

Signal Integrity Modeling of Gigabit Backplanes, Cables and Connectors Using TDR

Introduction

In recent years, the computer and communications industries have seen an emergence of several gigabit interface standards. Examples include: Infiniband and PCI Express, HyperTransport and RapidIO, Gigabit Ethernet, OC-48 and OC-192. Existing standards, such as FibreChannel, SCSI, ATA, Firewire and USB, are being up-rated to support gigabit speeds.

As digital designs are migrating into the gigahertz and gigabit speed range, interconnect performance becomes the key factor in enabling a digital system design that is capable of reliably performing at these speeds. Signal integrity issues such as reflections, crosstalk, frequency dependent transmission line loss and dispersion can significantly degrade the system performance and reliability. The ability for a designer 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 ability to obtain *accurate interconnect models*. It is clear that "bad models will result in bad electrical-network-simulation results," [1].

These models can be extracted using a number of pre-layout analysis and electromagnetic field solver tools. However, "it is paramount to compare the model with real measurements," [1]. The system prototype must be manufactured, (unless a test board prototype has been manufactured and characterized beforehand), and with these prototypes in hand, the designer will verify the accuracy of the pre-layout analysis tool assumptions using real-life measurements and modeling. It is these real-life measurement and modeling techniques that we will focus on in this paper. Deterministic jitter and eye diagram degradation are caused by transmission line frequency dependent losses and crosstalk, and therefore must be modeled using coupled and lossy transmission line models. Signal distortion and digital switching errors result from crosstalk, reflections and ringing. Modeling the crosstalk requires coupled line modeling techniques. Understanding reflections demands increased impedance measurement accuracy and transmission line modeling. Predicting

signal ringing requires understanding of interaction between the lumped (RLC) and distributed (transmission line) elements in the system.

All the interconnect models – lumped and distributed, lossy and coupled – can be extracted using modeling techniques based on Time Domain Reflectometry (TDR) and Transmission (TDR/T) measurements. A TDR oscilloscope, coupled with IConnect® TDR-based software modeling tools, becomes a powerful system for interconnect impedance measurements, signal integrity SPICE and IBIS modeling, and pre-layout and field solver model validation.

TDR-Based Modeling Methodology

The different pieces of the interconnect 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. Electrically short structures, such as vias, packages and connectors, can be modeled using a lumped (RLC) approach, whereas board traces and cables must be represented by distributed elements (transmission lines). As we will see later in this paper, if these backplane traces and cables are long, we must include frequency dependent losses in the transmission line model in order to accurately predict propagation delay, jitter, and eye diagram degradation.

We 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:

$$t_{prop\ delay} \ll t_{rise\ time} \quad (1)$$

If the rise time of the signal equals 2-3 times the propagation delay through the interconnect, most designers would use the lumped model for such an interconnect. The most conservative designers would use a factor of 6-10. The propagation delay through the interconnect can be measured using TDR, or estimated using the following equation:

$$t_{prop\ delay} = \sqrt{LC} \quad (2)$$

An important point implicit here is that the designer needs to know the rise time of the signal that will propagate through this interconnect. This rise time is typically determined as the fast corner of the drivers to be used with a given signaling or I/O standard, and this fast corner will then determine the *required rise time range of validity of the interconnect model*. The rise time range of validity of the interconnect model must be determined beforehand. Attempting to extract a model that operates to a faster rise time will result in a model that is unnecessarily complex, and using a model that is not valid at a given rise time will result in simulation results which have no relevance to reality.

Once the TDR-based model is extracted, it is also important to run a simulation, using this extracted model, in the designer's 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 accuracy, and ensuring that both reflection and transmission matches the measurement provides full confidence. In IConnect TDR software from TDA Systems, this model validation loop is closed by an integrated interface to several SPICE simulators. The modeling process flow in IConnect starts with a measurement, continues with model extraction in IConnect or any of the existing electromagnetic field solver tools, the model is simulated, and the simulation results are returned to IConnect waveform viewer, where the simulation results are directly compared with the previously acquired measurement data.

