

THE TDR (TIME-DOMAIN-REFLECTOMETRY) METHOD FOR SIGNAL-INTEGRITY ANALYSIS CAN HELP GIGABIT-SYSTEM DESIGNERS PRODUCE MORE ACCURATE INTERCONNECT MODELS, RESULTING IN MORE RELIABLE AND HIGHER PERFORMANCE DESIGNS.

Signal-integrity modeling of gigabit backplanes, cables, and connectors using TDR

IN RECENT YEARS, the computer and communications industries have witnessed the emergence of several gigabit interface standards. Examples include InfiniBand and 3GIO (now called PCI Express), HyperTransport and RapidIO, Gigabit Ethernet, OC-48, and OC-192. Upgrades of standards, such as FibreChannel, SCSI, ATA, FireWire and USB, also support gigabit speeds.

As digital designs migrate to gigahertz signal frequencies and gigabit-per-second speeds, interconnect performance becomes the key factor in enabling stable operation. Signal-integrity issues, such as reflections, crosstalk, frequency-dependent transmission-line loss and dispersion, can significantly degrade system performance and reliability. A designer's ability to simulate and accurately predict the effect of these signal-integrity issues is critical to achieving a working design, and this ability is contingent on the designer's obtaining accurate interconnect models. "Bad models will result in bad electrical-network-simulation results." (See Reference 1.)

You can extract these models using a number of prelayout-analysis and electromagnetic-field-solver tools. However, comparing the model with real measurements is paramount. With production prototypes in hand, the designer verifies the accuracy of the prelayout-analysis-tool assumptions using real-life measurements and modeling.

Transmission-line frequency-dependent losses and crosstalk degrade deterministic jitter and eye-diagrams; therefore, you must model them using coupled- and lossy-transmission-line models.

Signal distortion and digital switching er-

rors result from crosstalk, reflections, and ringing. Modeling crosstalk requires coupled-line techniques. Understanding reflections demands increased impedance-measurement accuracy and transmission-line modeling. Predicting signal ringing requires that you understand the interaction between the lumped (RLC) and distributed (transmission-line) elements in the system.

You can extract all of the interconnect models—lumped, distributed, lossy, and coupled—using modeling techniques based on TDR (time-domain-reflectometry) and transmission measurements. A TDR oscilloscope and TDR-based software-model-

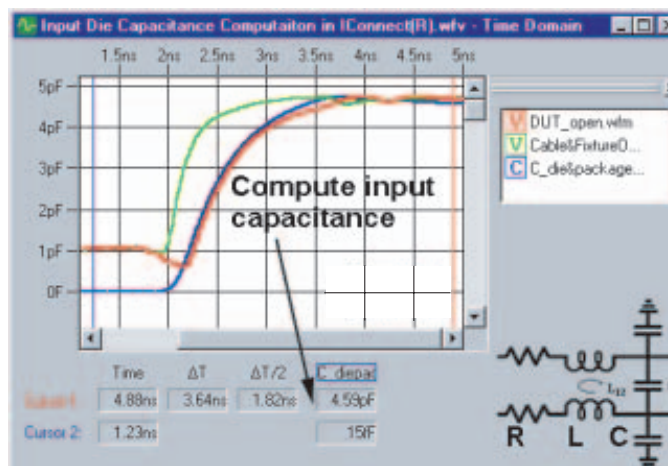


Figure 1

Input-package-and-die-capacitance computation is a two-part measurement process.

ing tools become a powerful system for interconnect-impedance measurements, signal-integrity Spice and IBIS modeling, and prelayout and field-solver model validation.

TDR-BASED MODELING

The pieces of the interconnection puzzle include backplane traces (single-run or differential, on a single layer or different board layers), vias, connectors and connector-cable assemblies, IC packages, and sockets. You can model electrically short structures, such as vias, packages and connectors, by an RLC approach, whereas you must represent board traces and cables by distributed elements (transmission lines). If these backplane traces and cables are long, you must include frequency-dependent losses in the transmission-line model to accurately predict propagation delay, jitter, and eye-diagram degradation.

