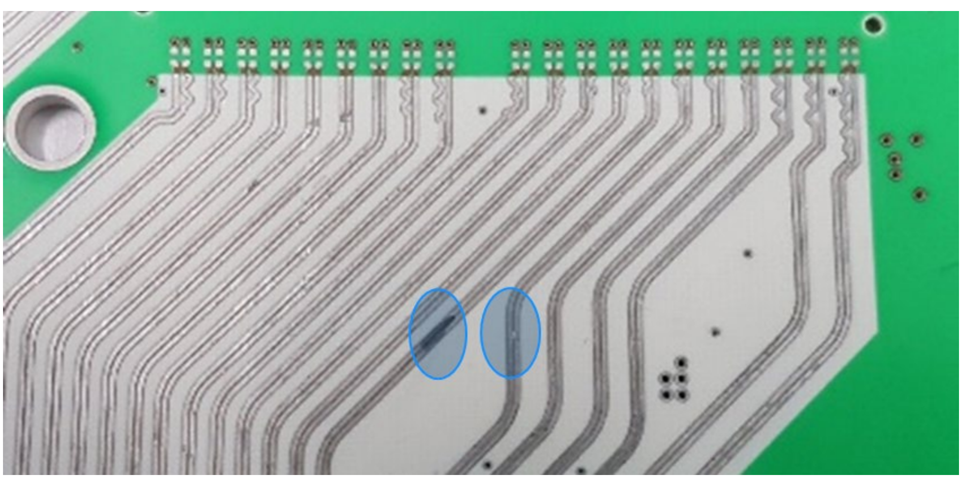


Figure 8: This enlarged photo of a 10 Gbps link shows two trouble spots on the PCB.

Measurements confirm the visual estimate. In Figure 9, the top trace places the etching problem at a distance of 27 mm from the pad (X2 and ΔX in the lower inset); the lower image places the discontinuity at about 27 mm from its pad (first upward step in the blue trace).

