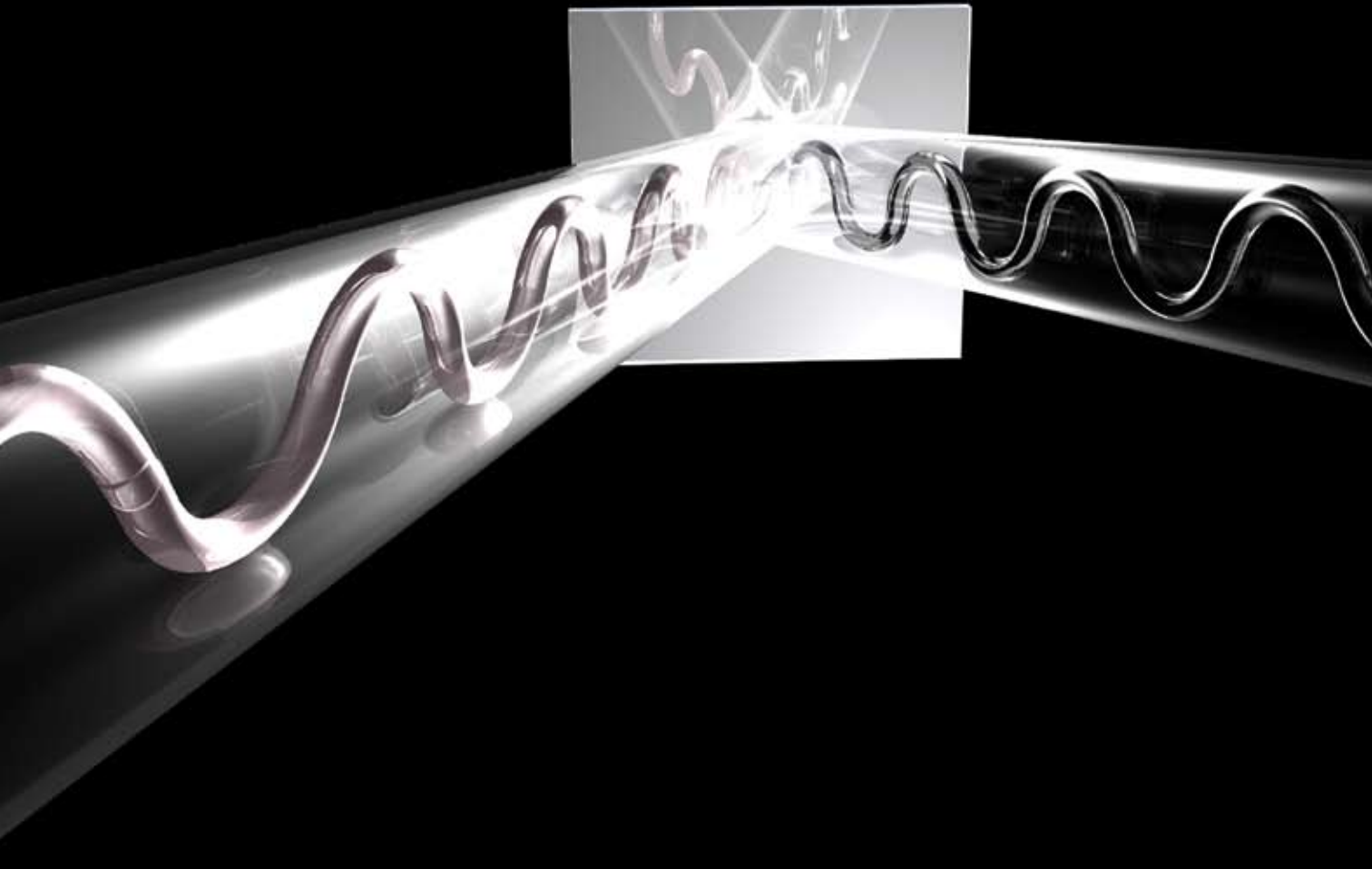


TDR: taking the pulse of signal integrity

BY PAUL RAKO • TECHNICAL EDITOR



TIME-DOMAIN REFLECTOMETRY WILL HELP YOU DESIGN AND TROUBLESHOOT CABLES, CONNECTORS, FAST PCB TRACES, AND HIGH-SPEED PACKAGES. WITH TDR INSTRUMENTS, YOU CAN ENSURE THE SIGNAL INTEGRITY OF FAST DIGITAL SIGNALS AS THEY TRAVEL ACROSS YOUR SYSTEM. BOTH ANALOG AND DIGITAL ENGINEERS NEED TO UNDERSTAND AND USE THESE TECHNIQUES.