You can use a lumped model for the interconnect or interconnect segment if the interconnect propagation delay is much shorter than the rise time of the signal propagating through the interconnect:

$$t_{PROP DELAY} \ll t_{RISE TIME}$$

When the rise time of the signal equals two to three times the propagation delay through the interconnect, most designers use a lumped model for the interconnect. More conservative designers use a factor of six to 10 times. You can measure the propagation delay through the interconnect using TDR or estimate it using the following equation:

$$t_{PROP DELAY} = \sqrt{LC}$$

An important implicit point is that designers need to know the rise time of the signal that propagates through this interconnect. You typically determine this rise time as the fast corner of the drivers that you use with a given

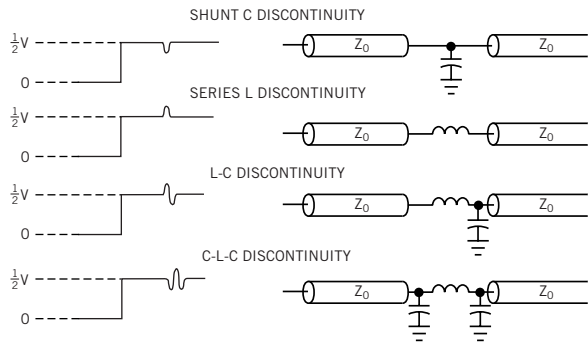


Figure 2 Straight-line segments in the true impedance profile correspond to the transmission lines, “peaks” correspond to inductances, and “dips” correspond to capacitances.

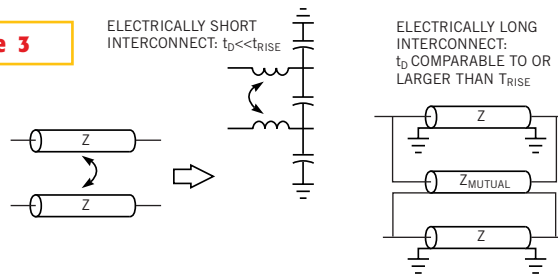


Figure 3 Methods for modeling differential transmission and crosstalk offer different levels of convenience and accuracy.

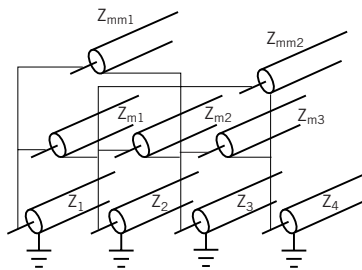


Figure 4 A sample model for a four-transmission-line structure derives from superposition of several differential TDR measurements.

Figure 5

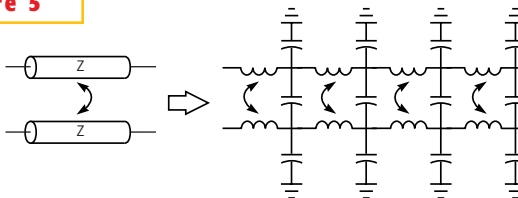


Figure 5 When using lumped-coupled subsegments to model a short transmission-line segment, each subsegment must be much shorter than the rise time of the signal propagating through the interconnect.

signaling or I/O standard, and this fast corner then determines the required rise-time range of validity for the interconnect model. Attempting to extract a model that operates to a faster rise time results in a model that is unnecessarily complex, and using a model that is not valid at a given rise time results in simulation results that have no relevance.

Once you extract the TDR-based model, you should also run a simulation using this extracted model in your simulator of choice to validate the accuracy of the model. Ensuring that the simulation matches the measured TDR waveforms gives a reasonable confidence level in the model’s accuracy. Ensuring that both reflection and transmission match the measurement provides full confidence. In TDA Systems’ IConnect TDR software, for example, an integrated interface to several Spice simulators closes the model-validation loop.

The modeling process flow begins with a measurement and continues with model extraction. You then simulate the model and return the simulation results to a waveform viewer, in which you directly compare the simulation results with the previously acquired measurement data.

RLC CONNECTOR AND PACKAGE MODELING

Designers who have the luxury of characterizing a connector or a package separately from the rest of the system should examine all options (references 2 and 3). The JEDEC extraction is typically the easiest and most accurate modeling technique in situations in which lumped RLC applies to modeling use. For example, to measure the input package and die capacitance of a socket-mounted IC on the board requires measuring the empty socket without the IC in place and with the device under test in the socket. (Figure 1).

