BY DIMA SMOLYANSKY • TEKTRONIX INC

TDR and S-parameter measurements: How much performance do you need?

TIME-DOMAIN TECHNIQUES ARE CHALLENGING ESTABLISHED FREQUENCY-DOMAIN MEASUREMENTS IN THE ANALYSIS OF HIGH-SPEED SERIAL NETWORKS. TO OBTAIN MEANINGFUL RESULTS, THE MEASUREMENT EQUIPMENT MUST HAVE ADEQUATE RISE TIME, BANDWIDTH, AND DYNAMIC RANGE. YOU CAN DERIVE THE INSTRUMENTATION REQUIREMENTS FROM THE NETWORK STANDARDS.

In computers, communications, and consumer electronics, the transition from parallel to high-speed serial-data transmission is creating new design challenges. Increasing data rates push more bits per unit time through the same interconnect link, entering the multigigabit-per-second regime and creating substantially tighter timing budgets. Because of high-frequency interconnect losses, higher data rates also exacerbate ISI (intersymbol interference). Moreover, to achieve still faster data transmission, many standards allow several serial links to operate in parallel, creating multilane configurations, in which crosstalk plays yet another important role.

As a result, you must more closely manage the characterization of interconnect reflections, losses, and crosstalk. You must also differentially perform this characterization, and do it in the frequency, rather than the time domain, using so-called S-parameters (see **sidebar**, “S-parameter backgrounder” at the Web version of this article at www.edn.com/ms4245). S-parameters provide quantitative insight into the causes of bit er-

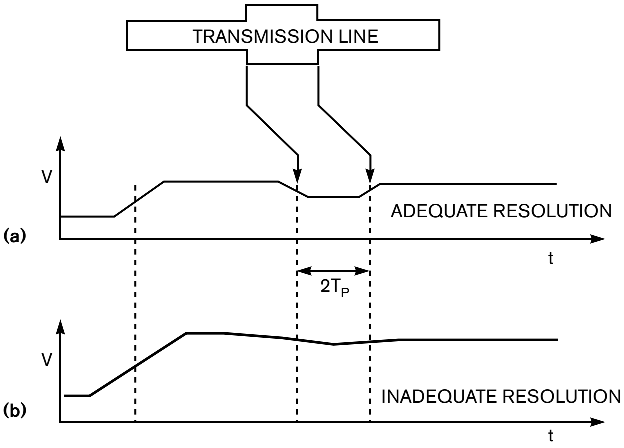


Figure 1 The IPC specification TM-650 summarizes the resolution and TDR rise-time requirements for typical surface microstrips in air (a) and on FR4 PCBs (b).

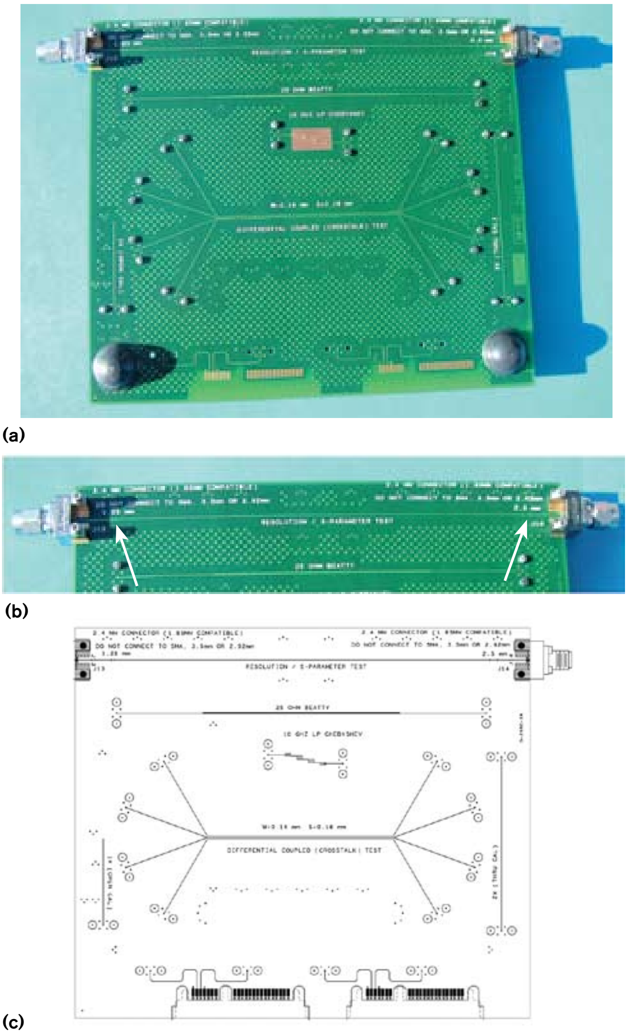
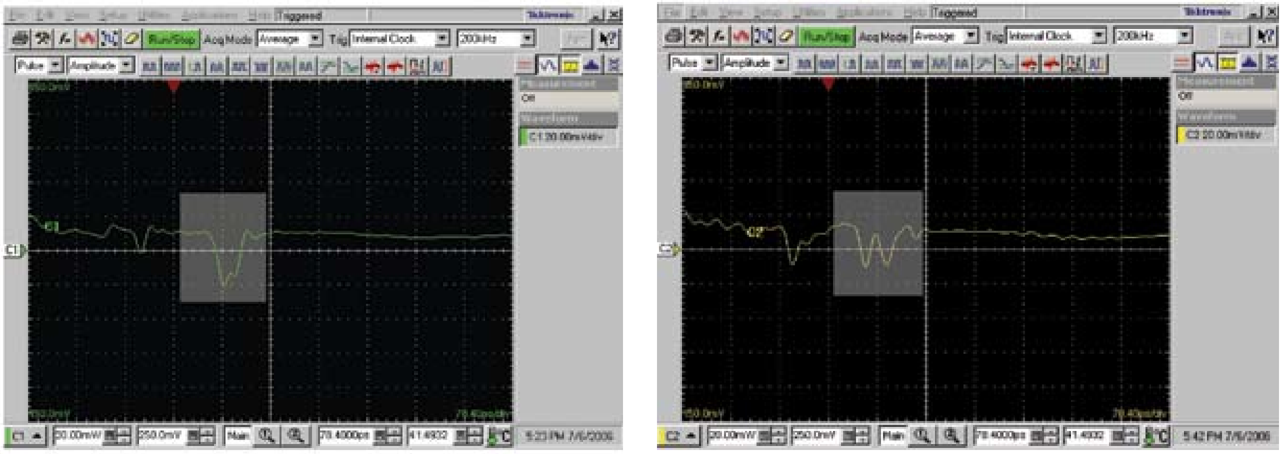