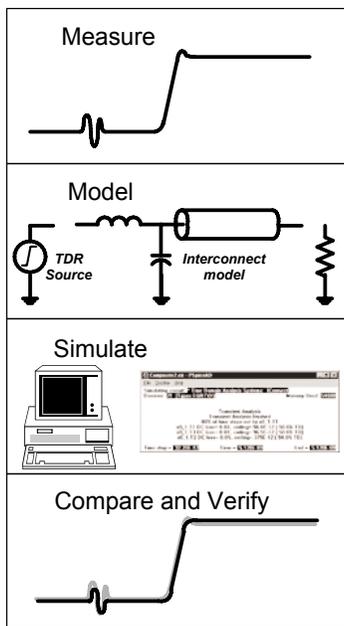


Figure 1. IConnect TDR software Measure-Model-Verify approach. The modeling process flow starts with a measurement, continues with model extraction in IConnect or any of the existing electromagnetic field solver tools, the model is simulated, and the simulation results are returned to IConnect waveform viewer, where the simulation results are directly compared with the previously acquired measurement data.

RLC Connector and Package Modeling

If the designer has the luxury of characterizing a connector or a package separately from the rest of the system, the techniques described in [2], [3] provide a complete set of solutions applicable in any circumstances. These modeling techniques are implemented in IConnect TDR software.

As we discussed above, before beginning a modeling session, it is important to determine whether a given connector or package can be modeled using a simple lumped RLC approach. If the lumped model is applicable, typically the JEDEC extraction method described in [2] is the easiest and most accurate modeling technique. As an example, we measure the input package and die capacitance of an IC on the board. The device under test (DUT) is mounted in the socket. Two measurements are required; one with the empty socket without the die in place, and another with the DUT placed in the socket. Resulting capacitance measurement in IConnect TDR software is shown Figure 2.

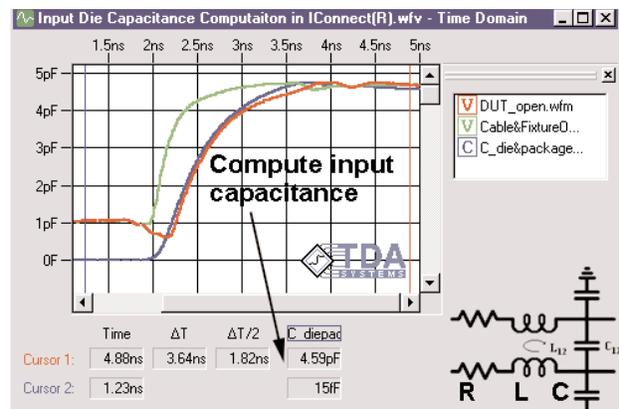


Figure 2. Input package and die capacitance computation in IConnect TDR software.

Even though these techniques have been initially developed for IC package characterization, connector characterization work should be performed in very much the same fashion¹. The key difference between connector and package characterization, however, is that a connector is a very symmetric structure. Being symmetric, connectors lend themselves much better to characterization technique based on differential TDR measurements. These techniques are also implemented in IConnect TDR software, and they will be discussed in more detail later in section Differential Transmission Line Modeling Techniques.

¹After all, an IC package is just another form of connector - a connector between the die and the board.

Impedance Profile Modeling of Backplanes and Cable Assemblies

TDR oscilloscopes are designed to look at the reflection from the DUT and measure impedance. They do so very accurately for single impedance interconnect, such as a backplane impedance test coupon. Most of the real life interconnects, however, are multi-segment and multi-impedance, which results in some impedance measurement errors in the TDR oscilloscope measurement due to the effect known as "multiple reflections," which need to be de-embedded in order to get the true impedance profile for the DUT [4]-[6]. The TDR "windowing", a technique widely used with TDR cannot really be applied until the true impedance profile is obtained². Once the true impedance profile for the DUT is computed, using an impedance deconvolution algorithm such as the Z-Line algorithm in IConnect TDR software, the designer can use the true impedance profile modeling approach discussed in [6] to generate a SPICE or IBIS signal integrity model for the interconnect. The straight-line segments in the impedance profile correspond to transmission lines, and the "peaks" and "dips" correspond to inductances and capacitances, Figure 3. The values of these transmission line impedances and delays, inductances, capacitances are computed automatically in IConnect TDR software.