Even though developers originated these techniques for IC-package characterization, you

should perform connector characterization in much the same fashion. The key difference between connector and package characterization, however, is that a connector is a symmetric structure. Therefore, connectors lend themselves to characterization techniques based on differential-TDR measurements.

IMPEDANCE-PROFILE MODELING

TDR oscilloscopes look at the reflection from the device under test and measure impedance. They accurately perform these tasks for single-impedance interconnect, such as in a backplane impedance test. Most real-life interconnects, however, are multi-segment and multi-impedance, which result in impedance errors in the TDR-oscilloscope measurement. These errors are due to multiple reflections, and you need to account for them to get the true impedance profile for the device under test (references 4 to 6). For example, you can't apply "windowing," a widely used TDR technique, until you obtain the true impedance profile.

Once you compute an accurate impedance profile for the device, you can use an impedance-deconvolution algorithm to generate the impedance-profile modeling approach to generate a Spice or an IBIS signal-integrity model for the interconnect (Reference 6). The straight-line segments in the impedance profile correspond to transmission lines, and the peaks and dips correspond to inductances and capacitances (Figure 2).

This visual and intuitive nature of TDR analysis makes interconnect modeling a straightforward task. The model generated using the impedance-profile approach has the advantage of a one-to-one correlation to the physical geometry of the backplane or cable interconnects.

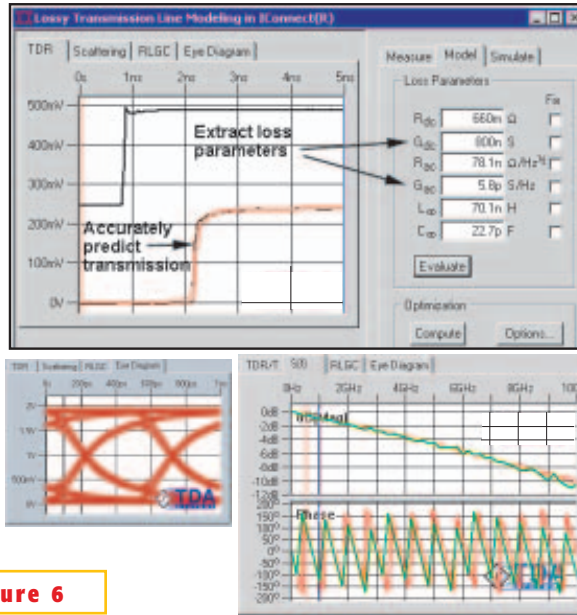


Figure 6

Losses in transmission-line parameters affect rise-time degradation, amplitude degradation, and the eye-diagram aperture.

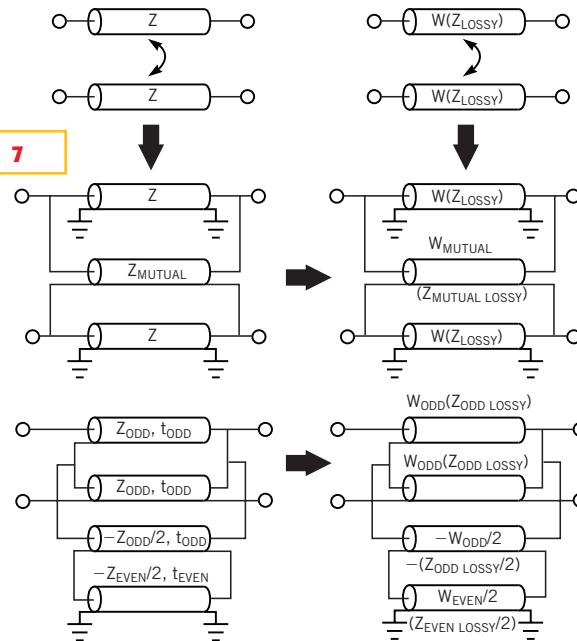


Figure 7

The lossless-transmission-line model, extracted via the true-impedance-profile technique, changes to the lossy-transmission-line model.

Each transmission line corresponds to a backplane trace or a cable segment; each lumped element corresponds to a board via or a connector.

