Application Note

Characterization of Differential Interconnects from TDR Measurements

Introduction

Differential signaling schemes are a common approach to achieving higher noise immunity for critical signals in a high-speed digital design. Measurement and modeling of the transmission lines carrying differential signals, however, pose several different challenges that need to be addressed in order to achieve an accurate picture of differential signal transmission in digital system design and simulation.

Differential line signaling and analysis

"Differential signaling" means that two transmission lines and two signals are used to transmit a single data bit from a driver to a receiver. The lines are not independent; when the signal on one line is logical low, the signal on the other line is logical high, and vice versa. In addition, the two lines are typically laid out quite close to each other and exhibit coupling of signal energy from one line to the other to a varying degree.

The reason we may choose to sacrifice precious space on a circuit board is to allow us to transmit the signals between a driver and a receiver in a situation where a clean, reliable common ground between the driver and the receiver is not available. Examples are when the path between the driver and the receiver traverses a large distance, or does not run over a reasonably continuous ground plane.

As an additional benefit, differential signaling schemes provide increased immunity to the common-mode noise in the system, because the receiver only sees relative (differential) voltage between the two transmission lines in the differential pair. In addition, because the fields radiated by each signal are of opposite polarity, they cancel out to significantly reduce the radiated energy, the main cause for electromagnetic interference (EMI) between devices. Differential signals are also less sensitive to the attenuation of the signal in the transmission medium, because the receiver design typically allows sufficient gain to reproduce the original signal [1]. Typical applications of differential signals are low-voltage differential signaling (LVDS), Fiber channel, disk drive flexible interconnect, and a Rambus™ clock signal.

Differential line circuit description

Differential lines are typically routed fairly close together. Because of the interaction (coupling) between the lines, propagation of the signal through the differential pair can not be described by a single impedance, capacitance or inductance value. Instead, set of L and C matrices is used to describe an electrically short section of transmission line [2]:

$$C = \begin{bmatrix} C_{tot} & -C_m \\ -C_m & C_{tot} \end{bmatrix} \quad L = \begin{bmatrix} L_{self} & L_m \\ L_m & L_{self} \end{bmatrix} \qquad (1)$$

where $C_{tot} = C_{self} + C_m$. The above quantities are related to a physical circuit by the diagram in Figure 2 of an electrically short section of a transmission line pair, in which C_{self} is the capacitance of one line to ground, and C_m is the mutual capacitance between lines. The quantities L_{self} and L_m are the self inductance of one

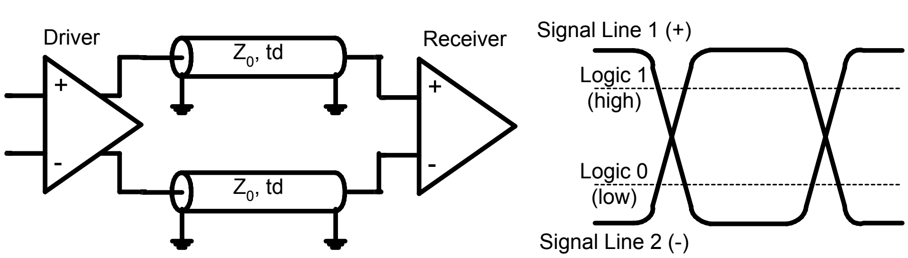

Figure 1. Differential signaling. Two signals are used to transmit a single bit of data from the driver to the receiver. When the signal on one line is logical high, it is logical low on the other line, and vice versa.

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line and the mutual inductance between lines, respectively. Electrically short simply means that the time required for a signal to transit the section is much shorter than the rise-time of the signal itself. Multiple sections of this type may be cascaded in order to represent a transmission line pair that is electrically long.

