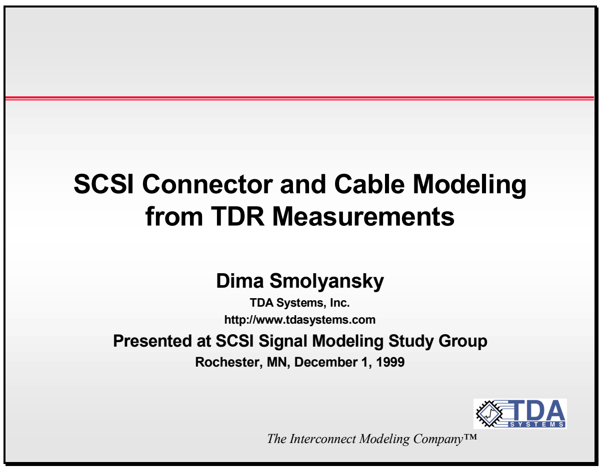
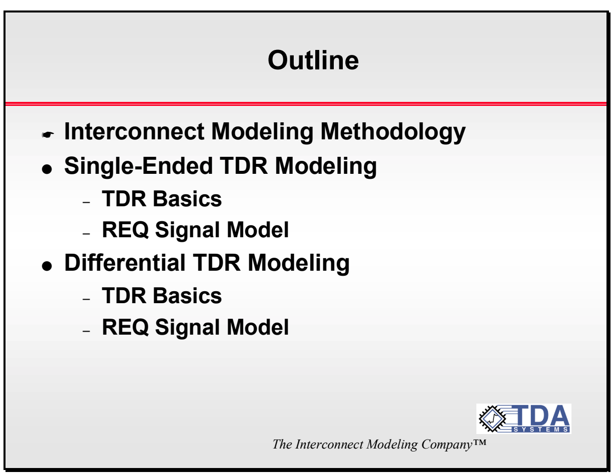
Application Note

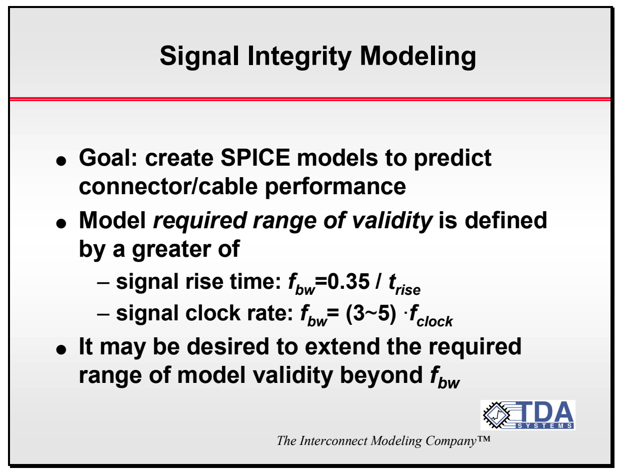
SCSI Connector and Cable Modeling from TDR Measurements



The author would like to thank Jonathan Fasig of Western Digital Corporation for providing device samples, fixtures and other assistance.

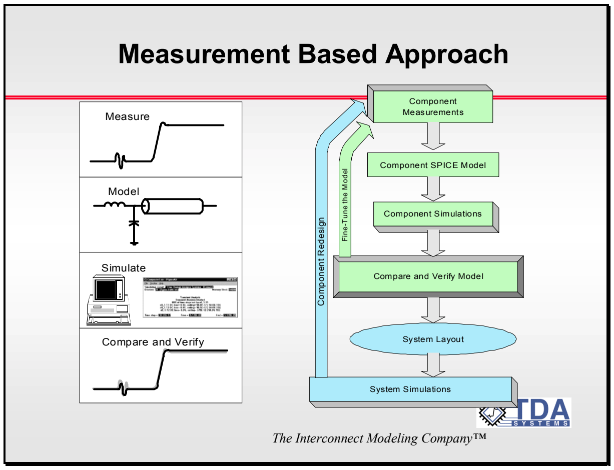


In this presentation, we will discuss an interconnect modeling methodology based on TDR measurements, and illustrate it on a sample of SCSI flat ribbon cable with IDC connectors. Both single ended and differential measurements and modeling results will be presented.



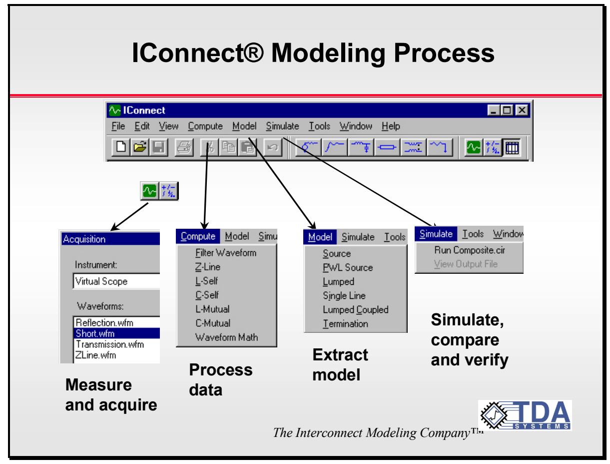
Our goal is to obtain a SPICE model that will enable us to predict the SCSI cable/connector assembly performance. Currently, differential SCSI signals run at about 1ns rise time, whereas the single-ended signals are typically limited to 3 ns rise time. We will validate our models with 100ps rise time; if our models are valid to 100ps, they will perform excellently at 1ns.

Clearly, if we can ignore the signal integrity issues in interconnects, life will be easy. However, if we cannot ignore these issues, we need to model the interconnects and to include the interconnect models in simulations. In addition, it is important to remember that the model must be valid within a certain frequency range, as defined by the signals in the digital system.