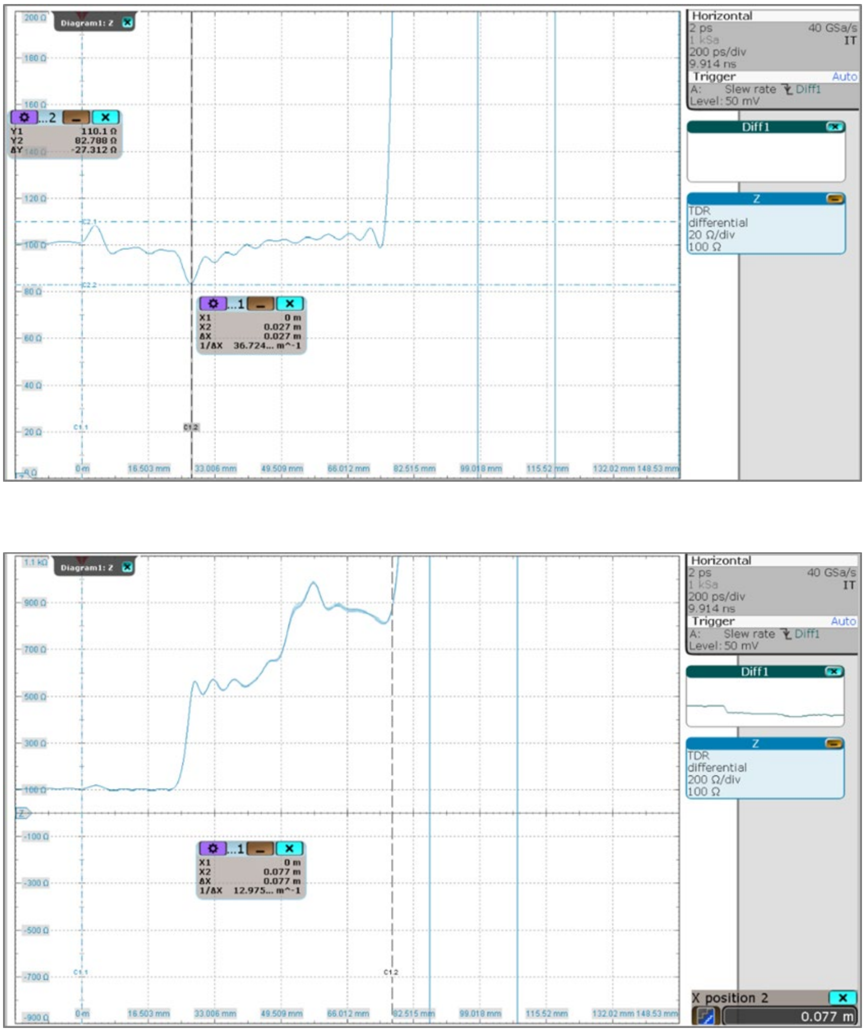


Figure 9: Separate measurements show the location of the etching problem (top) and the trace discontinuity (right) relative to their respective PCB pads.

5.3 Another useful technique

The preceding approaches are the foundation of a timesaving technique: identify a known-good PC assembly and use it to create a set of "golden reference" measurements. From those, you can set up a measurement mask with a known impedance profile. Then, when new boards arrive, measuring all against the golden test mask will quickly identify good and bad articles.

6 Examples from a Debug Workflow

As noted earlier, the eye diagram is an informative way to debug high-speed digital designs. In this example, TDR was used to optimize a USB3 test setup. A sequence of eye diagrams will illustrate the progressive improvement in measured results.

Figure 10a shows the initial measurement, made at the far end of the channel. The large areas of red in the hexagonal mask emphasize the numerous mask hits, and the failure rate was 1.039 percent.

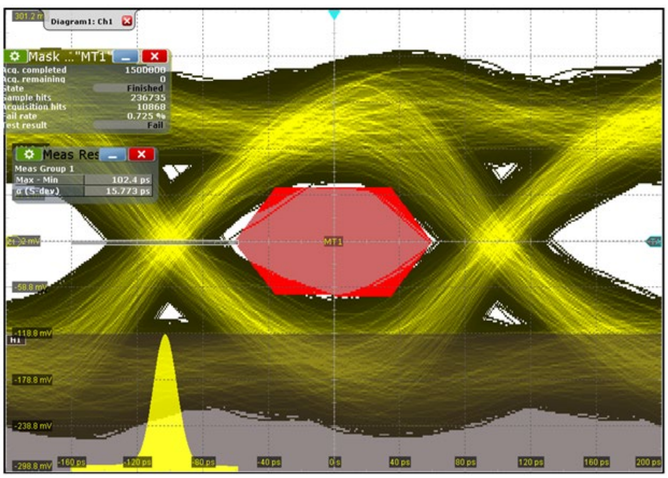


Figure 10a: In the early stages of debugging, the ability to eliminate problems in the test setup is often the first step toward better measurement results.

Figure 10b shows a slight improvement after applying de-embedding of the cables and test fixture used in the measurement setup. Here, the failure rate has decreased to 0.518 percent.

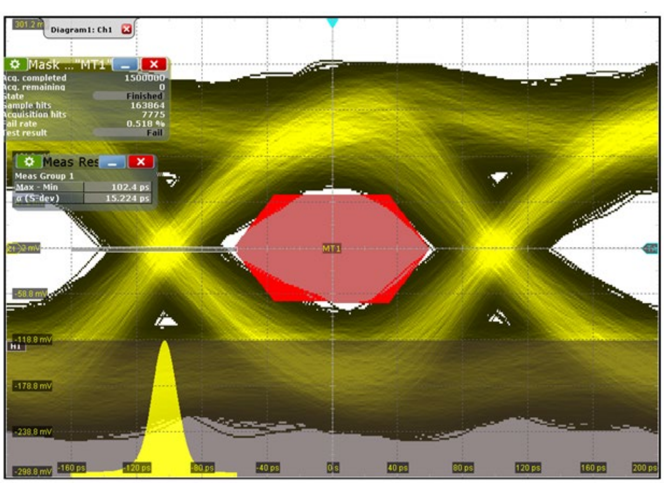


Figure 10b: Fast TDR measurements, with rapid convergence on useful results, provided useful de-embedding data.