Figure 2 A typical TDR demo board (a and b) includes a resolution structure (c). The arrows highlight discontinuities created by two pairs of vertical bars—the left-hand pair separated by 1.25 mm; the right-hand pair, by 2.5 mm.



(a) (b)

Figure 3 TDR testing of the structure in Figure 2 uses a 15-psec reflected rise time, producing these results for 1.25-mm spacing between discontinuities (a) and 2.5-mm spacing (b).

rors, BER (bit-error-rate) degradation, jitter, ground bounce, and EMI (electromagnetic interference). You can also measure crosstalk by using S-parameters to characterize signal transfer among adjacent transmission-line pairs. Many electrical standards, such as SATA (Serial Advanced Technology Attachment), PCIe (Peripheral Component Interconnect Express), Fibre Channel, and 10GbE (10-Gbps Ethernet), now use S-parameters in their compliance-test procedures. The umbrella term "SDNA" (serial-data-network analysis) describes differential serial-data-compliance testing and differential characterization of serial-data components.

The traditional S-parameter-measurement tools are VNAs (vector-network analyzers). These instruments are powerful, but that power may well be their undoing, because they achieve their accuracy with the aid of extensive calibration procedures. For SDNA applications, these differential calibration procedures can be excruciatingly lengthy and difficult to follow, resulting in long test times and sensitivity to human error. Electronic calibration modules for VNAs are available, but they operate only at frequencies that are relatively low for most SDNA applications. Moreover, the cost of VNAs tends to be higher than that of the instruments that most digital designers have on their workbenches.

TDR (time-domain-reflectometry)-based S-parameter measurement tools have proved to be cost-effective, easy to calibrate and use, and accurate enough for SDNA (see **sidebar** "TDR-based S-parameter measurements" at the Web version of this article at www.edn.com/ms4245). They also provide higher throughput than VNAs. For example, by using TDR and postprocessing software, you can obtain a differential insertion-loss measurement within a minute instead of the 15 minutes or so a VNA can require. Moreover, VNAs can't measure directly to dc, and on long devices under test, such as cables, they can take a long time to accurately measure low frequencies. Most VNAs also compute systems' differential response from single-ended measurements because, until recently, more accurate direct-differential measurement was too difficult and expensive.

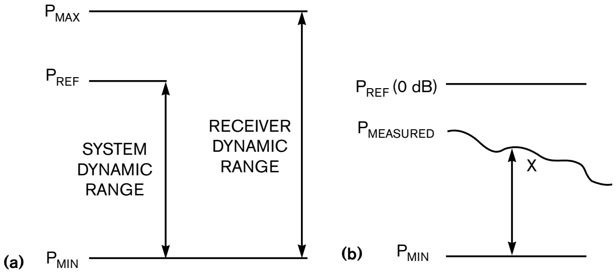


Figure 4 You typically define receiver dynamic range as the difference between the maximum and minimum measurable power—P_{MAX} and P_{MIN} (a)—and system dynamic range as the difference between the source's nominal power (P_{REF}) and the minimum measurable power (P_{MIN}) (b).

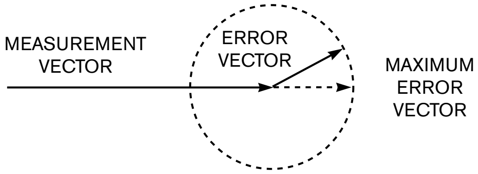


Figure 5 The diameter of the error circle represents the total peak-to-peak ripple.

TDR-based systems can directly measure dc and low frequencies. For example, by simultaneously firing multiple sources, Tektronix's (www.textronix.com) DSA8200 and IConnect S-parameter-measurement system can directly obtain true-differential TDR and S-parameters. IConnect also allows the acquisition of records as long as 1 million points, a requirement for S-parameter measurements on long devices, such as cables. Finally, the typical cost of a TDR-based system can be as little as half that of a VNA system that makes comparable SDNA measurements, and the TDR system provides higher time-domain resolution than does a VNA with comparable bandwidth. Several misunderstandings exist about TDR-based S-parameter measurements (see **sidebar** "Misconceptions about TDR-based S-parameter measurements" at the Web version of this article at www.edn.com/ms4245). Overall, TDR-based S-parameter-measurement systems provide an easy-to-use, high-throughput approach to performing S-parameter-compliance tests in accordance with many digital standards as well as tests used in characterizing digital devices that operate at gigabit-per-second speeds.