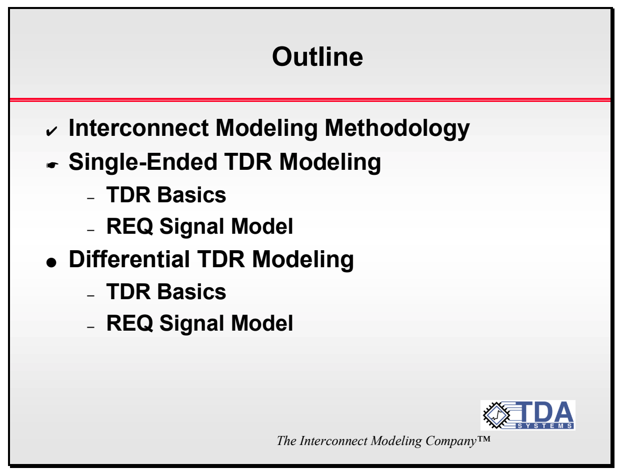


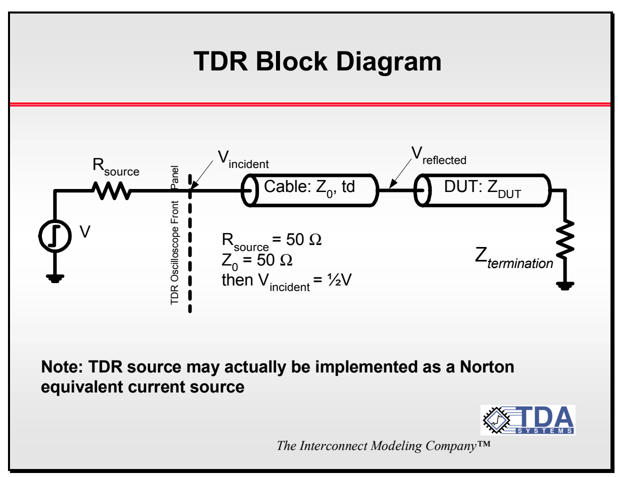
The measurement-based approach described here employs the Measure-Model-Verify philosophy. A prototype is measured using TDR techniques, and based on the acquired data, an equivalent circuit model is created. The model is verified through simulation, with the same excitation and termination used for simulation and measurement. The simulated and measured waveforms are then compared and the model is verified and adjusted if necessary.

This measurement-based approach does not contradict with the design approach that utilizes analytical tools, such as electromagnetic field solvers. If the component design was based on an electromagnetic field solver analysis, a prototype must still be fabricated. At this point, the prototype must be carefully characterized and accurate models for the prototype generated. The Measure-Model-Verify approach, again in this case, can be used in order to ease the modeling work and create an accurate prototype model from measurements. If the measurement-based model differs from the original analytical model, then the difference between assumptions in the field solver and the measurement reality must be reconciled and the model representing the prototype, as it will be used in the actual system, must be defined.



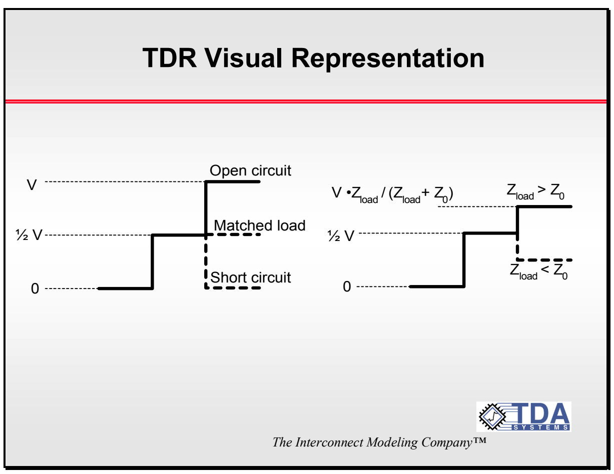
Here is the "Measure-Model-Verify" modeling process that we advocate. It is fully implemented in TDA Systems IConnect® software.



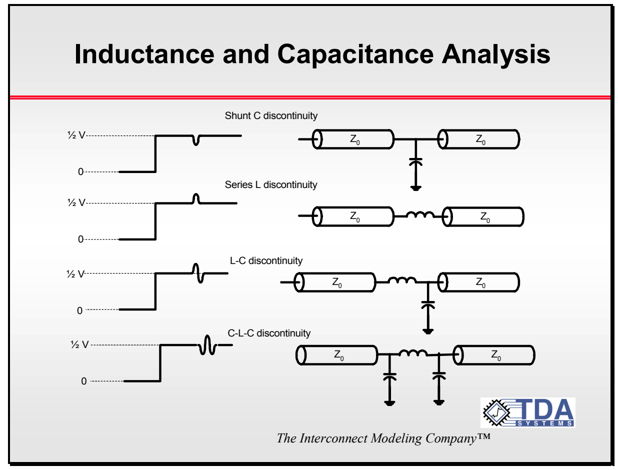


Time Domain Reflectometry measurements have always been the measurement approach of choice for board characterization work. Based on TDR measurements, a circuit board designer can determine characteristic impedances of board traces, compute accurate models for board components, and predict board performance more accurately.

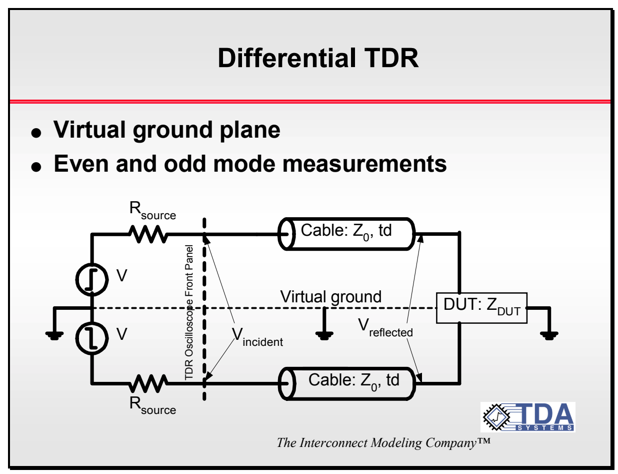
In a simple TDR setup, shown on this slide, the incident waveform amplitude at the Device Under Test (DUT) is typically half the original stimulus amplitude V at the TDR source. The smaller DUT incident waveform amplitude is due to the resistive divider effect between the 50 Ω resistance of the source and 50 Ω impedance of the coaxial cables connecting the TDR sampling head and the DUT. The impedance of the board trace can be determined from the waveform measured by the TDR oscilloscope, $V_{measured}$, which is the superposition of the incident waveform at the DUT and the reflected one, offset by 2 electrical lengths of the cable interconnecting the oscilloscope TDR sampling head to the DUT.