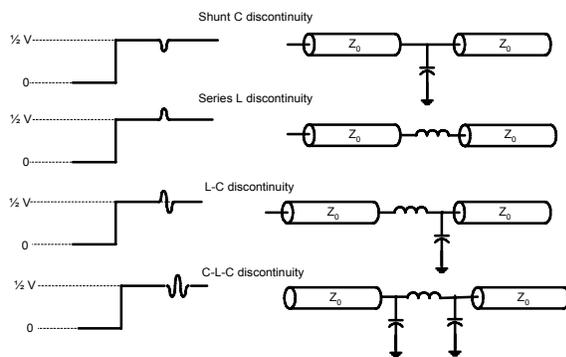


Figure 3. Straight line segments in the true impedance profile correspond to the transmission lines, "peaks" to inductances and "dips" to capacitances.

The visual and intuitive nature of TDR analysis makes interconnect modeling a very straightforward task. The model generated using the impedance profile approach has the advantage of having a one-to-one correlation to the physical geometry of the backplane or cable interconnects. Each transmission line corresponds to a backplane trace or a cable segment; each lumped element corresponds to a board via or a connector.

²The same "multiple reflections" issues apply to "windowing" in Vector Network Analyzers (VNA) with time domain capability

The only drawback of the impedance profile-based models is that they do not include the frequency dependent loss. However, this loss can be extracted using the technique described in the section Lossy Line Modeling Techniques below and automated in IConnect TDR software. Transmission line loss may need to be included in the model for the traces of substantial length, but is typically not required for short traces or for lumped element models.

Differential Transmission Line Modeling Techniques

Differential transmission line modeling techniques are designed to predict the signal propagation through a differential line pair, predict single ended and differential crosstalk, and crosstalk-induced jitter. For an electrically short interconnect (as described by inequality (1)), a lumped coupled interconnect model can be utilized. For an electrically long interconnect, one of the simulator-independent coupled transmission line models described in [7] or a simulator-specific coupled line model must be used, Figure 4.

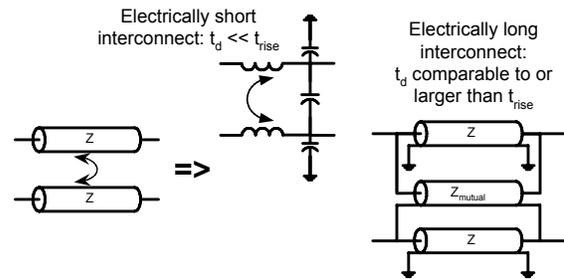


Figure 4. Different methods for modeling differential transmission and crosstalk.

When modeling crosstalk on more than two transmission lines simultaneously, or when modeling crosstalk between the two differential pairs, the designer may need to perform differential measurement on two lines at a time, and combine the overall model by applying superposition, Figure 5.

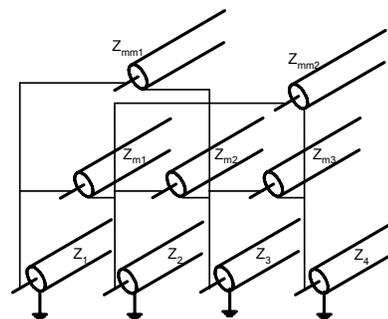


Figure 5. Sample model for a 4-transmission line structure, based on superposition of several differential TDR measurements.

A simple observation of the model shown in Figure 5 above suggests that making any simplifying assumption, such as ignoring the coupling segments Z_{mm} would contribute dramatically to simplifying the model and making it more usable in a real life application. At the very least, it is more appropriate to extract a model such as that shown in Figure 5 in an electromagnetic field solver, and then validate it using TDR measurements and IConnect TDR software.

Because of relative simplicity and ease of use of lumped coupled model compared to the distributed coupled line model, interconnect segments that are just slightly longer than the rise time of the signals, can be modeled by splitting the interconnect into several subsegments, each subsegment being shorter than the signal rise time, Figure 6. The "Subsegment" feature in IConnect Symmetric-Coupled Line modeling window allows the designer to do so easily.

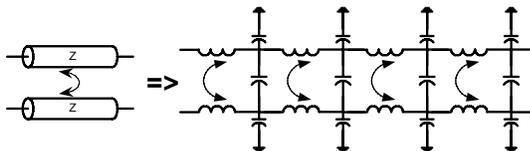


Figure 6. Using lumped-coupled subsegments to model a short transmission line segment. Each subsegment must be much shorter than the rise time of the signal propagating through the interconnect.