The only drawback of the impedance profile-based models is that they do not include the frequency-dependent loss. (However, you can extract this loss using the technique described in the sec-

tion titled "Lossy-line modeling.") You may need to include transmission-line loss when modeling pc-board traces of substantial length, but short traces or lumped element models typically do not require transmission-line-loss inclusion.

DIFFERENTIAL MODELING

Differential-transmission-line-modeling techniques calculate the signal propagation through a differential line pair to predict single-ended and differential crosstalk and to predict crosstalk-induced jitter. For an electrically short interconnect, you can use a lumped, coupled interconnect model. For an electrically long interconnect, you must use one of the simulator-independent, coupled-transmission-line models (Reference 7) or a simulator-specific coupled-line model (Figure 3).

When simultaneously modeling crosstalk on more than two transmission lines or when modeling crosstalk between the two differential pairs, a designer may need to perform differential measurement on two lines at a time and combine the overall model by applying superposition (Figure 4). A simple observation of the model suggests that making any simplifying assumption, such as ignoring the coupling segments Z_{mm} , would dramatically simplify the model, making it more usable in a real-life application. At the very least, it is more appropriate to extract such a model in an electromagnetic field

solver, then validate it using TDR measurements.

Because the lumped, coupled model is simpler and easier to use than the distributed, coupled-line model, you can model interconnect segments just slightly longer than the rise time of the signals by splitting the interconnect into several subsegments, each shorter than the sig-

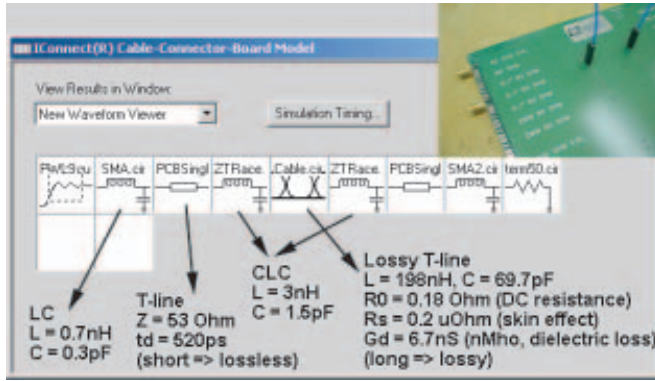


Figure 8 Modeling the cable-connector pc-board fixture interconnect is a multistep process.

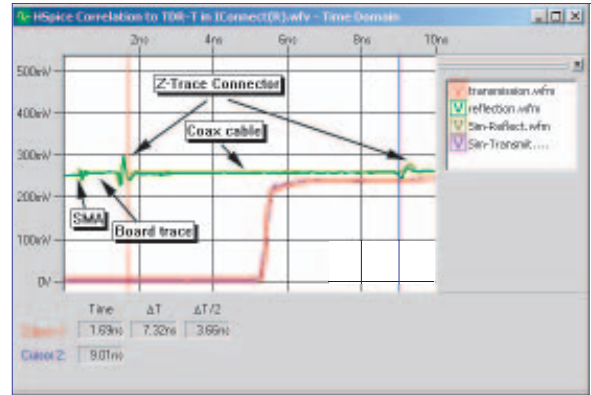


Figure 9 A high level of correlation between HSpice simulation and TDR measurements allows designers to rely on the accuracy of the interconnect model.

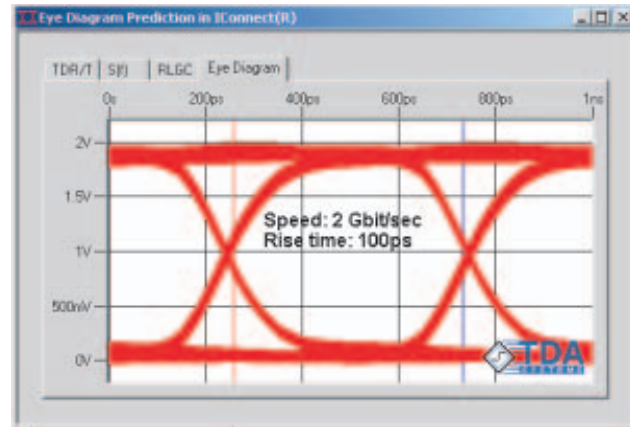


Figure 10 TDR software predicts the eye diagram.