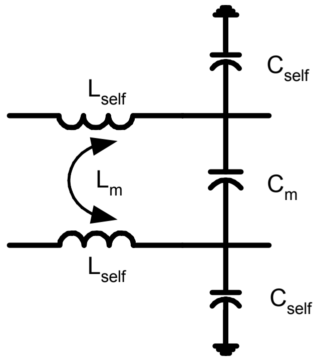

Figure 2. An electrically short section of a differential transmission line pair

In many applications, particularly if a large number of the sections in Figure 2 are required to represent a circuit, it makes more sense to use differential and common mode impedances and delays to describe differential transmission line behavior. *Differential impedance* is defined as the impedance measured between two conductors driven differentially, i.e., with identical, but opposite-polarity signals — as opposed to the *odd mode impedance*, which is the impedance of a single conductor (transmission line) in a differential pair when the two conductors are driven differentially [3]. *Even mode impedance* is the impedance of either conductor when the differential pair is driven with identical, same-polarity (even or common mode) signals. *Common mode impedance* is the impedance of the two conductors in a differential pair, when both conductors are driven with a single common mode signal, relative to ground.

In some cases, the differential impedance alone is the parameter of interest to a board designer. Based on the differential impedance value, he or she can make a first cut at predicting the propagation of the signal through the differential pair. In addition, the common mode impedance can help analyze the common mode noise rejection; if the common mode impedance is much higher than the differential impedance, the common mode rejection will be high.

For analysis purposes, a differential pair is often described according to its odd- and even-mode impedances and delays, which are closely related to differential- and common-mode counterparts, and can be computed using the following equations.

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

$$Z_{even} = \sqrt{\frac{L_{self} + L_m}{C_{tot} - C_m}} \qquad (2)$$

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

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

Using the definitions above, it is easy to conclude that

$$Z_{differential} = 2 \cdot Z_{odd}$$

$$Z_{common} = Z_{even}/2 \qquad (3)$$

with the delays for differential and odd mode, and common and even mode, being equal. Note that for the case in which no coupling between the lines in the differential pair is present, both even- and odd-mode impedance values simply collapse to the characteristic impedance of each line, given by

$$Z = \sqrt{\frac{L_{self}}{C_{self}}} \qquad t = \sqrt{L_{self} C_{self}} \qquad (4)$$

In most practical cases, the even and odd mode delays will also be different (Figure 3).

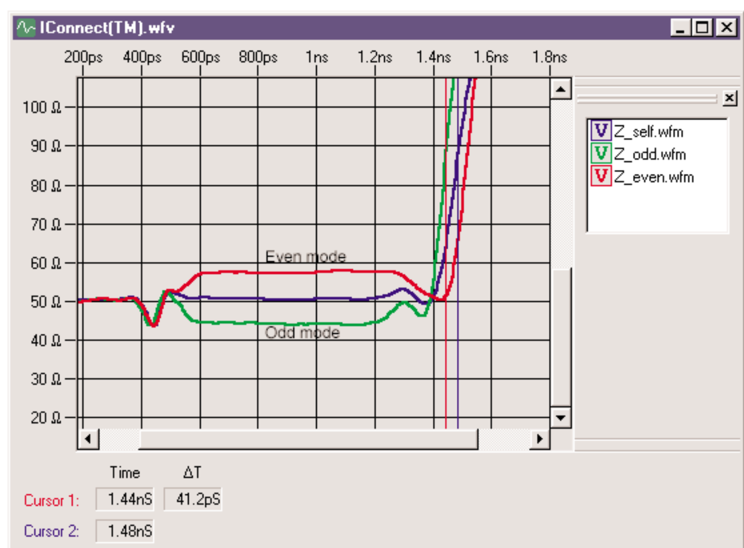

Figure 3. Even and odd mode impedance profiles displayed in the IConnect software waveform viewer. Both even and odd mode impedances and delays are clearly different

Differential line simulation in a SPICE or IBIS simulator

Since a differential pair, as we discussed above, is just typically a pair of closely routed symmetric and coupled transmission lines, it would be logical to model them as a symmetric coupled pair. A coupled L-C matrix is typically used to describe such a coupled transmission line structure. However, a large number of lumped LC components will be required to simulate transmission lines that are electrically long, which is often the case when a differential transmission scheme has to be used.