TDR SPATIAL-RESOLUTION REQUIREMENTS

Start with the most basic requirement for TDR: providing sufficient resolution for locating faults in a device package or on a PCB (printed-circuit board). The IPC (Institute for Printed Circuits) document TM-650 2.5.5.7a defines TDR resolution as "the resolution limit … wherein two discontinuities or changes on the transmission line … begin to merge together … According to this definition, the resolution limit is half the … 10 to 90% rise time or 90 to 10% fall time (depending on whether the TDR response is calibrated with a short or open circuit)" (**Reference 1**).

Using **Table 1**, which you can find at the Web version of this article at www.edn.com/ms4245, IPC TM-650 summarizes the resolution and TDR rise-time requirements for typical surface microstrips in air and on an FR4 PCB (**Figure 1**). (In FR4, propagation velocity of electromagnetic waves is approximately 2×10^8m/sec—approximately two-thirds that in free space.) A board's inner layer, or stripline, is more representative of a typical board run. In addition, it is useful to provide resolution data for propagation in air. For a stripline, assume a propagation of 0.446 times the propagation velocity of light in free space. **Table 2**, also at www.edn.com/ms4245, summarizes the resulting resolution data. Now look at a practical situation. On a typical TDR-demonstration board (**Figure 2**), the resolution structures are reasonably close to the board's 2.4-mm S connector (see **sidebar** "Precision microwave-connector care and compatibility," also at www.edn.com/ms4245).

Figure 3 presents the results of TDR testing with a 15-psec reflected-rise-time TDR module, with the signal launched from the left to access the 1.25-mm structure and the signal launched from the right to access the 2.5-mm structure. Clearly, on the structure with 2.5-mm separation, the two discontinuities have perfect resolution, whereas on the structure with 1.25-mm separation, you start to lose resolution. (The trace on the demo board is a microstrip, and, according to **Table 1**, there is a different limit on the resolution for microstrips.) The interesting question is, however: What happens for spacing shorter than 1.25 mm between discontinuities? The discontinuities do not disappear; they simply become one discontinuity. Clearly, then, when a failure analyst attempts to locate a single discontinuity, even a submillimeter discontinuity is observable with the TDR module. The following is an important conclusion: With 15-psec reflected rise time, an advanced module can achieve submillimeter resolution.

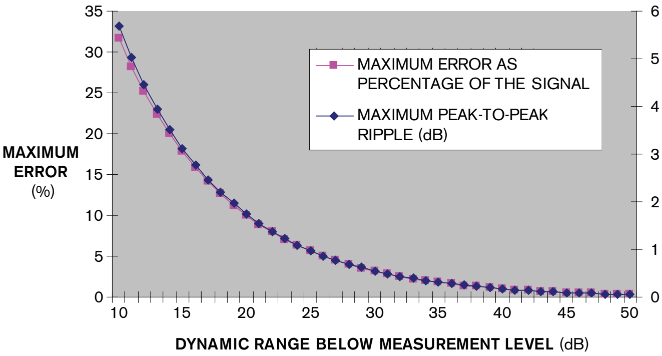
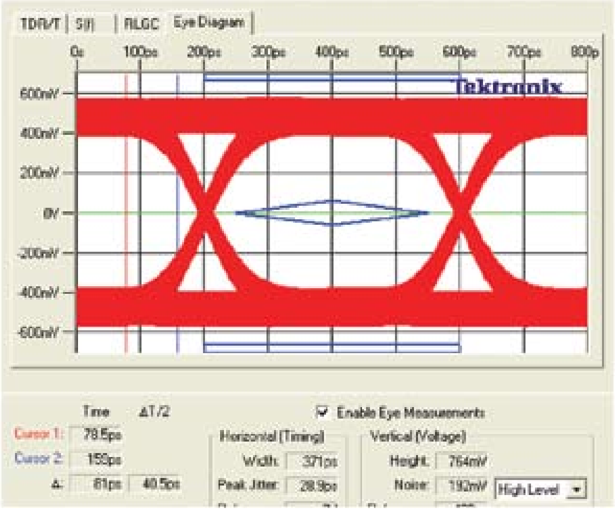


Figure 7 Increasing the dynamic-range requirement decreases the maximum allowable ripple and error.



Time ΔT/2

☑ Enable Eye Measurements

Cursor 1: 78.5ps

Cursor 2: 159ps

Δ: 81ps 40.5ps

Horizontal (Timing)

Width: 371ps

Peak Jitter: 28.9ps

Vertical (Voltage)

Height: 764mV

Noise: 192mV

Figure 6 In this 2.5-Gbps signal, crosstalk causes eye closure that is 10% of the amplitude.