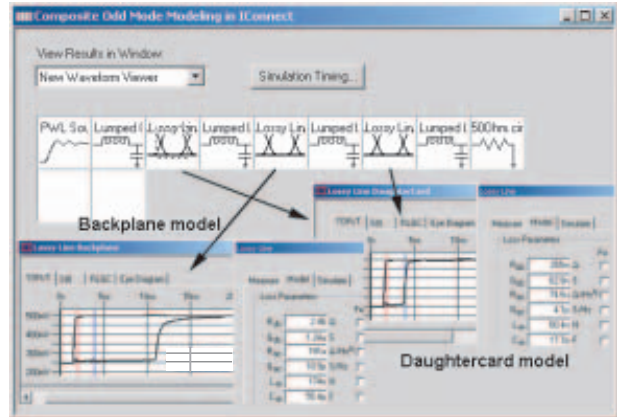


Figure 11 An odd-mode-only focus simplifies the creation of an equivalent circuit model for a lossy backplane-and-daughtercard assembly.

nal rise time (Figure 5). A lumped, coupled interconnect model typically finds use for a lumped, coupled segment in an IC package, a connector, or a via. You may use a distributed, coupled (transmission-line) model for a coupled or differential backplane trace or a segment of a cable.

For a balanced, symmetric interconnect, driven by a well-balanced differential driver, a simple odd-mode impedance-profile analysis based on the differential TDR measurements is often sufficient, thereby converting the complex model in Figure 4 to a simple two-coupled-line model in (Reference 7). If this assumption is invalid, then you must also perform an even-mode analysis, based on the common-mode TDR measurements. The simplification in the case of a balanced, symmetric interconnect allows a designer, for example, to model crosstalk between the two differ-

ential pairs by simply looking at the crosstalk between two odd-mode transmission lines. A complete model, on the other hand, would require a complex transmission-line configuration (Figure 3).

LOSSY-LINE MODELING

You need to model frequency-dependent transmission-line losses for longer segments of backplane traces and cables. Skin effect and dielectric loss are the two key components of the transmission-line losses, degrading rise time and amplitude in the signal (Reference 8). Rise-time degradation can cause significant difference in delay between the driver and a receiver, and amplitude degradation can prevent the receiver from switching. Both of these effects combine with the crosstalk-related pattern-dependent jitter to significantly degrade the eye diagram.

Different circuit simulators support different lossy-transmission-line-simulation capabilities. Reference 9 discusses a practical approach to lossy-transmission-line modeling using TDR, and Figure 6 presents sample results. Once you extract the loss parameters, you can save the model in several lossy-transmission-line simulator-specific or simulator-independent formats, depending on your requirements.

Good time-domain correlation between simulation and measurement for both reflection and transmission data observed in Figure 6a is typically sufficient to obtain good delay-prediction accuracy. However, when predicting the eye diagram, it may be necessary to ensure that both the time and the frequency domains for the model correlate (Figure 6b).

For differential transmission-line modeling and coupled lossy-transmis-

(continued on pg 72)

sion-line analysis, follow the discussion above. If your coupled-transmission-line structure is symmetric, and you can focus on the differential- or odd-mode analysis, you need to perform only the odd-mode loss characterization. If you need to produce a complete coupled-line structure, including both differential and common mode, then you must perform differential and common-mode measurements (Reference 7). For both differential and common-mode measurements, it is sufficient to acquire only one stimulus or response channel on the oscilloscope.

Even though you do not acquire the second channel, you capture the interaction (coupling and losses) in the lines. Based on these measurements, you can extract the loss characteristics, and save either the simulator-independent coupled-line configuration or a simulator-specific lossy-coupled-line model (Reference 7). If you use the simulator specific configuration, the modeling process may flow more smoothly and easily if you start the modeling with the true-impedance-profile computation, create a lossless-transmission-line configuration, and then change the lossless-transmission-line configuration into a lossy line (Figure 7). Once you extract and validate the loss parameters for a given transmission-line structure, you can put together a complete model of the interconnect system.

PUTTING IT ALL TOGETHER

The first example, covering a cable-connector pc-board fixture, demonstrates characterization of a single-ended test fixture, with the SMA connectors attached to the fixture to enable an easy connection to the TDR oscilloscope. The fixture under test, for characterization of coaxial-cable assemblies, uses the Joy Signal Technology/Meritec Z-Trace shielded female coaxial connector.