An alternative, of course, is to use a distributed approach. Single line impedance clearly is not enough to characterize the differential transmission line pair, as one needs to take line coupling into account. Differential impedance alone is not enough either, since one also needs to take into account common mode rejection and propagation.

The solution comes from a relatively simple mathematical analysis of the differential pair, which can also be viewed as a symmetric coupled transmission line pair. The model shown on Figure 4 and presented in [4] is an accurate representation of a coupled transmission line pair based on its even and odd mode impedances. It is a simple exercise in circuit analysis to demonstrate that this transmission line configuration will present twice the odd mode impedance to a differential signal, and two separate even mode impedances to a common mode signal. Since any signal can be decomposed into its differential and common mode components, this model will predict propagation of any combination of differential and common mode signals, accurately representing the behavior of the differential transmission line pair.

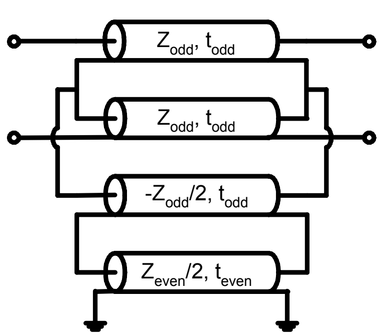

Figure 4. Differential pair model based on the even and odd impedance and delay values

One disadvantage of this 4-line model is its relative complexity. In addition, this model is difficult to extend to a case of more than 2 coupled lines. If it is known, however, that the common mode impedance is significantly larger than the differential mode impedance, the common mode signal will be mostly rejected, and mainly the differential signal will be observed at the receiver end. The high common mode rejection will make the difference in differential and common mode signal delay irrelevant due to the small amplitude of the common mode signal, and will allow us to use a simplified model illustrated on Figure 5. Here, $Z=Z_{even}$, and Z_{mutual} can be found as

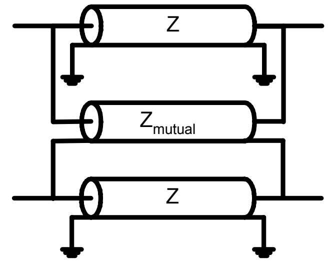

Figure 5. Simplified differential transmission line model

$$Z_{mutual} = \frac{2 \cdot Z_{odd} \cdot Z_{even}}{Z_{even} - Z_{odd}} \quad (5)$$

Again, under the assumption that $t_{odd}=t_{even}$, it can be easily shown that this model will accurately represent both differential and common mode signal propagation through the differential pair.

Both the four-line and three-line models can be easily utilized in a SPICE or IBIS simulator, making them extremely usable for high-speed differential interconnect modeling and simulation. The negative-impedance line in the four-line model may be realized with dependent voltage sources, if care is taken to ensure that the resultant model represents a physically realizable structure (discussed in the "Even and odd mode analysis" section). The resulting accurate models help the designer to achieve a better understanding of his differential interconnects, resulting in higher performance system design.