Lumped coupled interconnect model is typically used for a lumped coupled segment in an IC package, a connector, or a via. Distributed-coupled (transmission line) model may be used for a coupled or differential backplane trace or segment of a cable.

For a completely 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, converting the complex model in Figure 5 to a simple 2-coupled line model discussed in [7]. If the latter assumption cannot be made, then an even mode analysis, based on the common mode TDR measurements, must be performed as well. The simplification made in case of a balanced symmetric interconnect allows the designer, for example, to model crosstalk between the two differential pairs by simply looking at the crosstalk between two odd mode transmission lines, whereas a complete model would require a complex transmission line configuration, such as that presented in Figure 4 above.

Lossy Line Modeling Techniques

Frequency dependent transmission line losses need to be modeled for longer segments of backplane traces and cables. Skin effect and dielectric loss are the two key components of the transmission line losses, contributing to rise time degradation and amplitude degradation in the signal [8]. Rise time degradation can cause significant difference in delay between the driver and a receiver, and amplitude degradation can completely prevent the receiver from switching. Both of these effects, combined with the crosstalk-related pattern dependent jitter, may result in significant degradation of the eye diagram.

Different circuit simulators support different capability of lossy transmission line simulation. A practical approach to lossy transmission line modeling using TDR and IConnect TDR software has been discussed in [9], and sample results are presented in Figure 7. Once the loss parameters are extracted, the model can be saved in IConnect in several different lossy transmission line simulator-specific or simulator-independent formats, depending on designer's requirements.

Good time domain correlation between simulation and measurement for both reflection and transmission data observed in Figure 7a is typically sufficient to obtain good delay prediction accuracy. However, when predicting the eye diagram is involved, it may be necessary to ensure that both time and frequency domain for the model correlate well (Figure 7b), and such analysis can be performed in the S-parameters window in IConnect TDR software.

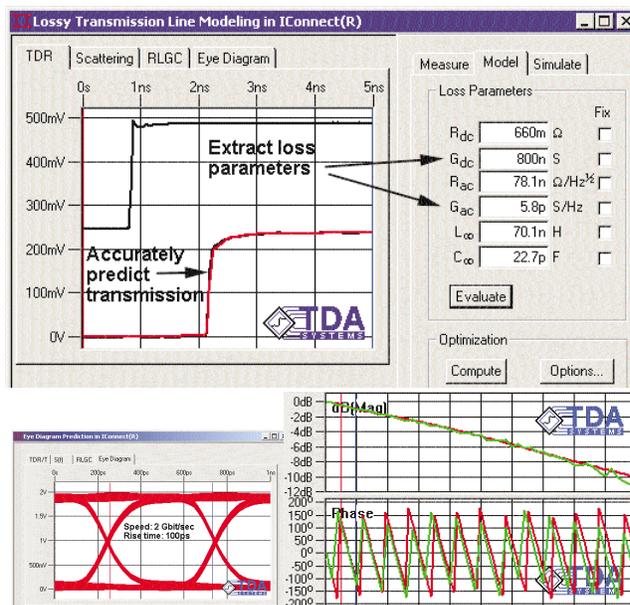


Figure 7. Extraction of lossy transmission line parameters. Losses affect rise time degradation, amplitude degradation, and the eye diagram aperture.

For differential transmission line modeling and coupled lossy transmission line analysis, we will follow the discussion in section Differential Transmission Line Modeling Techniques above. If our coupled transmission line structure is symmetric and we can focus on the differential³ (odd) mode analysis only, only the odd mode loss characterization will need to be performed. If we need to produce a complete coupled line structure, which includes both differential and common mode, then it is necessary to do differential and common mode measurements, which are performed as discussed in [7]. For both differential and common mode measurements, it is sufficient to acquire only one stimulus or response channel on the oscilloscope. Even though we will not be acquiring the second channel, we will capture the interaction (coupling and losses) in the lines. Based on these measurements, the loss characteristics can be extracted in IConnect TDR software, and either the simulator-independent coupled line configuration discussed in [7], or a simulator-specific lossy-coupled line model can be saved. If the designer chooses to use the simulator-specific configuration, the modeling process may flow smoother and easier if the designer starts the modeling with the true impedance profile computation, creates a lossless transmission line configuration, and then changes the lossless transmission line configuration into a lossy line, as suggested in Figure 8.