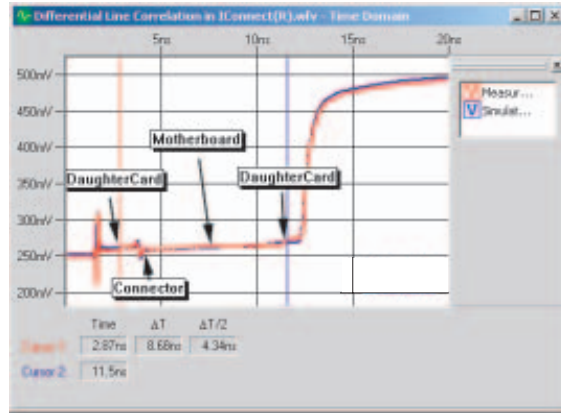


Figure 9 Simulation in Berkeley Spice correlates to TDR measurements for odd mode in a differential backplane assembly.

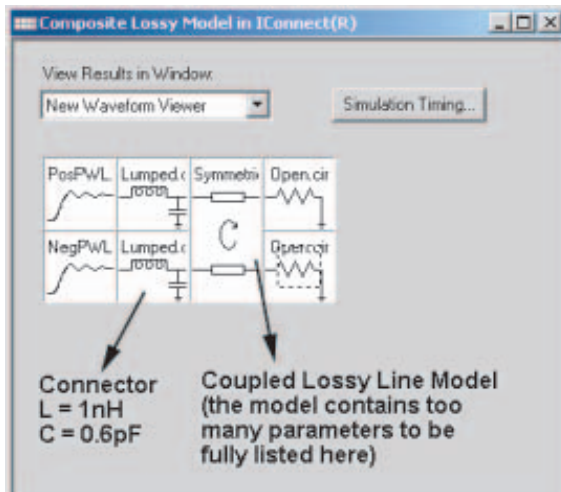


Figure 10 A fully coupled lossy-transmission-line model in TDR software includes both coupling characteristics and the loss characteristics of the structure.

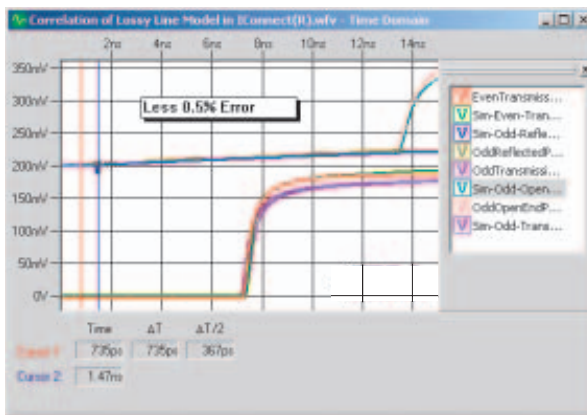


Figure 11 Simulations of the symmetric coupled-lossy-line model correlate with TDR measurements.

connector, pc-board trace, and Z-Trace connector models. The model for the pc-board trace was lossless, because the trace on the board was short, and the losses were insignificant. Lossy-line extraction created the cable model, based on matched TDR (matched-transmission) measurement of the cable. Figure 9 shows the resulting correlation between the TDR measurement and HSpice simulations.

With this level of correlation for both the TDR and TDT waveforms, a designer can rely on the interconnect model to produce accurate simulation results. Note that you can easily see the discontinuity due to the Z-Trace connector at the beginning of the coax cable, but the discontinuity is less obvious at the end of the cable. This effect occurs due to the degradation of the signal's rise time as it propagates through the lossy cable, resulting in a slower rise time at the second Z-Trace connector and a smaller signal amplitude at the connector discontinuity. The extracted model accurately predicts this effect. Figure 10 shows the resulting predicted eye diagram.

The second example, covering a lossy symmetric differential backplane, demonstrates characterization of a Mysticom Gigabit Ethernet backplane populated with two daughtercards. The only measurement access to the backplane is through the SMA connectors on the daughtercards. The traces under test are differential, but, because of the symmetry, characterization focused only on odd-mode modeling, thereby simplifying the process. Figure 11 shows the equivalent circuit model.