Next, TDR revealed the coupling of PDN noise onto the clock line (e.g., a lower impedance value is a sign of capacitive coupling). Addressing this issue provided further improvement in the failure rate, bringing it down to 0.086 percent.

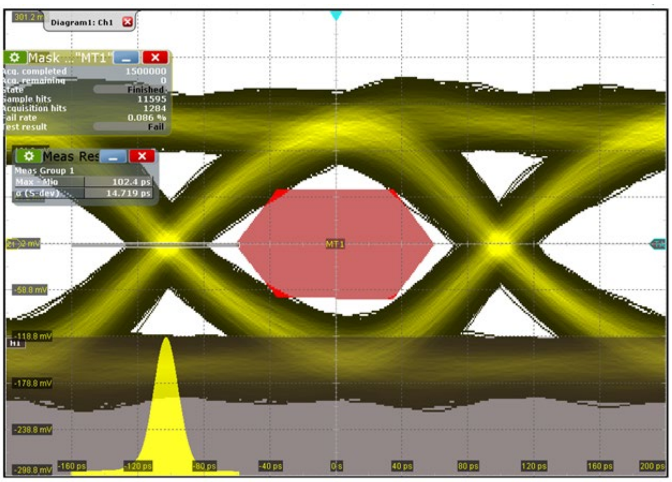


Figure 10c: Detecting PDN noise and reducing its effects provided a significant reduction in mask hits.

Finally, TDR also revealed a variety of layout issues related to lane skew and PCB stubs. Addressing these issues and also optimizing the test setup provided a significant improvement in the eye diagram measurement: as shown in Figure 10d, there are no mask hits and the failure rate is zero percent.

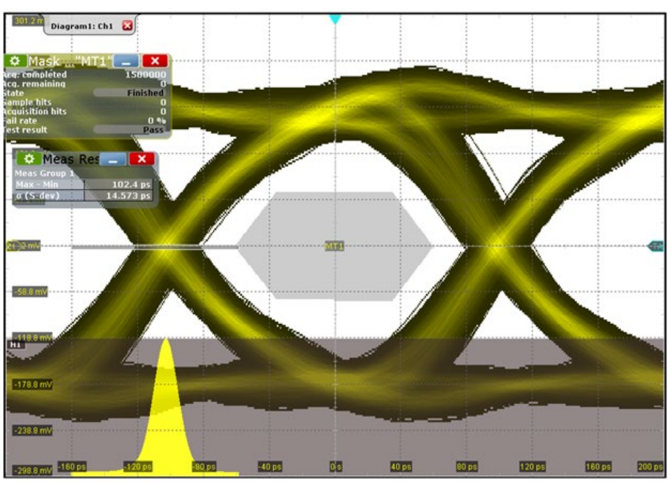


Figure 10d: Thorough debugging of the test setup led to a true measurement of the SUT and, ultimately, greater confidence in the "PASS" test result.

7 Solutions from Rohde & Schwarz

Oscilloscopes and vector network analyzers (VNAs) and are both capable of making valid, informative TDR measurements. In general, choosing a solution has as much to do with the user's comfort zone—time domain versus frequency domain—as it does the relative strengths and weaknesses of each instrument:

- **Oscilloscope:** The ability to work with time, frequency, logic and protocol measurements along with eye diagrams and TDR makes this the preferred choice for digital designers and signal integrity engineers.
- **Vector Network Analyzer:** Lower noise and higher dynamic range means greater measurement accuracy. Also, the ability to perform measurements such as S-parameters makes this the preferred choice for component developers and RF designers.

Table 3 provides a side-by-side comparison of these two widely used instruments.