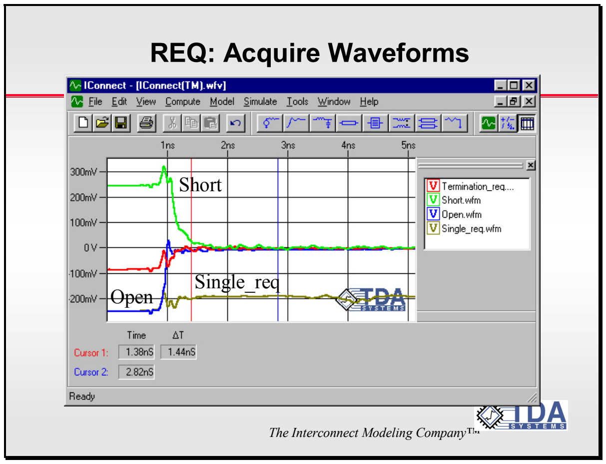
Visually, TDR waveform for an open circuit termination will reach the full amplitude of the original TDR step after 2 roundtrip delays from the TDR sampling head to the open termination. Short termination will be represented by a waveform that goes to 0 V, whereas a matching termination (50 Ohm) will stay at half the initial step voltage. Impedances with values that are between open and 50 Ohm, and 50 Ohm and short (0 Ohm) will be represented accordingly. One immediately notices that there is more resolution for computing termination values between short (0 Ohm) and 50 Ohm than there is between 50 Ohm and open.



TDR users have used this visual analysis for years. The same analysis can be applied not only qualitatively, but also quantitatively.

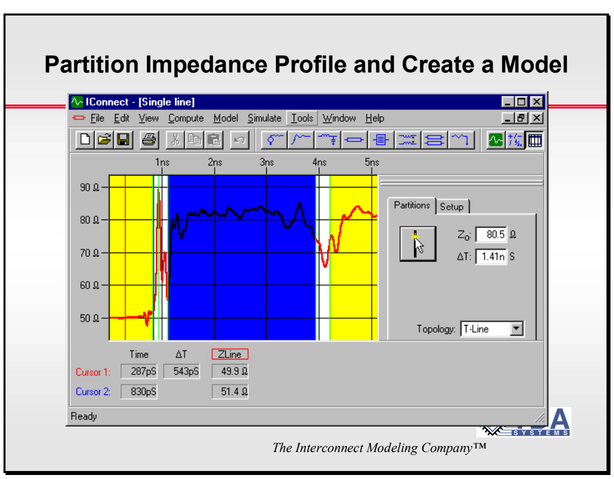


Differential TDR measurements can come in handy when it is difficult to achieve good reference to a ground plane, or when a differential line analysis must be performed. A virtual ground plane, created by two TDR sources of opposite polarity, arriving simultaneously at a device under test with clear symmetry, helps achieve the desired measurement results.

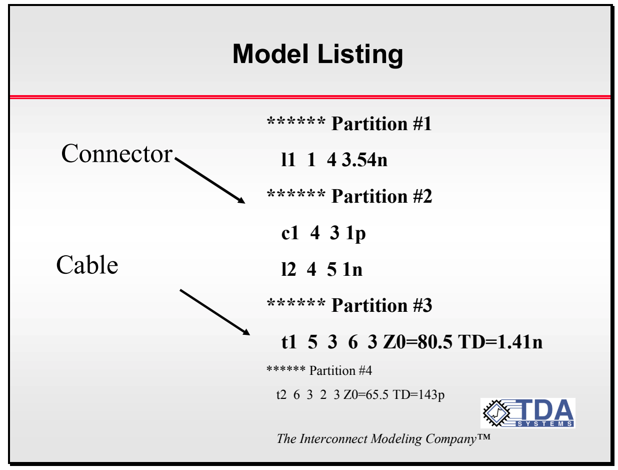


First, we acquire the Device Under Test (DUT) TDR waveform on channel 1 of the TDR oscilloscope, into IConnect® waveform viewer, with only channel 1 TDR stimulus being turned on. Reference short and open waveforms, as well as reference 50 Ohm termination, are acquired under the same conditions. Having acquired the TDR waveforms, we notice that the reference short waveform (short.wfm) has ringing, which can cause problems with the consecutive computation of the impedance profile. Because of that, we may want to use reference open to compute the impedance profile, since in this case the quality of the reference short may not be sufficient. Reference short also includes some of the cable connector effects in the reference waveform, which may not be desirable. We want to be able to model these connector effects, not remove them from the modeling session but including them into the reference waveform.

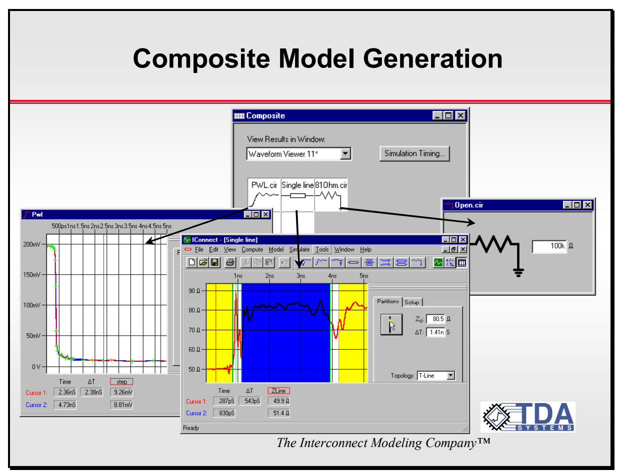
Termination can be handy to correct for some imperfections in the fixturing. However, in many cases it may actually hurt rather than help the measurement due to insufficient measurement repeatability.