TDR (time-domain-reflectometry) measurements can provide a direct representation of the signal integrity of a cable or PCB (printed-circuit-board) trace and can analyze ICs' performance and failure. A TDR setup sends a fast pulse down the cable or PCB trace and displays the returning reflections, which indicate changes in impedance. The impedance changes can be radical, such as an open or a short, or they can be as subtle as the few femtofarads that a PCB via adds. The technique, in the form of OTDR (optical TDR), takes advantage of the equivalence between dielectric constants in electronic systems and the index of refraction in optical systems.

HISTORY OF TDR

Engineers in the late 1930s began taking TDR measurements to measure dielectric constant and moisture content in soils. Engineers today still use the technique to evaluate many geophysical measurements, such as earthquake faults and bridge "scour," a hazardous condition that occurs during times of rapid river flow and especially under icy conditions. Currents transporting sediments away from bridge piers, buried utilities, and similar structures cause this condition (references 1, 2, and 3). After World War II, engineers performed TDR testing with separate pulse generators and oscilloscopes. Digital-logic chips generated pulses with 5V swing—more than enough amplitude to create reflections large enough to detect. A major advance occurred in the late 1960s when Hewlett-Packard (now Agilent) introduced the 1415A plug-in instrument for its 140 mainframe scope. This high-performance instrument was the first to integrate the pulse generator

and sampling head into one unit. In the 1970s, Tektronix announced the 1502 and 1503 TDR-test sets, which found wide use in testing cable integrity. The military was an avid user of TDR equipment, and Tek offered military-specification versions of these products. Nuclear-bomb testing needed TDR to evaluate the miles of cables going "down hole" as well as to evaluate geophysical phenomena in the blasting area.

The technical achievements of Tektronix and HP would continue through the coming decades. HP developed the 20-GHz 54120A mainframe and 54121A test head (Figure 1). These products consisted of the first computerized-TDR-test set and performed TDT (time-domain transmission), which required another input to monitor the transmission of the circuit in addition to the input that sends the pulse and digitizes the reflection. This approach allows characterization of the losses experienced through the circuit; you cannot measure these losses with a purely re-

flective instrument. The scope used the detector from an HP network analyzer in its sampling head.

By the 1980s, Tektronix had introduced the 50-GHz 11801 scope mainframe and the 20-GHz SD-24 differential TDR module (Figure 2). By monitoring the transmission with another module, the 11801 could perform TDR and TDT and could evaluate differential signals, such as those in LVDS (low-voltage-differential-signaling) and SCSI (small-computer-system-interface) circuits. The scope evolved to the 11801C, whereas the module, with a 35-psec-rise-time pulse generator, remained unchanged. This scope was for many years the workhorse of the industry, despite its somewhat arcane user interface, perhaps more suited to operation through GPIB (general-purpose-interface-bus) control than for use by an engineer using the front panel. HP did not rest on its laurels, soon thereafter introducing the 18-GHz 54754A module for the 86100A mainframe. Tektronix followed with the 17-psec 80E04 module for the CSA803, which it derived from the 11801C. Current Tek models include the 70-GHz DSA8200 mainframe and the 50-GHz 80E10 modules. Competitor LeCroy, meanwhile, offers the 100-GHz WaveExpert 100H with a 20-GHz ST-20 TDR module (Figure 3).

Picosecond Pulse Labs makes what is perhaps the ultimate TDR: The 4022 add-on module accepts the pulse from a Tek, an Agilent, or another TDR and speeds it to an astonishing 9-psec rise time. Picosecond also makes pulse generators, but making the 4022 speed a pulse that a scope launches has advan-

tages. “We did it that way so it would work with the existing software in the scopes,” says Clayton Smith, Picosecond’s chief technology officer. Picosecond also makes the TDR modules for various scope OEMs.

In addition to this high-end evolution of TDR, several instruments have evolved to do what TDR started out doing in the 1950s: examine long cables for shorts, opens, and breaks. This function was important to the US Navy because modern warships have miles of cables. Frustrated radio and TV broadcasters also have used TDR to find nicks in the coaxial cable on antenna towers, the results of youngsters’ using the towers for target practice. The Tektronix TS90 TelScout TS90 100 is one such machine; another, the Spirent model E2520 tester, can evaluate twisted-pair cable runs as long as 9800 feet.