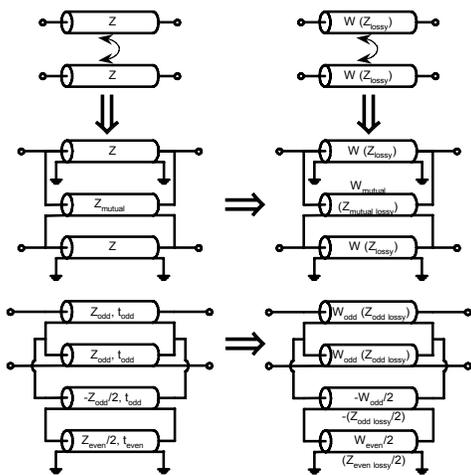


Figure 8. Transition from lossless transmission line model, extracted via the true impedance profile technique discussed above, to the lossy transmission line model.

Once the loss parameters for a given transmission line structure have been extracted and validated, a complete model of the interconnect system can be put together.

Putting It All Together

Example 1: Cable-Connector-PCB fixture characterization

Our first example demonstrates characterization of a single-ended test fixture, with the SMA connectors attached to the fixture in order to enable an easy connection to the TDR oscilloscope. The fixture under test was designed for characterization of coaxial cable assemblies using the Joy Signal Technology/Meritec Z-Trace shielded female coaxial connector. The DUT characterization used in IConnect TDR software produced the following circuit model, Figure 9.

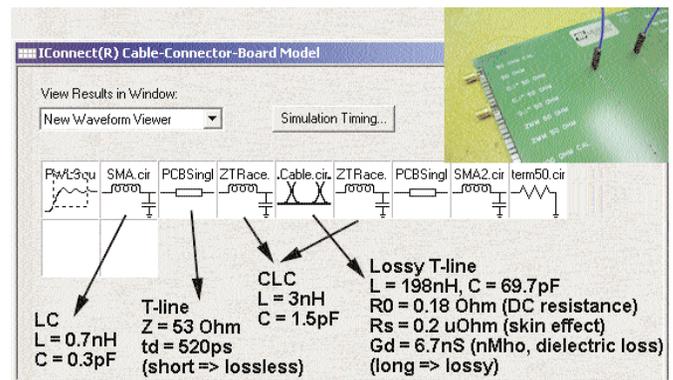


Figure 9. Modeling the cable-connector-PCB fixture interconnect.

The building blocks in this model were extracted as follows. The SMA connector, PCB trace and Z-Trace connector models were extracted using the impedance profile (Z-line) approach. The model for the PCB trace was lossless, since the trace on the board was short and the losses were not significant. The cable model was extracted using the lossy line extraction, based on matched TDT (matched transmission) measurement of the cable. The resulting correlation between the TDR measurement and HSpice simulations are shown in Figure 10.

³We will use the terms "differential" and "common" modes when applied to lossy line analysis instead of "odd" and "even," since, technically, the "even" and "odd" terms lose their physical meaning when applied to lossy transmission line structures.

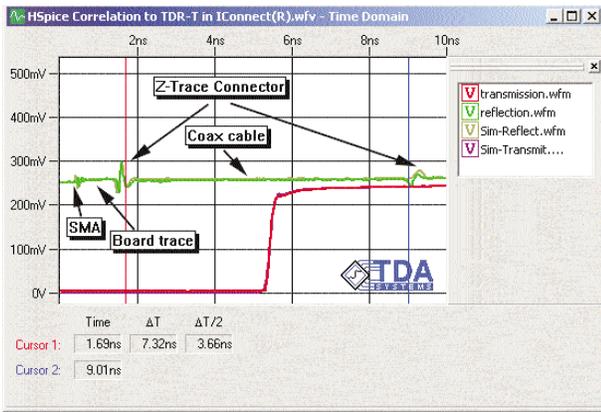


Figure 10. Correlation between HSpice simulation and TDR measurements in IConnect TDR software. With this level of correlation, the designer can rely on the accuracy of the interconnect model.