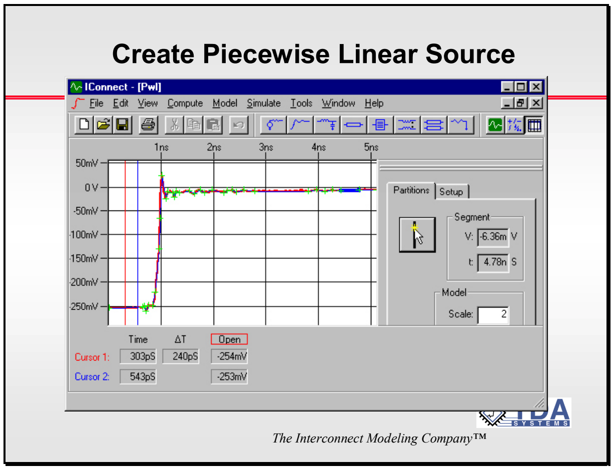
IConnect® computes the true impedance profile for the DUT based on the DUT TDR waveform and the reference step waveform. The computed impedance profile is partitioned into segments, and appropriate topologies are selected for each segment (transmission line, LC, CL, LCL etc.). The software automatically computes the values for each topology.



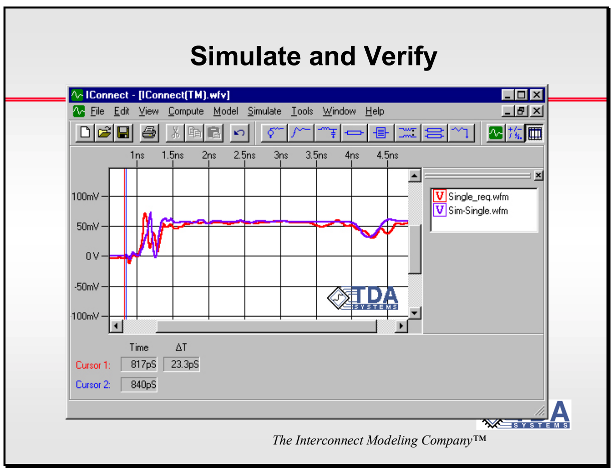
Once the model is saved, IConnect® outputs a SPICE listing that can be directly used in simulations.



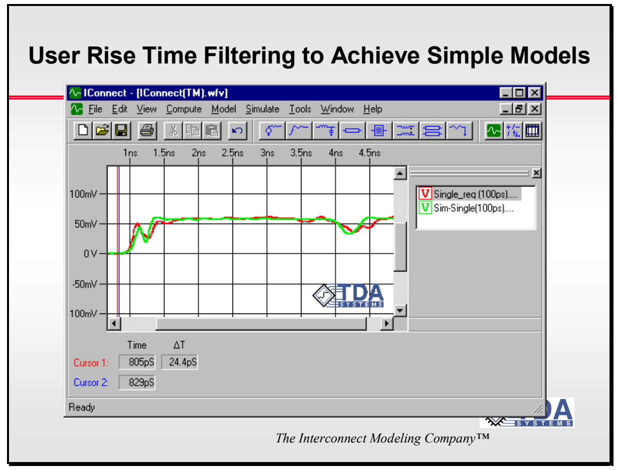
The model can then be verified using an integrated interface to SPICE. The extracted model is complemented with a piecewise linear source that accurately represents the TDR oscilloscope incident step waveform during the simulation, and the same termination as was used during the measurement. The resulting IConnect® composite model for the DUT can be simulated using an integrated interface to a SPICE simulator.



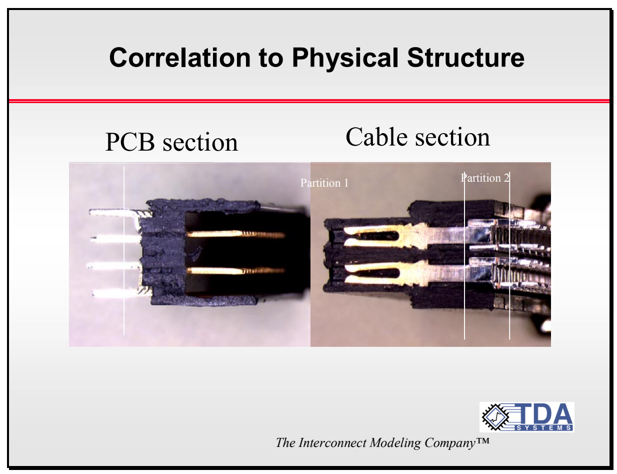
Piecewise linear model for the TDR source is based on reference step waveform (open in this case).



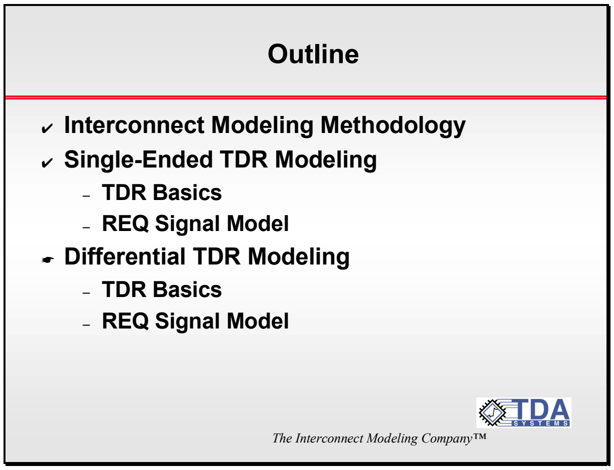
After the model is simulated, the simulated data is returned into IConnect® software waveform viewer and can be easily compared to the measurement data. Since our stimulus and termination conditions are the same for the simulation and measurement, the only discrepancy is due to the computed model, which can be easily adjusted to correct for these discrepancies.