RISE-TIME REQUIREMENTS

When using a TDR-based S-parameter measurement system for characterization or for a compliance test that a specific standard defines, it is important to know what the rise time must be to permit accurate measurements or testing. When specifying the rise time, standards focus primarily on the maximum, or slowest, rise time and look at the minimum rise time only as an informative parameter. SATA test procedures, for example, state the required minimum rise time, but then a footnote clarifies: "Failures at minimum rate have not been shown to affect interoperability and will not be included in determining pass/fail for interoperability testing" (**Reference 2**). So, for most standards, the question for a designer remains: What is the TDR rise time I need to test in accordance with the standard for compliance with a given specification, at a given data rate, with a given S-parameter bandwidth?

A recent study of standards revealed a clear trend in which rise times for first-generation standards, such as InfiniBand SDR (single data rate) and PCIe (Peripheral Component Interconnect Express), constituted a substantially smaller portion of the bit duration, or unit interval, than those of the second-generation standards, such as InfiniBand DDR (double data rate), PCIe 2.0, and 4-Gbps Fibre Channel, or third-generation standards, such as 8-Gbps Fibre Channel and 10GbE (gigabit Ethernet). You can draw an approximate dividing line between the generations of standards at 3.125 Gbps for the first- to second-generation transition and 6.5 Gbps for the second- to third-generation transition. The rise time constituted approximately 15% of the bit duration for the first-generation standards, 20% for the second generation, and 25% for the third generation. All rise times are 20 to 80% of the transition time (**Table 3** at www.edn.com/ms4245).

A designer who uses a TDR rise time that is 50% faster than the rise time of the devices in the controlling standard can achieve complete characterization of the channel with a more-than-adequate guardband. Note that TDR rise time is the time it takes a signal to traverse 10 to 90% of the transition range, which provides an additional guardband compared with the standards' 20 to 80% rise-time specification. This assumption ensures that the rise time is sufficiently fast for characterization. If you need to slow down the rise time, you can either mathematically filter the oscilloscope or use sufficiently lossy cables or filters. Using this 50% guardband assumption specifies how much TDR rise time several standards require.

DYNAMIC RANGE

Typically, receiver dynamic range is the difference between maximum and minimum measurable power—P_{MAX} and P_{MIN} (**Figure 4a**). System dynamic range is the difference between the nominal power of the source (P_{REF}) and the minimum measurable power (P_{MIN}, **Figure 4b**). In TDR-based S-parameter measurements, P_{MAX} relates to a sampling module's maximum operating specification and is less relevant when you focus on passive-component, or interconnect, measurements. As a consequence, system dynamic range matters for serial-data-interconnect characterization.

You may wonder how the definition of dynamic range relates to serial-data dynamic-range requirements. Dynamic range is, in essence, the difference between 0 dB and the noise

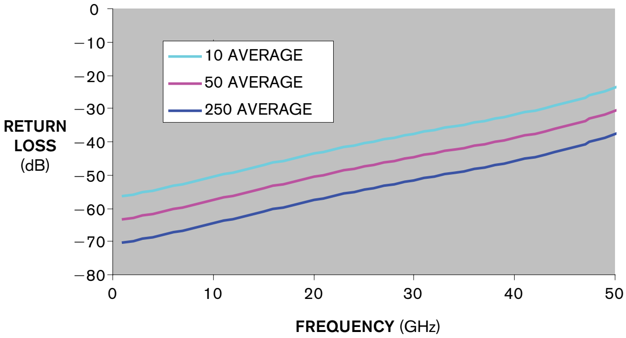


Figure 8 The dynamic range of a high-end TDR module depends slightly on what you are measuring, decreases with increasing frequency, and increases with the number of averaged signals.

floor. The accuracy of the measurement at a given frequency depends on the difference between a measurement level ($P_{MEASURED}$) and the noise floor (P_{MIN}). If your device under test has a measured noise floor of X dB below the measurement-reference level, you can show that the accuracy, or error, in percentage points relates to X dB below the reference value by the following **equation**:

$$\text{ACCURACY} = 10^{\left(\frac{-X(\text{dB})}{20}\right)}\%.$$

Note that, in the frequency domain, because the signal and noise add vectorially, the **equation** shows worst-case error when the noise vector is in phase or 180° out of phase with the signal vector. Additionally, you can show that the total peak-to-peak ripple, the error-circle diameter in **Figure 5**, on that signal is Y dB using the following **equation**: Y dB=20[log(100%+accuracy%)−log(100%−accuracy%)].

This **equation** includes both the positive and the negative ripple on the waveform. You can now show accuracy that you can achieve depending on how far the dynamic range is below the measurement level (see **Table** "Accuracy versus dynamic range below measurement level" at the Web version of this article at www.edn.com/ms4245). For a typical characterization in any of the serial-data standards, you would want to measure a voltage no smaller than approximately 10% of the full-signal amplitude. Such a voltage glitch can result from reflections or from crosstalk from an adjacent differential-line pair. A voltage glitch of this type still provides an 80% eye opening (**Figure 6**).

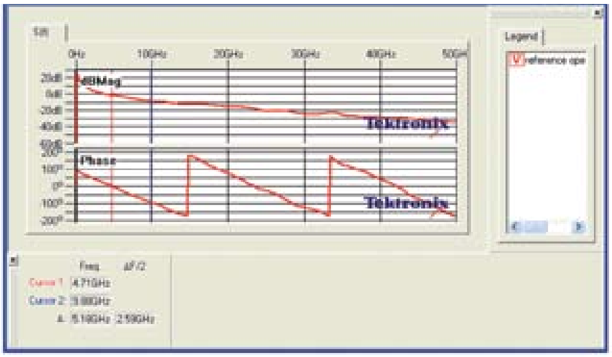


Figure 9 The TDR module is phase-linear, but its incident power declines with increasing frequency.