	Oscilloscope	Vector Network Analyzer
Source	Fast pulse	Discrete continuous wave (CW)
Receiver	Broadband	Narrowband
TDR measurement	Voltage waveform of incident and reflected step	Post-processed via inverse Fourier transform of frequency-domain measurements
Speed	Fast: single pulse, rapid reflections	Slow: multiple discrete CW stimuli plus post-processing to compute TDR
Resolution	Limited to pulse rise time	Depends on bandwidth
Accuracy	Limited dynamic range, good noise performance	High dynamic range, excellent noise performance
Calibration	Basic	Advanced
Applications	Fault location, de-skew, propagation delay, impedance, and probe/cable de-embedding (e.g., for debug)	Fault location, impedance plus S-parameters, and cable/fixture de-embedding (e.g., for characterization)

Table 3: Eight key items differentiate the strengths and weaknesses of oscilloscopes and VNAs when making TDR measurements.

A brief look at specific solutions from Rohde & Schwarz will highlight the benefits of each approach.

7.1 R&S®RTP and R&S®RTO2000 oscilloscopes

These two families of oscilloscopes are the leading choice for general-purpose measurements plus TDR/TDT characterization:

- **R&S®RTO2000:** Offering bandwidths from 600 MHz to 6 GHz, this series excels at time- and frequency-domain testing. With excellent signal fidelity, 1M waveforms/sec, up to 16-bit vertical resolution, and intuitive SmartGrid operation, you can measure quickly and with confidence.

- **R&S®RTP:** The R&S®RTP high-performance oscilloscope combines high-class signal integrity with a fast acquisition rate. Customized frontend ASICs and realtime processing hardware enable highly accurate measurements with unprecedented speed in a compact form factor.

Recently introduced options add TDR capabilities to the R&S®RTP and R&S®RTO2000 oscilloscopes:

- **Option R&S®RTP-B7/RTO-B7:** This plug-in module adds an integrated 16 GHz differential pulse source to the oscilloscope.
- **Option R&S®RTP-K130/RTO-K130:** This software option creates a TDR/TDT analysis system that supports the characterization and debugging of signal paths using differential and single-ended measurements.
- **Option R&S®RTP-K121/RTO-K121:** This software option adds de-embedding capabilities and realtime waveform correction; it also leverages TDR/TDT to characterize and de-embed probe and cable effects (e.g., Proven Probe and Proven Cable).

7.2 R&S®ZNB vector network analyzers

More than 60 years of experience in the field of vector network analysis pays off: the R&S®ZNB family of VNAs sets new benchmarks in speed, dynamic range, precision and ease of operation. The ability to make high-resolution measurements enables detailed analyses of the fine structures within the device under test.

Four ports are needed to perform differential measurements, and four-port models are available with 4.5 to 40 GHz bandwidth. Two options add the necessary capabilities for TDR and time-domain analysis:

- **Option R&S®ZNB-K2:** This software option adds time-domain analysis, including TDR. It transforms S-parameters into the time domain, making it possible to display discontinuities versus time delay or electrical/mechanical length.
- **Option R&S®ZNB-K20:** This software option adds extended time-domain capabilities such as the eye diagram; requires option K2.

Time-domain analysis is based on the inverse Fourier transform of the VNA’s frequency-domain measurements.

8 Conclusion

Every digital design includes transmitters, channels and receivers. When a signal travels through the channel to the receiver, noise and other disturbances can cause signal integrity issues, especially at higher frequencies. Reflection problems are the result of impedance mismatches, and oscilloscope-based TDR measurements are an efficient and effective way to identify, isolate and debug the associated discontinuities.

Understanding what you *need to measure* versus *how your instrument operates* will help you understand the tradeoffs between TDR rise time and resolution. Applying proven best practices and a three-step measurement process—calibrate, measure and analyze—will ensure better results. These techniques are equally applicable to the DUT and the connected test setup.

Within the Rohde & Schwarz lineup, our scopes are engineered to fit your requirements and your budget, from top value to top performance. Across the portfolio, our focus is on delivering oscilloscope innovation that inspires measurement confidence.

Rohde & Schwarz

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| Version 1.00 | 08.2020
Application Note | Using TDR to Debug Signal Integrity Issues
Data without tolerance limits is not binding | Subject to change