PREMISE OF A TECHNIQUE

The theory of TDR involves some mathematics relating to wave propagation and transmission-line impedance (references 4 and 5). The physical phenomena of TDR are far more accessible and intuitive. It seems normal that a wave bounces off a short or an open section of cable. Most of you have directly observed this phenomenon. Slightly more challenging is the notion that a wave propagating into an open circuit adds to the incoming wave, doubling it, whereas a wave propagating into a dead short reflects back the negative potential, bringing the incident wave to 0V. As you would expect, if the trans-

AT A GLANCE

- ▣ TDR plots provide a representation of impedance over distance.
- ▣ Modern high-speed instruments can resolve distances of millimeters.
- ▣ You can use software to convert TDR (time-domain-reflectometry) data to S parameters.
- ▣ You can create SPICE models from TDR data.
- ▣ Sampling scopes can provide wide bandwidths at relatively low cost.

mission line is terminated in its characteristic impedance—50Ω for a 50Ω cable—then no reflection occurs, and the pulse remains unscathed. It is only logical that a terminating resistor with a value a bit higher than matching causes a slight bump in the pulse reflection and that a resistor with a slightly lower value causes a dip in the pulse. The reflection cases for terminations that are inductive or capacitive are also intuitive, because a capacitor is a short at high frequencies, and an inductor is an open at high frequencies (Figure 4).

The classic lumped-element model of a transmission line yields another handy fact: That model is a string of inductors with interstitial capacitors shunting to ground. The ratio between the capacitance and the inductance determines the exact value of the characteristic impedance—50, 75, or 300Ω, for instance. Physics demonstrates that a wire in space has inductance, because, whenever a current flows through that wire, the current

creates a field that must satisfy Gauss’ Law: If the volume within an arbitrary closed mathematical surface holds a net electric charge, Q , then the electric flux, Φ , through its surface is Q/ϵ_0 .

Think of a wire in space as providing the distributed inductance that you see in a lumped-element model of a transmission line. Now, imagine bringing that wire in space close to a ground or reference plane. This proximity provides the lumped capacitance of the model. It seems that bringing the wire closer to the plane should lower the impedance, because the capacitance has increased. Similarly, a wide spot over a ground plane in a PCB trace also increases capacitance and decreases the impedance along the spot. A via acts as a small capacitor, coupling to the plane and lowering the impedance. Conversely, a small jumper wire, such as that in a connector finger, rises off the board and away from the ground plane, thus lowering the distributed capacitance and increasing impedance along that section of the transmission line. With a TDR setup, you can touch your finger or a metal tool to the PCB trace and watch the resultant impedance change—as you add capacitance—directly on the scope screen.

The theory of TDR states that the faster the pulse rise time, the smaller the features the instrument can resolve. The simple cable testers of the past had rise times of nanoseconds. Today’s TDR instruments, however, can examine short cable and PCB-trace runs, connector impedance, and IC-package impedance. As such, they require rise times on the order of 10 to 30 psec. These fast pulses require a fast scope to record the reflections and transmissions. The extreme speed requirements for high-reso-



Figure 1 The HP 54120A mainframe, in concert with the 54121A test head, can take single-ended TDR and TDT measurements.



Figure 2 This Tektronix 11801B with four SD-24 TDR modules can take four pairs of differential TDR measurements. The scope traces show 10Ω of variance on PCB traces that should be 50Ω. The TDR shows how to improve this situation with layout and connector selection.



Figure 3 You can equip LeCroy’s top-of-the-line sampling scope, the WaveExpert 100H, with ST-20 TDR modules.

lution TDR measurements dictate that TDR modules almost always are parts of sampling, or “equivalent-time,” oscilloscopes, with relatively low sample rates. Fast analog amplifiers in the front end of these units support bandwidth that is far higher than that of the best real-time

scopes. The trigger circuit in the scope slightly shifts the unit’s acquisition points after each trigger event (Figure 5). This technique “paints” the fast wave as one set of slew samples appears on the screen for each trigger event. Sampling scopes work only with repetitive waveforms, however. A video, radar, or cell-phone signal that differs on every sweep would display as just a blur. This limitation is not a problem with TDR testing because the pulses are repetitive waveforms that you can continuously launch into the test circuit, giving the sampling scope time to build the waveform.