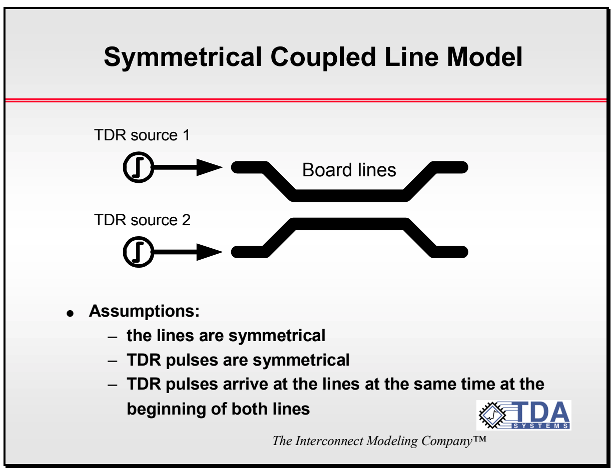


To ensure that the model is no more complex than required, simulated and measured data are filtered with 100ps rise time filter. The discrepancies between the model and simulation are almost gone. No more refinement is required to the model, and the model should perform satisfactorily at 100ps or slower rise time.

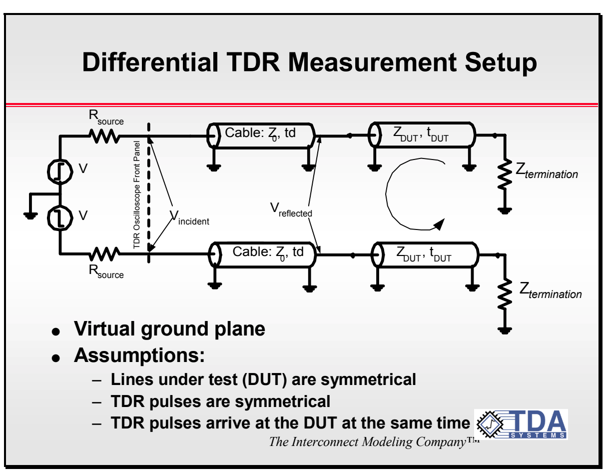


It is important to see if the extracted model makes sense when compared to the physical device geometry. In this case, the deduced correlation to the IDC connector geometry is shown on the cable section of the connector. The mating PCB section of the connector is included in this mental analysis.

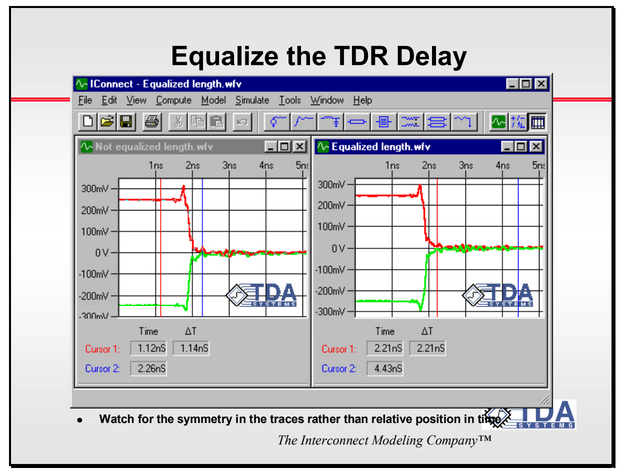




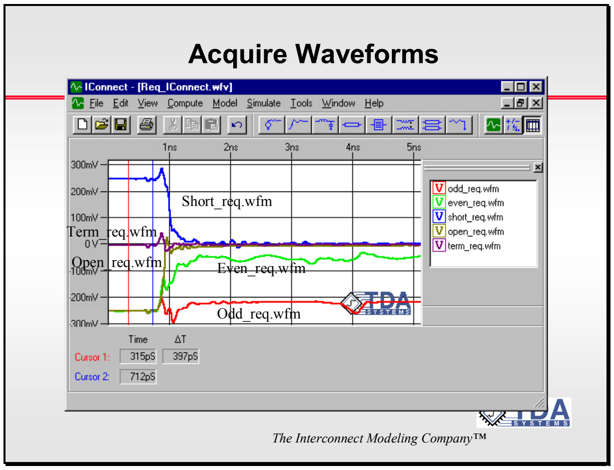
To model differential lines on a board, a symmetric coupled line model can be used. The assumptions listed on this slide, however, must be met.



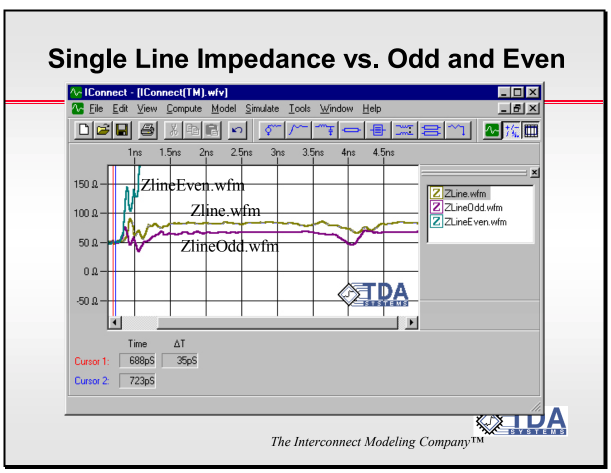
Differential TDR measurements can come in handy when it is difficult to achieve a good ground plane reference, or when a differential line analysis must be performed. A virtual ground plane, created by two TDR sources of the same shape and opposite polarity arriving simultaneously at a DUT interface, helps achieve the desired measurement results. We mentioned previously that TDR measurement accuracy suffers from multiple reflection effects when multiple discontinuities are involved in the measurement. The true impedance profile of the DUT can be obtained, however, through the inverse scattering algorithm discussed above. Based on the incident step and TDR response of the system, the multiple reflections can be dynamically deconvolved from the TDR response.