It is adequate to measure this voltage glitch with 10% accuracy, which translates into accuracy that is 1% of the full-signal amplitude). The minimum measured voltage size and accuracy requirements for 10%±1% at 0.5, 1V, and 2V signals are 50±5, 100±10, and 200±20 mV, respectively. Using the curves of **Figure 7**, you can determine that a signal that is 10% of the total amplitude is −20 dB. To measure this signal with no more than 10% error, the noise floor must be another 20 dB below the measurement level, making the total dynamic-range requirement 40 dB.

FREQUENCY REQUIREMENTS

Later generation standards place less stringent requirements on characterization of digital components. In the first- and second-generation standards, designers talked about characterization to the clock's fifth harmonic, even though the standards required much less stringent compliance testing. In third-generation standards, designers talk about characterizing to the third harmonic. Overall, performing characterization to the fifth harmonic ensures adequate characterization bandwidth and provides designers with sufficient confidence. Using the fifth harmonic as a guideline, **Table 4** at www.edn.com/ms4245 provides the frequency requirements.

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+ For more on TDR, see this issue's cover story by Paul Rako on pg 48 or visit www.edn.com/070903cs.

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Figures 8 and **9** present the dynamic range that TDR test equipment requires for SDNA applications. Notably, dynamic range degrades with frequency. The degradations result primarily from the steplike nature of the TDR-incident waveforms, which cause the incident power to roll off as 1/f. **Table 4** at www.edn.com/ms4245 shows how several standards relate to the dynamic-range and bandwidth requirements.

Based on expert user knowledge, this article identifies accuracy requirements for SDNA debugging, compliance, validation, and characterization and defines the requirements for SDNA applications. Those requirements are TDR rise time to resolve the smallest relevant discontinuity, TDR rise time for component characterization in accordance with various standards, and dynamic-range and bandwidth requirements for such characterization.**EDN**

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AUTHOR'S BIOGRAPHY

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S-PARAMETER BACKGROUNDER

S-parameters are defined in terms of incident and reflected waves at each port. Each S_{IJ} parameter is the ratio of the reflected or transmitted wave at Port J to the incident wave at Port I (Figure A). The S_{IJ} parameter is the ratio of the reflected or transmitted wave at Port J to the incident wave at Port I. The generalized term for reflection or transmission is "scattering." If you assume that the power transmitted is $½|V_I^+|^2$, then you can define the voltages at each port as $V=V^++V^-$ and the currents as $I=I^++I^-$. For a reciprocal junction, such as an interconnect, the scattering matrix is symmetrical; that is, $S_{21}=S_{12}$.

$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix}.$$

For a four-port definition, the picture is more complicated, even though a four-port configuration is a direct extension of a two-port definition (Figure B).

$$\begin{bmatrix} V_1^- \\ V_2^- \\ V_3^- \\ V_4^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \\ V_3^+ \\ V_4^+ \end{bmatrix}.$$

The differential- and common-mode measurements are really of interest, however. You perform differential measurements between the lines, whereas you perform common-mode measurements from the lines, tied together, to ground. In practical terms, the type of stimulus and response defines the type of S-parameters you are regarding. Differential stimulus and differential response define the differential S-parameter quadrant. Common-mode stimulus and response define the common-mode quadrant. Differential stimulus and common-mode response define the differential-to-common-mode-conversion mixed-mode quadrant. And common-mode stimulus and differential response define the common-to-differential-mode-conversion mixed-mode quadrant (Figure C).

Figure A The S_{IJ} parameter is the ratio of the reflected or transmitted wave at Port J to the incident wave at Port I.

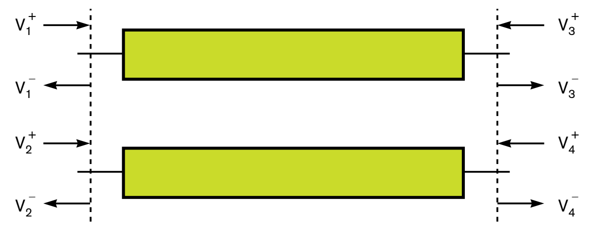

Figure B A four-port definition is more complicated, even though it is a direct extension of a two-port definition.

The resulting S-parameter matrix looks as follows:

$$\begin{bmatrix} V_{D1}^- \\ V_{D2}^- \\ V_{C1}^- \\ V_{C2}^- \end{bmatrix} = \begin{bmatrix} S_{DD11} & S_{DD12} & S_{DC11} & S_{DC12} \\ S_{DD21} & S_{DD22} & S_{DC21} & S_{DC22} \\ S_{CD11} & S_{CD12} & S_{C11} & S_{CC12} \\ S_{CD21} & S_{CD22} & S_{CC21} & S_{CC22} \end{bmatrix} \begin{bmatrix} V_{D1}^+ \\ V_{D2}^+ \\ V_{C1}^+ \\ V_{C2}^+ \end{bmatrix}.$$

S-parameters are relevant in different degrees to digital design. The differential S-parameter quadrant relates to direct degradation of bandwidth, bit-error rate, and jitter. Common mode explains skew and ground-bounce problems. Mixed mode illustrates EMI (electromagnetic interference) for differential-to-common mode and EMS (electromagnetic susceptibility) for common-to-differential mode. However, a time-domain view of the same data produces more intuitive results when you are looking for sources of EMI and EMS. Crosstalk, on the other hand, is a form of insertion loss, except that it is insertion loss between lines that have no direct connection from the input to the output.