“Originally, sampling scopes were developed to address the bandwidth needs that couldn’t be addressed with real-time scopes,” says frequent *EDN* contributor and Tektronix Product Marketing Manager Dima Smolyansky, whose article, “TDR and S-parameter measurements: How much performance do you need?” appears on pg 61 of this issue. “Real-time scopes are in the 10- to 20-GHz domain, but sampling scopes can still get you to wider bandwidths—70 GHz and beyond. ... A sampling scope is more accurate in the time domain, but, even better, for the same bandwidth, it is a low-cost solution compared to a real-time scope.”

DESIGN CONCERNS

System-level engineers feel more comfortable in the time domain than in the frequency domain that RF and analog-IC designers favor. System-level engineers see TDR as a more natural and intuitive way to explore the performance of high-speed circuits. In contrast, the frequency-domain equivalent to TDR is scattering, or S, parameters. One elegant body of theory depicts the equivalence of the information in either measurement technique (Reference 6). You can measure S parameters directly in the frequency domain with a VNA (vector-network analyzer), which sweeps a sine wave of fixed amplitude into a circuit while recording the amplitude and phase of the reflections and transmitted signal. Knowing the phase and amplitudes of these S parameters allows you to characterize the circuit for as wide a frequency band as the oscillator in the VNA can sweep. VNAs have a wide dynamic, or SNR (signal-to-noise-ratio), range and

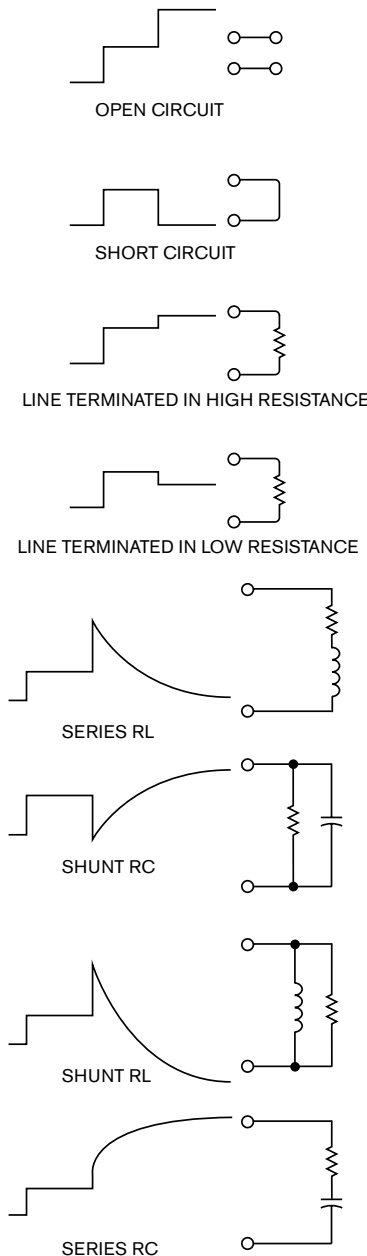


Figure 4 The reflections from various terminations or transmission-line variations reveal the nature of the impedance along the line and at its termination. The transmission line can be a long cable or the bond wire inside an IC.

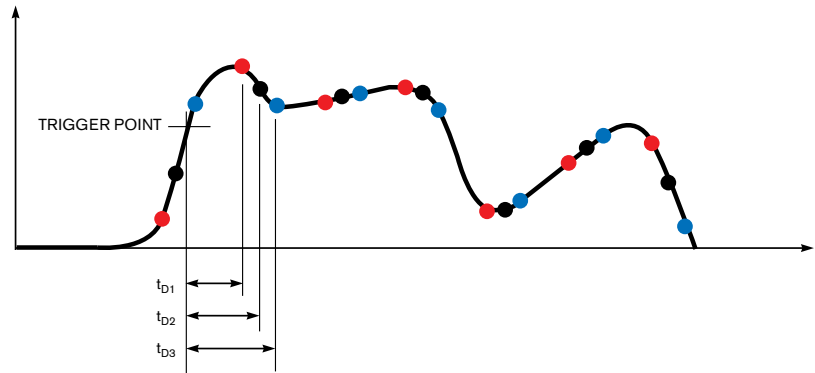


Figure 5 A sampling, or equivalent-time, oscilloscope does not take all the points in a single sweep. It varies the delay from the trigger to the acquisitions to build up a representation of the waveform over many repeated sweeps by adding a small set of points to the waveform each sweep. It first takes the red points; adds to the delay; and then adds the black points, the blue points, and so on. Because the scope is acquiring constantly, it also provides a pretrigger acquisition.

narrow-bandpass filters that sweep in concert with the oscillator; thus, they reject most of the out-of-band noise. In contrast, you must take TDR measurements using a wideband oscilloscope, so it has the higher rms-noise floors that all wideband circuits exhibit.