First, an open-reflection-loss technique extracts the lossy-line model for the daughtercard. Next, the impedance-profile (Z-line) method extracts the daughtercard-to-back-

plane-connector model. Then, you extract the lossy-line model for the backplane. No direct access to the backplane means that you again need to use the

plane-connector model. Then, you extract the lossy-line model for the backplane. No direct access to the backplane means that you again need to use the

open-reflection-loss extraction technique. You could use the daughtercard reflection as a reference waveform, and backplane reflection as the device-under-test waveform. Alternatively, you could extract a total loss in the daughtercard and backplane and subtract the daughtercard loss and delay parameters from total extracted loss and delay parameters.

In either case, you must allow for the daughtercard-backplane connector delay. Simulations using this model run under PSpice and Berkeley Spice; **Figure 12** shows the resulting correlation. Similarly, you can predict the eye diagram based on this TDR-modeling result or based on TDT measurements.

The last example covers a lossy, symmetric backplane, including the even mode. It demonstrates characterization of a 1m, broadside-coupled differential test trace on a Sun Microsystems board and requires a complete coupled-line model for the differential-transmission-line pair. You can use either a simulator-independent coupled-lossy-line model or one of the simulator-specific coupled-lossy-line structures. This example uses the true-impedance-profile approach to obtain the lossless-coupled-transmission-line model, including the connector (**Figure 13**). Then, using the configuration in the extracted circuit file, you replace the lossless transmission lines with lossy ones.

Figure 14 shows the resulting correlation between the simulation of the symmetric coupled-lossy-line model and TDR measurements of the structure. Because both differential and common-mode simulation results match the measurement with less than 0.5% error, the model produces more than satisfactory accuracy for the backplane simulation and eye-diagram prediction. □

REFERENCES

1. Haller, RJ, "The nuts and bolts of signal-integrity analysis," *EDN*, March 16, 2000, pg 61.
2. "Guideline for measurement of electronic package inductance and capacitance model parameters," *JEDEC Publication No. 123*, JC-15 Committee, October 1995.
3. Smolyansky, Dima, "TDR techniques for characterization and modeling of electronic packaging," *High Den-*

sity Interconnect Magazine, March/April 2001, reprinted as TDA Systems application note PKGM-0101.

4. Hayden, LA and VK Tripathi, "Characterization and modeling of multiple line interconnections from TDR measurements," *IEEE Transactions on Microwave Theory and Techniques*, Volume 42, September 1994, pg 1737.

5. Hsue, CW and TW Pan, "Reconstruction of nonuniform transmission lines from time-domain reflectometry," *IEEE Transactions on Microwave Theory and Techniques*, Volume 45, No 1, January 1997, pg 32.

6. Smolyansky, Dima and SD Corey, "PCB interconnect characterization from TDR measurements," *Printed Circuit Design Magazine*, May 1999, reprinted as TDA Systems application note PCBD-0699-02.

7. Smolyansky, Dima and SD Corey, "Characterization of differential interconnects from time domain reflectometry measurements," *Microwave Journal*, Volume 43, No. 3, pg 68, reprinted as TDA Systems application note DIFF-1099.

8. Johnson, Howard and M Graham, *High-Speed Digital Design: A Handbook of Black Magic*, Prentice Hall, 1993.

9. Bogatin, E, S Corey, and M Resso, "Practical characterization, analysis and simulation of lossy lines," DesignCon 2001, Santa Clara, CA, January 2001, reprinted as TDA Systems application note LOSS-0601.

ACKNOWLEDGMENT

Thanks to Steve Corey, PhD, of TDA Systems for his valuable review of this article.

AUTHOR'S BIOGRAPHY

Dima Smolyansky has spent his professional career in the instrumentation and measurement industry, working with TDR oscilloscopes and frequency-domain network analyzers. At Time Domain Analysis Systems (www.tdasystems.com), he works on applications and technical marketing for IConnect TDR software products, which help ensure signal integrity in high-speed digital systems. He holds an MSEE from Oregon State University (Corvallis, OR) and an MS in electronics engineer from Kiev Polytechnic Institute (Kiev, Russia). You can reach him at dima@tdasystems.com.