		STIMULUS	
		DIFFERENTIAL	COMMON
RESPONSE	DIFFERENTIAL	S_{DD}	S_{DC}
	COMMON	S_{CD}	S_{CC}

Figure C Differential stimulus and differential response define the differential S-parameter quadrant. Common-mode stimulus and response define the common-mode quadrant. Differential stimulus and common-mode response define the differential-to-common-mode-conversion mixed-mode quadrant. And common-mode stimulus and differential response define the common-to-differential-mode-conversion mixed-mode quadrant.

TABLE 1 RESOLUTION OF TDR SYSTEMS PER IPC TM-650

TDR-system rise time	Resolution
10 psec	5 psec/1 mm (0.04 in.)
20 psec	10 psec/2 mm (0.08 in.)
30 psec	15 psec/3 mm (0.12 in.)
100 psec	50 psec/10 mm (0.39 in.)
200 psec	100 psec/20 mm (0.79 in.)
500 psec	250 psec/50 mm (1.97 in.)

TABLE 2 RESOLUTION DATA

Rise time (psec)	Resolution in air (mm)	Resolution in FR4, buried run (mm)
10	1.5	0.67
15	2.25	1
20	3	1.34
28	4.2	1.87
40	6	2.68
150	22.5	10.04

TABLE 3 VARIOUS STANDARDS' REFLECTED-TDR RISE-TIME REQUIREMENTS

Standards		Standards characteristics				10 to 90% reflected-TDR-rise-time needs/20 to 80% reflected-rise-time needs (psec)
		Data rate (Gbps)	Bit width (psec)	Specified 10 to 80% rise time (psec)	Estimated 20 to 80% rise time (psec)	
First-generation standards (rise time is 15% of bit width)	InfiniBand	2.5	400	100	60	40/30
	PCI Express	2.5	400	50	60	40/30
	SATA II	3	333	67	50	34/25
	XAUI	3.125	320	60	48	32/24
Second-generation standards (rise time is 20% of bit width)	4-Gbps Fibre Channel	4.25	235	60	47	32/24
	Sata III	6	167	NA	33	22/17
	Double-speed XAUI	6.25	160	NA	32	21/16
Third-generation standards (rise time is 25% of bit width)	8-Gbps Fibre Channel	8.5	118	NA	29	20/15
	100G Base-R	10.31	97	24	24	16/12
	10G Base-R FEC	11.1	90	24	23	15/11

TABLE 4 SUMMARY OF BANDWIDTH REQUIREMENTS FOR CHARACTERIZATION OF SERIAL-DATA STANDARDS

Characterization of standards		Data rate (Gbps)	Required bandwidth (GHz)	Typical dynamic range at required bandwidth (dB)	Tektronix module
First-generation standards	InfiniBand, PCI Express	2.5	6.25	–64	80E04
	SATA II	3	7.5	–62	80E04
	XAUI	3.125	7.813	–61	80E04
Second-generation standards	4-Gbps Fibre Channel	4.25	10.63	–60	80E04
	SATA III	6	15	–63	80E08
	Double-speed XAUI	6.25	15.63	–63	80E08
Third-generation standards	8-Gbps Fibre Channel	8.5	21.25	–58	80E08
	10G Base-R	10.31	25.78	–54	80E10
	10G Base-R FEC	11.1	27.75	–53	80E10

MISCONCEPTIONS ABOUT TDR-BASED S-PARAMETER MEASUREMENTS

Many misconceptions exist about TDR (time-domain-reflectometry)-based S-parameters. One of these and the easiest to refute is that the sampling rate of the TDR limits bandwidth. In fact, the bandwidth of the TDR-based S-parameters does not relate to the sampling rate. Instead, it depends on the TDR rise time. With the Tektronix (www.tektronix.com) DSA8200 mainframe, 80E10 TDR module, and IConnect software, you can achieve 50-GHz bandwidth due to 12-psec incident TDR rise time (Figure 9).

A second misconception is that TDR-based S-parameters do not provide insertion loss. In fact, TDR gives insertion loss, and differential TDR gives differential insertion loss. Yet another misconception is that the noise floor of TDR is inherently higher because of lack of IF filtering. However, digital averaging in the time domain achieves the same effect as IF filtering in the frequency domain. Nothing inherently limits the TDR-noise floor. Adding advanced calibration to TDR would bring its noise floor in line with that of a VNA (vector-network analyzer), although you would also lose the TDR's ease of use. Because of measurement-accuracy requirements, truncated calibration procedures are better for TDNA (time-domain-network-analyzer) applications. These procedures include a reference, such as an open, a short, or a through, and optional 50Ω load-calibration measurements.

Many people mistakenly believe that the TDR power roll-off at higher frequencies results in substantially lower dynamic range at those frequencies–an effect that does not exist in VNAs. This idea is partially true: The power in a TDR system does roll off with frequency. However, it is not true that the VNA power is flat. In fact, it substantially varies with frequency. The calibration procedures, which are powerful, lengthy, and not user-friendly, make the calibrated power in a VNA flat. You can achieve the same results in TDR-based parameters with similar calibration procedures. But, then again, you probably would not trade off TDR's ease of use for additional dynamic range for TDNA applications.