With this level of correlation for both the TDR and TDT waveforms, the designer can rely on the interconnect model to produce accurate simulation results. Note that the discontinuity due to the Z-Trace connector can be easily seen at the beginning of the coax cable, but is not as obvious at the end of the cable. This effect occurs due to the fact that the rise time of the signal is being degraded as it propagates through the lossy cable, resulting in slower rise time at the second Z-Trace connector and smaller signal amplitude at the connector discontinuity. The extracted model accurately predicts this effect. The resulting eye diagram, predicted in IConnect TDR software, is shown in Figure 11.

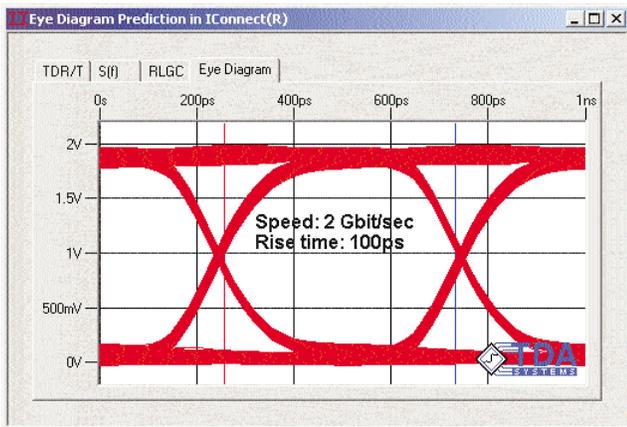


Figure 11. Eye diagram predicted in IConnect TDR software.

Example 2: Lossy Symmetric Differential Backplane Characterization

In this example, we demonstrate characterization of a Mysticom Gigabit Ethernet backplane populated with two daughtercards. The only measurement access to the backplane was through the SMA connectors on the daughtercards. The traces under test were differential, but because of the symmetry we chose to focus characterization on odd only, thereby simplifying the process. The equivalent circuit model is shown in Figure 12.

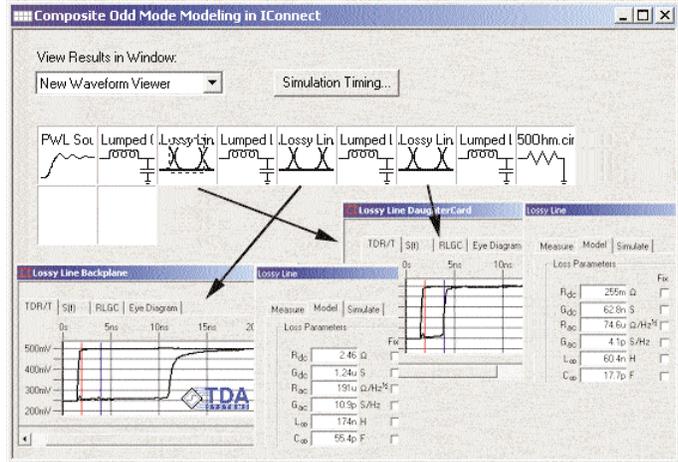


Figure 12. Equivalent circuit model of a lossy backplane and daughtercard assembly.

First, we extracted the lossy line model for the daughtercard, using the open reflection loss extraction technique in IConnect TDR software. Second, the daughtercard-to-backplane connector model was extracted using the impedance profile (Z-line) method in IConnect. Then, we extracted the lossy line model for the backplane. Since there was no direct access to the backplane, the open reflection loss extraction technique has to be used again. To extract the model, we can use the daughtercard reflection as a reference waveform, and backplane reflection as the DUT waveform. Or, alternatively, we could have extracted 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, we need to allow for the daughtercard-backplane connector delay. The simulations using this model are performed in PSpice and Berkeley SPICE, and the resulting correlation is shown Figure 13.