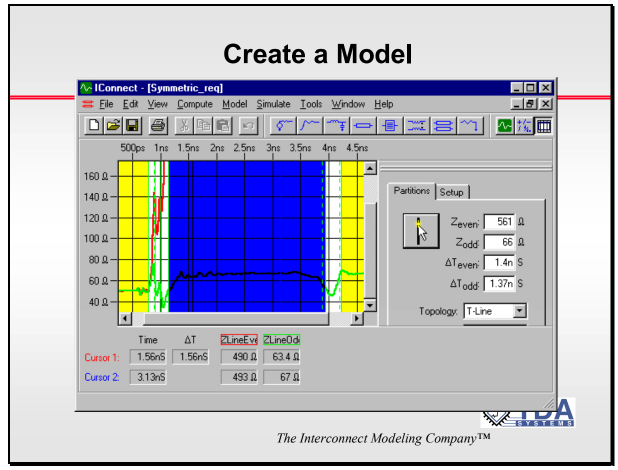
First action required when performing the differential measurements is to ensure that the signals arrive at the DUT at the same time. One has to keep in mind that anything one measures on TDR oscilloscope reflects the round-trip delays and the scope acquisition offsets, and because of that it is easier to equalize the line length of the DUT measurement interface by observing the waveform shape in differential mode, rather than absolute delay. To ensure that the signals arrive to the DUT at the same time, connect a reference short in place of the DUT and vary the TDR stimulus delay, observing the waveform shape. When the signals look symmetric (the picture on the right), the goal is achieved.



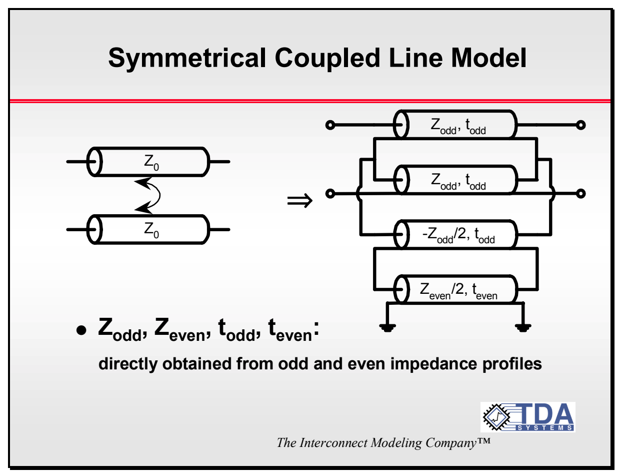
Now, we acquire the DUT TDR waveforms on channel 1 of the TDR oscilloscope, into IConnect® waveform viewer, with TDR being in differential and common mode. In addition, we acquire the reference short and open waveforms in differential mode, as well as reference termination. Having acquired the TDR waveforms, we notice that the reference short waveforms (blue), again, has some ringing. Because of that, again, we will use reference open to compute the impedance profile.



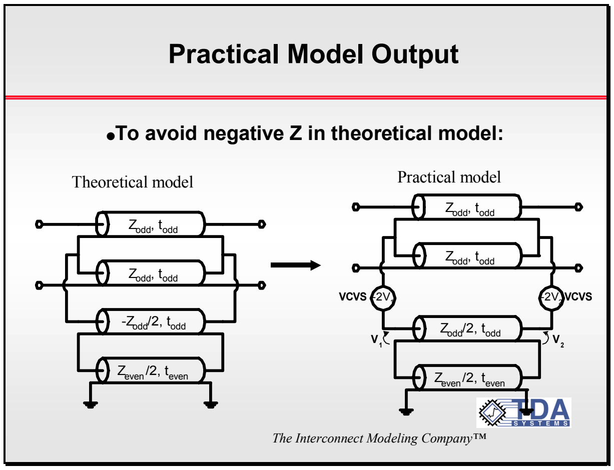
It is important to know that the impedance of single line will always be different from impedance of a single line in a differential pair when the two lines in the pair are driven with differential or common mode signals. Odd mode impedance (impedance of a single line when the pair is driven differentially, purple waveform) will always be lower than the impedance of a single line due to interaction and energy transfer between two lines, common mode impedance will always be higher.



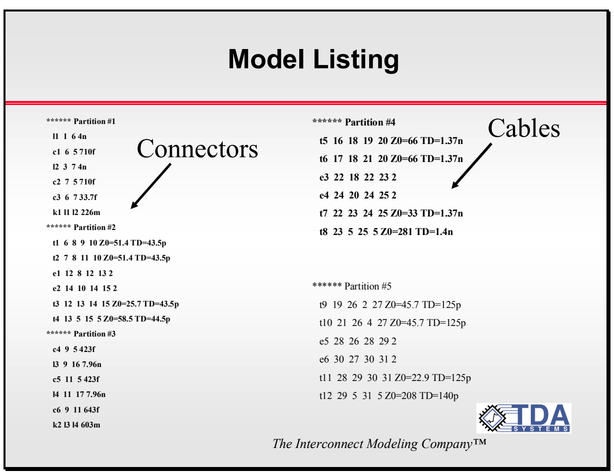
Again, the impedance profiles (for both odd and even mode waveforms) are computed in IConnect®, and a model is created based on simultaneous partitions of even and odd impedance profiles.