Obtaining differential line model from TDR measurements

Differential TDR measurement basics

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

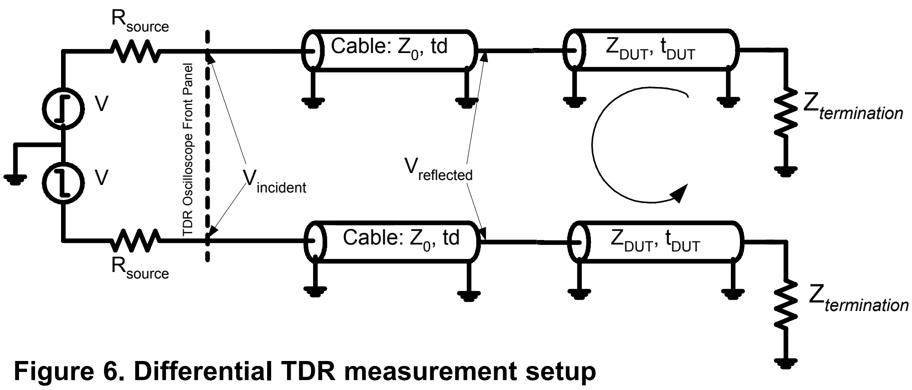

Figure 6. Differential TDR measurement setup

DUT can be obtained, however, through an inverse scattering algorithm reported by several authors [5], [6]. Based on the incident step and TDR response of the system, the multiple reflections can be dynamically deconvolved from the TDR response.

Even and odd mode analysis

The odd impedance profile is obtained from a differential TDR measurement with two TDR sources of opposite polarity, and the even impedance profile is obtained through a measurement with two TDR sources of the same polarity. In each case, only a single TDR channel needs to be acquired. A differential reference short is also used for computing the impedance profile. The reference short waveform is most easily obtained by disconnecting the DUT and connecting the two signals to ground in close proximity of each other, or connecting them directly to each other and then connecting them to ground. Once the even and odd impedance profiles of the differential pair are obtained, the model shown on Figure 4 or Figure 5 can be easily computed.

In addition, the L-C matrices can be easily extracted from the even and odd TDR impedance profiles for a line with constant impedance using the following equations:

$$
\begin{aligned}
L_{self} &= \frac{1}{2}\left(Z_{even}t_{even} + Z_{odd}t_{odd}\right) \\
L_m &= \frac{1}{2}\left(Z_{even}t_{even} - Z_{odd}t_{odd}\right) \\
C_{tot} &= \frac{1}{2}\left(\frac{t_{odd}}{Z_{odd}} + \frac{t_{even}}{Z_{even}}\right) \\
C_m &= \frac{1}{2}\left(\frac{t_{odd}}{Z_{odd}} - \frac{t_{even}}{Z_{even}}\right)
\end{aligned}
\qquad (6)
$$

From a practical modeling perspective, the capacitor and inductor values from (6), e.g. L_{self}, may be computed if a lumped model is desired. The above equations also point out that if the mutual capacitance C_m is to remain positive, it is necessary that

$$\frac{t_{odd}}{Z_{odd}} - \frac{t_{even}}{Z_{even}} > 0 \qquad (7)$$

A model that does not satisfy this constraint should not be used, since it does not represent a physically realizable structure, and could result in inaccurate simulations.

Differential line modeling example

As an example, a differential pair on an FR-4 board was measured and modeled. The transmission lines in this Device Under Test (DUT) have SMA connectors as an interface to a TDR oscilloscope. The lines are closely coupled (the spacing to the ground plane on the board was half the gap between the lines). The impedance profiles for the same differential pair are shown on Figure 3 above.

After the data was acquired from a TDR oscilloscope, it was processed using the Z-line impedance deconvolution algorithm in the IConnect™ software. As was mentioned previously, it is necessary to have two waveforms to compute the impedance profile: the DUT waveform and the reference step waveform. The reference step waveform for a differential measurement can be obtained by connecting the signals on both of the differential TDR channels together and then to ground, if possible. When using cables with SMA connectors, the easiest way to achieve this measurement is to connect the cables together using an SMA barrel interconnect. Only the waveform on one channel of a TDR instrument needs to be acquired; no additional adding or subtracting the waveforms in the oscilloscope is necessary.

The resulting even and odd impedance profiles are shown on Figure 3, and based on these impedance profiles, one can easily extract the model for the DUT. Note that without the impedance deconvolution algorithm, the impedance profiles are subject to the multiple reflection effects in TDR oscilloscopes and the impedance readout values may not be correct at each point on the TDR trace.