Another misconception is that TDR-based S-parameters' dynamic range is limited to 40 dB. You in fact can easily achieve 70 dB when using Tektronix's DSA8200, 80E10, and IConnect with 256 averages on the mainframe (Figure A). Additional averaging helps further improve this performance.

Two final misconceptions exist. The first is that TDR calibration is a complex, multistep process. Although it is desirable to perform vertical-dc compensation on TDR modules, these compensation procedures are much simpler than VNA-calibration procedures. Overall, TDR calibration and compensation are substantially simpler than those of a VNA.

The other is that you can achieve limited bandwidth when testing longer devices with TDR because of the long record-time-window requirements and limited record lengths, or number of points, in a typical TDR oscilloscope. Although these statements used to be true, users of the latest generation equipment can acquire records of as many as 1 million points. You can now measure S-parameters for cable assemblies as long as 100m. Now, the TDR-based system is more accurate than a VNA, because it can measure the long cables to dc, rather than to the 300 kHz or 40 MHz that most VNAs can achieve.

PRECISION MICROWAVE-CONNECTOR CARE AND COMPATIBILITY

TDR (time-domain-reflectometry) modules come with precision microwave connectors. Table A summarizes the connector type of the front of the module and the other connectors to which you can mate your module. Note that when you mate two connectors, the bandwidth of the connection is limited to the lower bandwidth of the two.

Mating incompatible connector types causes damage to the connector. TDR modules come with a female version of the connector. Using an appropriately sized male-to-female adapter as a connector saver is an easy way to avoid expensive damage to the module, especially in environments in which many designers use the same TDR instrument. When mating two microwave connectors, make sure that they mate without any force. Rotate only the connector nut–not the device to which the connector attaches or the connector body. Use a torque wrench to make final connection. Regularly clean connectors with isopropyl alcohol. Use lint-free swabs for cleaning. Always wear a static strap when cleaning or handling the connectors. You can visually check connector quality. However, connector gauges are precision instruments, so carefully determine connector quality and look for possible deterioration of the precision connector.

SMA connectors have a fundamentally different design from that of precision connectors. SMA has a dielectric-based design, whereas other connectors have an air-interface design. An air-interface design provides a more repeatable connection and better electrical performance. Even though SMA connectors are common and less expensive, their dimensions and performance are less precisely maintained than those of the other precision microwave connectors. Continuous mating of SMAs with precision microwave connectors can increase wear and degrade performance of the precision connectors.

TABLE A CONNECTOR TYPES AND MATES

Connector type	Maximum connector bandwidth (GHz)	Mates with
1.85 mm (V)[1]	67	2.4 mm
2.4 mm (S)	50	1.8 mm
2.92 mm (K)	40	3.5 mm, SMA[2]
3.5 mm	26.5 or 34	2.92 mm, SMA
SMA	18 or 26.5	3.5 mm, 2.92 mm

Notes:

[1] The 80E10 comes with an S-to-K connector adapter to enable compensation only. The V connector mates directly with the S connector, and the K connector mates directly with a 3.5-mm or an SMA connector. Using this adapter to perform measurements results in degradation of the module's performance.

[2] SMA connectors are common and less expensive. However, their dimensions and performance are less precisely maintained than those of the other precision microwave connectors. Continuous mating of SMAs with precision microwave connectors can increase wear and degrade performance of the precision connectors.

TDR-BASED S-PARAMETER MEASUREMENTS

The US National Institute of Standards and Technology and various research institutions in the United States and abroad have extensively studied TDR (time-domain-reflectometry)-based S-parameter-measurement techniques (references A and B). Conceptually, the similarity between VNA (vector-network-analyzer)-based and TDR-based S-parameters is obvious (Figure A). The main conceptual difference is in the use of a wideband, steplike source for TDR versus a narrowband, sine-wave generator for VNA. Additionally, TDR is a transient measurement, in which all transitions are observable, whereas VNA is a steady-state measurement, in which all transitions are lumped together and you perform the measurement at a single frequency with narrowband filtering to minimize the effects of noise.

VNAs, designed with microwave design in mind, target such applications as microwave filters and mixers. The need for high dynamic range resulted in the development of some advanced calibration procedures, such as SOLT (short-open-load-through) or TRL (through-reflect-line) techniques, and the overall design of the instrument targets high dynamic range rather than ease of use. The frequency domain has become the domain of choice for microwave design, and thus microwave designers more easily understand frequency-

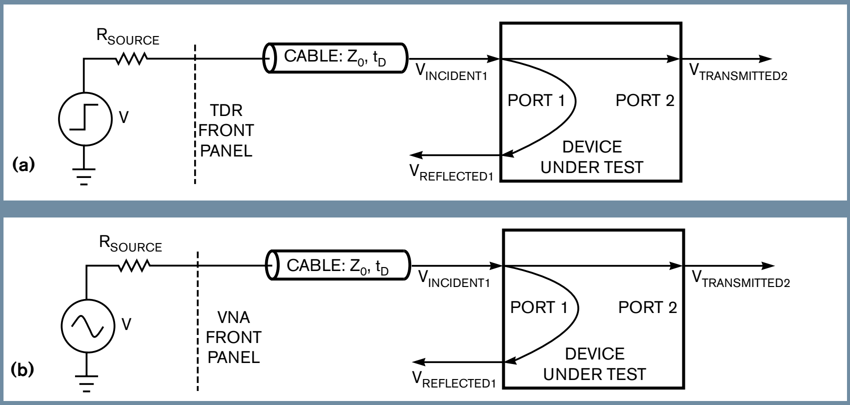

Figure A The main conceptual difference between TDR- (a) and VNA-based (b) systems is the use of a wideband, steplike source for TDR versus a narrowband sine-wave generator for VNA.