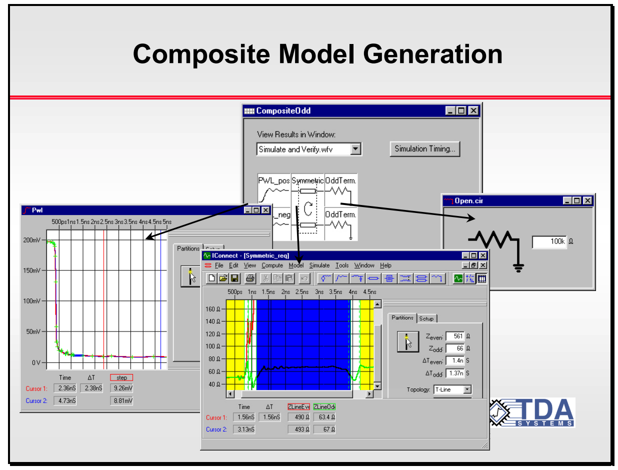
This is a simple and accurate symmetric coupled lines model obtained from even and odd mode analysis. This model is accurate and mathematically rigorous; the only disadvantage is that you have to use 4 lines to model the coupled line structure. Recommended self test: demonstrate using basic circuit analysis techniques that this equivalent circuit will accurately propagate even and odd mode excitation (hint: the circuit will reduce to even only and odd only impedances in each case).



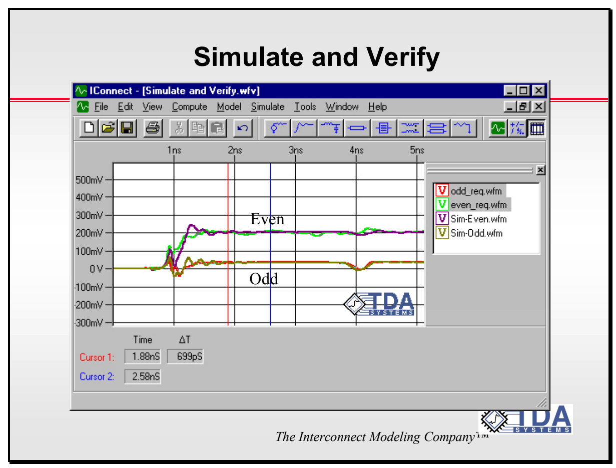
To avoid the negative impedance in the theoretical model, which may not be properly simulated with an off-the-shelf SPICE simulator, the model is converted using Voltage Controlled Voltage Sources (VCVS). Effectively, the VCVSs invert the voltage on the transmission line in question, without affecting the current; positive current resulting from negative voltage is, effectively, producing the negative impedance effect.



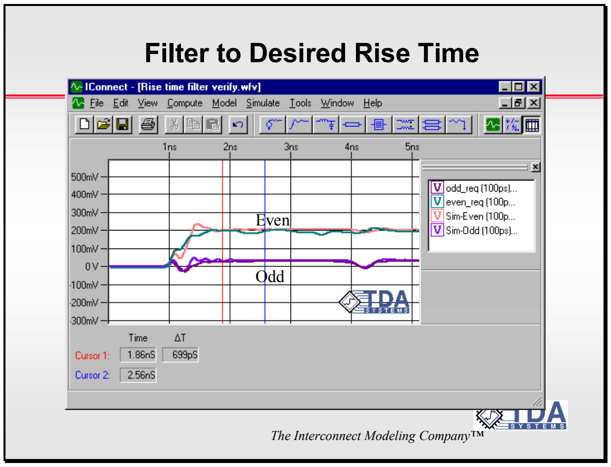
When the model is saved, IConnect® outputs the listing that represents the differential circuit discussed above.



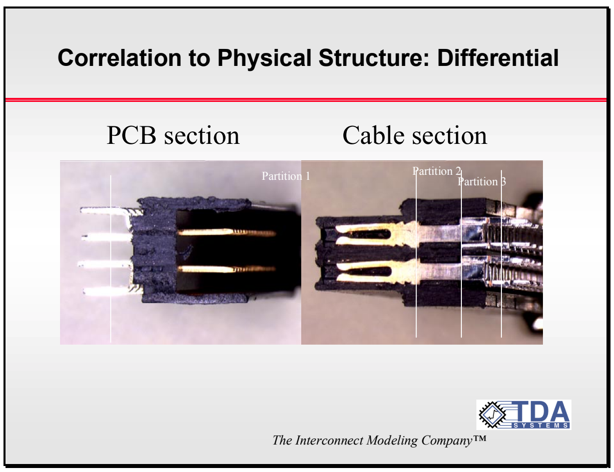
The model can then be verified using an integrated interface to SPICE. The extracted model is complemented with a piecewise linear source that accurately represents the TDR oscilloscope incident step waveform during the simulation, and the same termination as was used during the measurement.



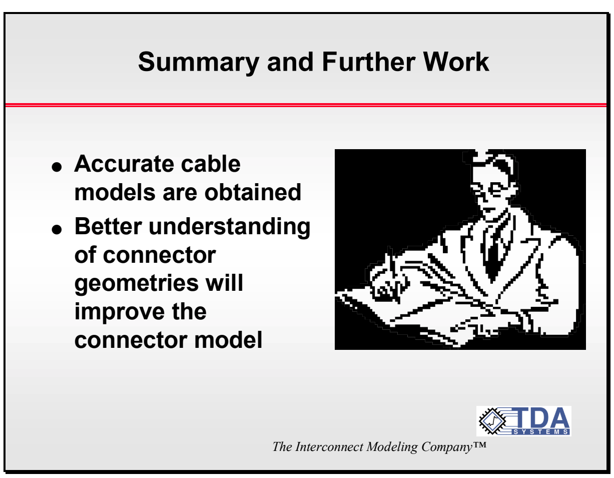
Both even and odd mode excitation are simulated and compared to the measured data. Here, we can observe very good correlation between simulation and measurement.



At the 100ps rise time, this correlation improves even further.



Correlation analysis between the electrical model and the physical device geometry is given for the differential model, similarly to that analysis performed on the single-ended model.