RF and microwave engineers prefer S parameters over VNAs for good reasons; one reason is their dynamic range, which can approach 130 dB. In addition, RF engineers often need to know the steady-state behavior of the circuit. They assume that the oscillators in their circuit are running and that a fairly narrow frequency band—say, the 1900-MHz cell-phone frequency—is passing through the system. Engineers who worry about signal integrity, on the other hand, must worry about the entire frequency spectrum. They may need to know how their system will react to a string of pulses after a dc voltage has been on the cable or trace. This situation makes it even more preferable to use TDR measurement. Engineers designing PLLs (phase-locked loops) have both problems: They must characterize the operation of the loop once it is running, and they also have the time-domain problem of having to watch the loop lock in after milliseconds or more. This problem might represent millions or billions of cycles of the dominant operating frequency of interest and makes PLL development especially challenging. These issues make the design, simulation, and testing of PLLs daunting tasks (**Reference 7**).



Figure 6 This test fixture has two small wires soldered across the transmission line connecting the two connectors. These wires add capacitance and show up as reduced impedance on a TDR plot (courtesy Picosecond Pulse Labs).

Engineers should heed some warnings despite the mathematical equivalence of S parameters in the frequency domain and TDR in the time domain. The FFTs (fast Fourier transforms) and inverse FFTs that exist between the time and the frequency domains are important calculations, often involving causality and passivity (**Reference 8**). A causality problem occurs when the calculation does not account for transit time and other delays leading to time-domain issues. A similar problem occurs with passivity: The inverse transform into the time domain may impart energy in passive-circuit elements, producing erroneous results. Going from the time domain to the frequency domain also imposes SNR limitations. Because the time-domain measurement suffers from broadband noise, even the best TDR setups produce only 50-dB SNR at high frequencies. This figure may be adequate. Alternatively, you may need to take the

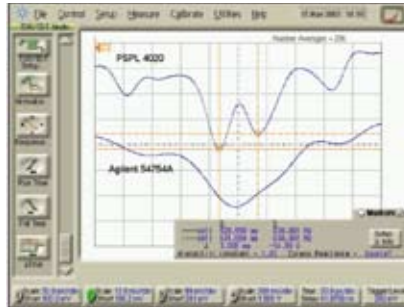


Figure 7 The two small wires in Figure 6 cause these dips in impedance. Using a 9-sec pulse generator causes the top trace, and the scope's internal pulse generator causes the bottom trace (courtesy Picosecond Pulse Labs).

S-parameter data directly in the frequency domain with a VNA. Remember to balance the convenience of being able to take S parameters and TDR measurements on one machine with the need to verify at least one measurement in both domains. Still, some TDR setups perform correlation with a 9-psec-rise-time TDR and a 50-GHz VNA, so you can convert between domains if you properly use the appropriate equipment (Reference 9). Reliable S-parameter data from a TDR setup requires a pulse generator with short rise times and an oscilloscope with wide bandwidth. Similarly, generating TDR data by taking an inverse FFT of S-parameter data requires adequate bandwidth on the VNA to give the detail you wish to see in the time domain.

You can achieve impressive spatial resolution with a good TDR setup (figures 6 and 7). The advent of faster-than-10-psec pulse generators and 50- or 100-GHz-bandwidth scopes allows the use

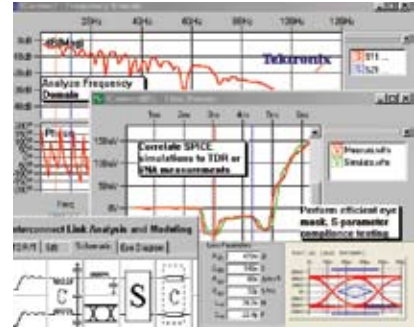


Figure 8 Tektronix offers iConnect software that can convert TDR data to S parameters and can create SPICE models from the data.

of TDR in IC-package development and failure analysis. If the TDR setup can resolve impedance over millimeters, then you can see the effects of bond wires and whether metallization damage is causing an IC to behave unexpectedly. With a fast pulse generator and scope, you can achieve small spatial resolutions (Table 1). In addition, some high-performance scopes incorporate software techniques that further improve the effective resolution by calibrating out reflections from fixtures and cables leading to the circuit or device under test.