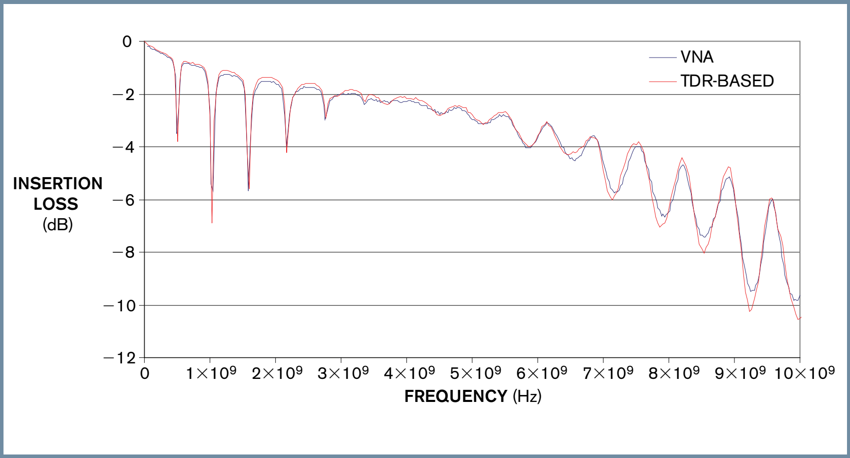

Figure B The insertion loss of VNA versus TDA shows excellent correlation (courtesy Samtec).

domain network analyzers. However, the same calibration procedures that make these analyzers so accurate also make them much more difficult to use and make performing the required tests much more time-consuming–undesirable qualities, especially in situations involving manufacturing test.

The developers of TDR-based S-parameters designed them as extensions of TDR technology. TDR is more intuitive to the digital designers than to the microwave designers, and, as a result, the conversion of TDR into S-parameter data is an intuitive and straightforward process. Even though you can apply advanced calibration, such as SOLT and TRL, to TDR to improve its accuracy, these procedures would make TDR measurements more difficult and less intuitive. Even without these calibration procedures, the dynamic range of TDR-based S-parameters is well into the −50- to −60-dB range, which is more than adequate for a typical measurement in digital design or signal integrity (Reference C). You can improve the dynamic range of TDR-based S-parameters by increasing the number of points and the number of averages in the time-domain-acquisition window; a greater amount of averaging and more points play the same role as narrowband filtering of the signal does in VNA. Overall, researchers have extensively studied the correlation between VNA and TDR-based S-parameters, and many standards groups have accepted the TDR parameter as more than adequate (Figure B and Reference D). When you combine it with the substantially lower cost of the typical TDR S-parameter-measurement system, the TDR approach provides an excellent, easy-to-use technique.

Another important point is that the compliance test-point for many standards requires that the fully mated connector must be part of the compliance test and that it must be part of the passive-physical-layer measurement. The receptacle must be de-embedded, excluding the connector that is mated on the board. Even though that task is not impossible with a VNA, it adds yet another layer of complexity to VNA measurements. With TDNAs (time-domain-network analyzers), the ease of calibration, which requires only a short, an open, or a through circuit, allows you to easily de-embed the receptacle, providing additional advantage to the TDNA approach. Overall, the de-embedding fixture eliminates VNA's accuracy advantage, and the ease-of-use and high-throughput advantages of TDNA remain intact, making TDNA a more attractive approach for most standards-compliance testing (Reference E).

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ACCURACY VERSUS DYNAMIC RANGE BELOW MEASUREMENT LEVEL

Dynamic range below measurement level (dB)	Maximum error of the signal (%)	Maximum peak-to-peak ripple (dB)
10	31.6	5.6884
11	28.2	5.0322
12	25.1	4.459
13	22.4	3.9561
14	20	3.5133
15	17.8	3.1224
16	15.8	2.7766
17	14.1	2.4703
18	12.6	2.1986
19	11.2	1.9574
20	10	1.743
21	8.9	1.5524
22	7.9	1.3828
23	7.1	1.2319
24	6.3	1.0975
25	5.6	0.9779
26	5	0.8714
27	4.5	0.7765
28	4	0.6919
29	3.5	0.6166
30	3.2	0.5495
31	2.8	0.4897
32	2.5	0.4365
33	2.2	0.389
34	2	0.3467
35	1.8	0.309
36	1.6	0.2753
37	1.4	0.2454
38	1.3	0.2187
39	1.1	0.1949
40	1	0.1737
41	0.9	0.1548
42	0.8	0.138
43	0.7	0.123
44	0.6	0.1096
45	0.6	0.0977
46	0.5	0.0871
47	0.4	0.0776
48	0.4	0.0692
49	0.4	0.0616
50	0.3	0.0549