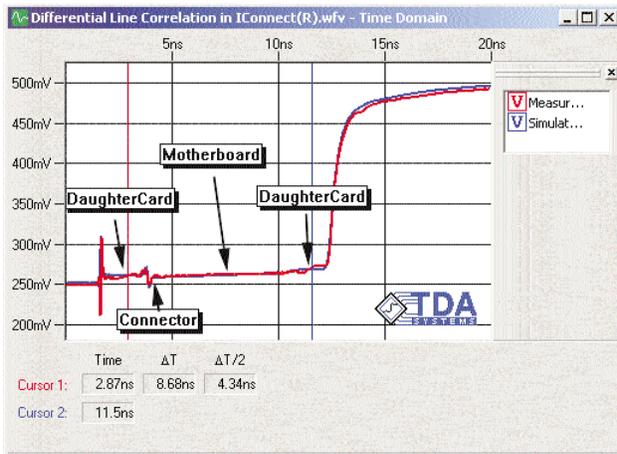


Figure 13. Correlation between Berkeley Spice simulation and TDR measurements in IConnect TDR software for odd mode in a differential backplane assembly.

Similarly, the eye diagram can be predicted based on this TDR modeling results, or directly predicted based on TDT measurements.

Example 3: Lossy Symmetric Backplane, Including the Even Mode

In this example, we demonstrate characterization of a 1 meter broadside coupled differential test trace on a Sun Microsystems board, where a complete coupled line model is required for the differential transmission line pair. We can utilize either a simulator independent coupled lossy line model, or use one of the existing simulator-specific coupled lossy line structures.

In this example, we used the true impedance profile approach in IConnect to get the lossless coupled transmission line model, including the connector, and then, utilizing the configuration in the extracted circuit file, replaced the lossless transmission lines with lossy ones. [The lossy transmission line characteristics for the differential and common mode of propagation were extracted separately in IConnect TDR software].

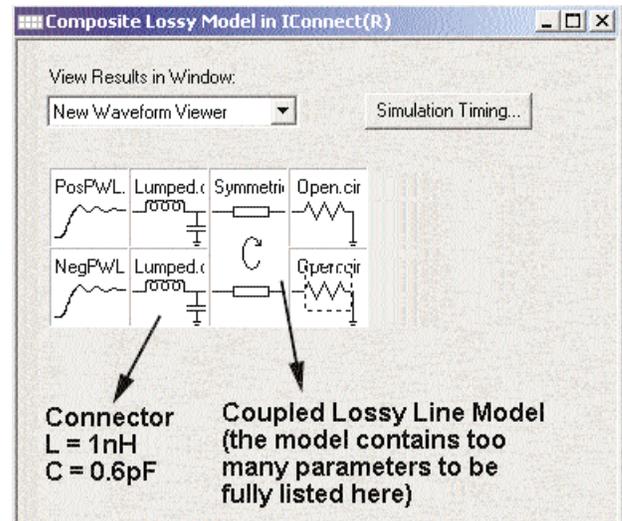


Figure 14. Fully coupled lossy transmission line model in IConnect TDR software. The model includes both coupling characteristics as well as the loss characteristics of the structure.

The resulting correlation between the simulation of the symmetric coupled lossy line model and TDR measurements of the structure are shown in Figure 15. Since both differential and common mode simulation results match the measurement with less than 0.5% error, the model will produce more than satisfactory accuracy for the backplane simulation and eye diagram prediction.

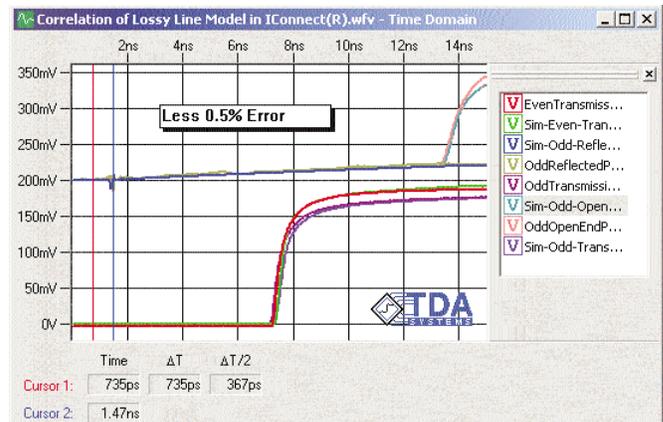


Figure 15. Correlation between the simulations of the symmetric coupled lossy line model and TDR measurements.

Summary

We presented a complete methodology for signal integrity analysis of the interconnect system running at gigabit speeds. With the TDR-based analysis techniques presented in this paper, the gigabit system designer can produce more accurate models for the gigabit system interconnect, which will result in more reliable higher performance system design.

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