Eliminating the effects of the test fixture is only one of the benefits of modern TDR-scope software. The Agilent 86100A mainframe's software allows you to take differential-TDR measurements with two positive pulses. Using pulses of the same polarity on both channels ensures that the same waveform excites both channels. It is difficult to make the rise time and fall time of a pulse exactly opposite, so differential-pulse generation introduces a common-mode error. The Agilent scope

TABLE 1 SPATIAL RESOLUTION OF TDR MEASUREMENTS

Rise time (psec)	Dielectric				
	Air (microns, $\epsilon_R=1$)	Teflon (microns, $\epsilon_R=2.1$)	FR4 (microns, $\epsilon_R=4.6$)	Alumina (microns, $\epsilon_R=9.8$)	Gallium arsenide (microns, $\epsilon_R=12.9$)
5	750	518	350	240	209
10	1500	1035	699	479	418
15	2250	1553	1049	719	626
40	6000	4140	2798	1917	1671

Courtesy Picosecond Pulse Labs



⊕ For more on time-domain reflectometry in *this* issue, turn to pg 61 or visit www.edn.com/ms4245.

⊕ Go to www.edn.com/070903cs for this article's associated references. At this URL, you can also click on Feedback Loop to post a comment on this article.

sends two pulses of the same polarity; its software then inverts and applies superposition to the response, so that the resultant waveform is identical to—but has less error than—that of a differential TDR. “The accuracy goes up because of the much better matching of the electronics,” says Joachim Vobis, a product manager at Agilent.

LeCroy has similarly powerful software in its WaveExpert 100H scope. The standard TDR-analysis package can calibrate out the test fixture and generates two-port differential S parameters from the TDR data. The scope includes a wizard to guide the user through the setup and calibration procedure. You can also set the rise times of the internal pulse generators for 20 psec to lower values that serial-interface standards groups specify.

Inside Tektronix's DSA8200 sampling scope, software provides TDR and TDT as just one part of an entire package that analyzes communication parameters. Tek also offers iConnect software that can run on the DSA8200 mainframe or stand-alone on a PC (Figure 8). It converts TDR data to S parameters, analyzes jitter, and enhances the native TDR resolution of the DSA8200. The software also uses TDR data to deduce a SPICE model of the circuit under analysis, allowing you, for example, to create a SPICE model of a ribbon cable that carries LVDS serial data at high speeds. You can then give this SPICE model to IC designers to show the complex impedance of load or to evaluate the transmission medium in a system-level simulation.

TDR has gone from a simple technique used to check cables to a sophisticated method of performing complete time-domain characterization of fast digital signals. TDT has also evolved, achieving resolutions at which you can use it to examine and characterize the internal structures and circuits inside ICs. In addition, capable software has pushed the art of TDR from looking at bumps on a scope trace to calibrated results in ohms and inches. The software allows the TDR data to generate S-parameter frequency-domain characterizations and even deduce an equivalent SPICE model. The scope traces that generate the models can also verify any simulations with the models and produce valid results.

TDR results have one important ad-

vantage over frequency-domain analysis: A TDR plot shows the location of impedance problems in a circuit. “It helps you isolate problems that may show up with a VNA in the frequency domain, but you will not know where in the circuit the problem is,” says Picosecond Pulse Labs' Smith. “The TDR shows you the exact spot in the signal path where the problem is occurring.” Smith goes on to note some real-world issues with high-speed connectors: “We bought a whole slew of edge-launch SMA [Sub-Miniature Version A] connectors to evaluate with our test setups. We saw a huge difference in the signal integrity through these connectors. In one, it was obvious that the engineers used a VNA and frequency-domain analysis, but the TDR response was horrible.” You would not want to use those connectors for fast digital data streams or any analog signal that had fast edges. With TDR, you get instant, intuitive results that show you where you can improve your circuits. Be sure to have this valuable measurement technique in your arsenal of troubleshooting skills. **EDN**

FOR MORE INFORMATION

Agilent
www.agilent.com

Spirent
www.spirent.com

LeCroy
www.lecroy.com

Tektronix
www.tek.com

Picosecond
Pulse Labs
www.picosecond.com

REFERENCES

For the references to this article, see the Web version at www.edn.com/070903cs.

You can reach
Technical Editor
Paul Rako at
1-408-745-1994
and paul.rako@reedbusiness.com.