Transmission line equation reference

$$Z_0 = \sqrt{\frac{R + jwL}{G + jwC}} \approx \sqrt{\frac{L}{C}}$$

$$V_p = \frac{1}{\sqrt{LC}}$$

$$L = Z_0 \cdot t_p \qquad C = \frac{t_p}{Z_0}$$

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Differential Transmission Line

$$Z_{even} = \sqrt{\frac{L_{self} + L_m}{C_{tot} - C_m}} \qquad Z_{odd} = \sqrt{\frac{L_{self} - L_m}{C_{tot} + C_m}}$$

$$t_{even} = \sqrt{(L_{self} + L_m)(C_{tot} - C_m)}$$

$$t_{odd} = \sqrt{(L_{self} - L_m)(C_{tot} + C_m)}$$

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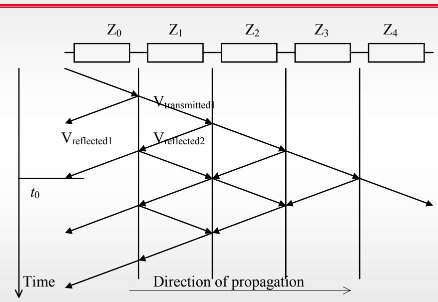
TDR Multiple Reflection Effects



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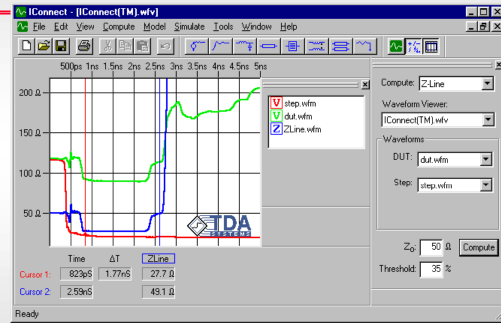
We mentioned previously that TDR measurement accuracy suffers from the multiple reflection effects when multiple discontinuities are involved in the measurement. True impedance profile of the DUT can be obtained, however, through an inverse scattering algorithm reported by several authors. Based on the incident step and TDR response of the system, the multiple reflections can be dynamically deconvolved from TDR response; because of that, another name used for this algorithm is "dynamic deconvolution."

Z-line Example



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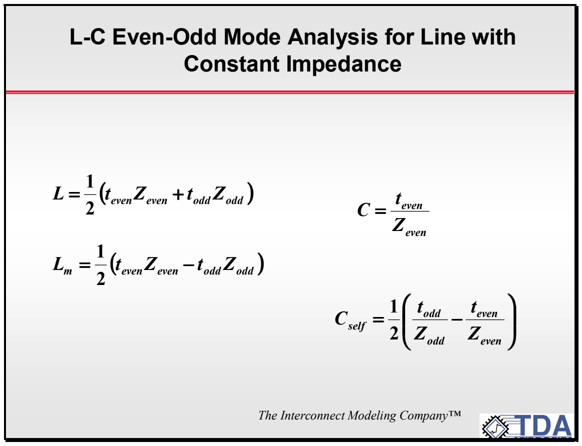
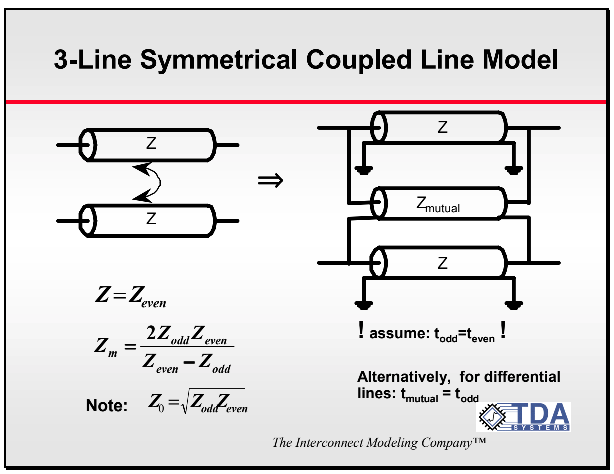
To compute the impedance profile waveform, both the incident and reflected waveforms must be known. The reflected waveform is the TDR measurement of the DUT. The incident waveform, on the other hand, can be computed in several ways. The easiest is to compute it from an acquired reference short or open waveform, where a short or open termination is connected at the interface between the instrument cables (probes) and the DUT, in place of a DUT. A short termination typically has less reactance, but an open termination can be easier to measure repeatedly.

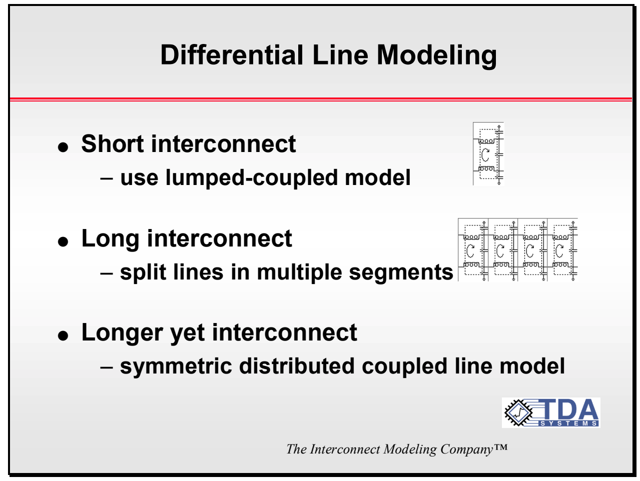
The green (upper) waveform is the DUT TDR waveform; by observing this waveform alone, one could conclude that it represents a series of transmission lines of different impedance, going through multiple discontinuities on the board. The reality is, however, that there is only one nominally 25 Ohm line involved, surrounded by two very short 50 Ohm lines, and terminated at the far end with an open. The true impedance profile (blue waveform), computed by TDA Systems' IConnect® software automatically, immediately shows the correct impedance profile of the DUT structure; the actually impedance of the middle section is 26.9 Ohm, as displayed by a cursor impedance readout.



L and C values for electrically short or lumped systems can also be easily computed from even-odd impedance profiles.



A simplified version of the same model can be used if one can assume that $t_{odd}= t_{even}$ - or if one can focus on one of the two modes of propagation and disregard the other. For example, in the case of differential signaling schemes, mainly the differential mode is excited. Therefore, one can assume that $t_{mutual}=t_{odd}$ and simplify the model.



To summarize, there are several options for modeling differential lines, which are outlined above.

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