After the impedance profiles have been computed, the impedance profile waveforms are partitioned in the IConnect software Symmetric Coupled Line modeling window (Figure 7). The distributed model is the most appropriate in this case, since the electrical length of the lines approaches or exceeds 1ns. Since we have assumed that in practice there could be significant common-mode propagation on the pair, the more accurate four-line model is more appropriate.

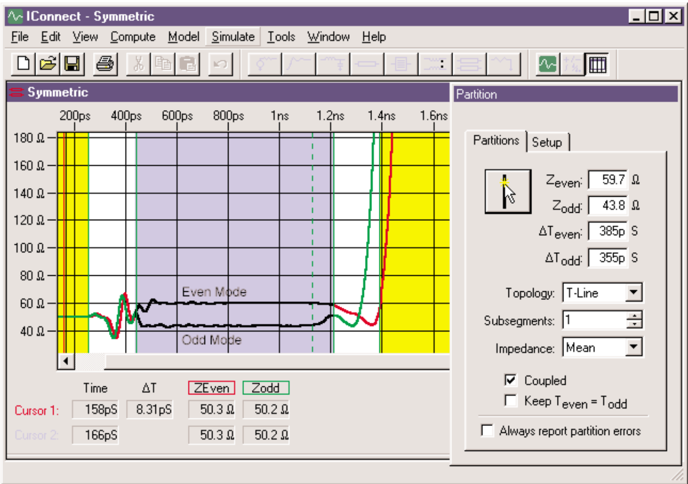

Figure 7. Partitioning the impedance profile waveforms in the IConnect software Symmetric Coupled Line modeling window.

When the model is saved, the equivalent SPICE circuit that describes a model depicted in Figure 4 is obtained. A sample listing of such circuit is given in Appendix I.

To verify the created model, a designer needs to create a composite model in the IConnect software. The composite model complements the extracted DUT model with the source and termination that emulate the TDR measurement source and termination. Using an integrated interface to a SPICE simulator, the designer can simulate this composite model, and based on the resulting simulation waveforms, verify the accuracy of the DUT model. Both even and odd mode stimuli must be used in simulations in order to ensure that the model accurately predicts both even and odd modes of signal propagation (Figure 8). One can see that with the exception of the SMA connectors, which are not part of the differential line, the model accurately predicts the signal propagation. In addition, the connectors can be modeled using lumped circuit modeling capability in the IConnect software.

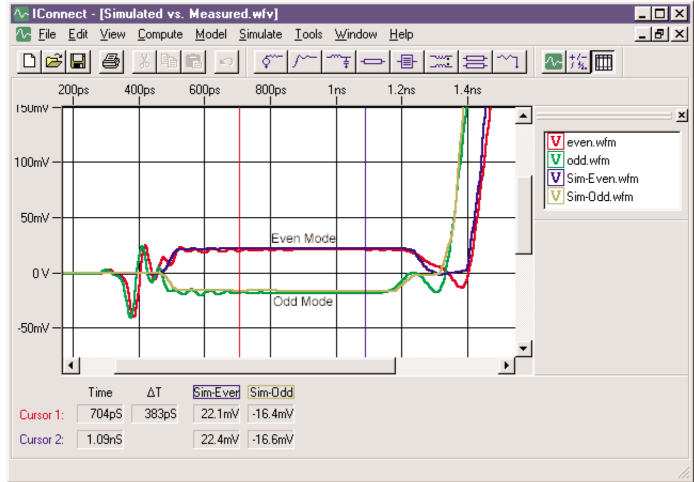

Figure 8. Verifying the differential line model in IConnect software. Simulations with both even and odd mode stimuli are performed using an integrated interface to a SPICE simulator and the simulation results are compared to the measurement data

Even and odd mode analysis can also be utilized for characterization of lumped interconnect structures, even when a single-ended signaling schemes are utilized. Such structures as high-speed connectors, BGA packages, high-performance ATE sockets can be easily modeled using even and odd TDR measurements and equations (6). Based on the even and odd impedance profiles, the L-C matrices for the

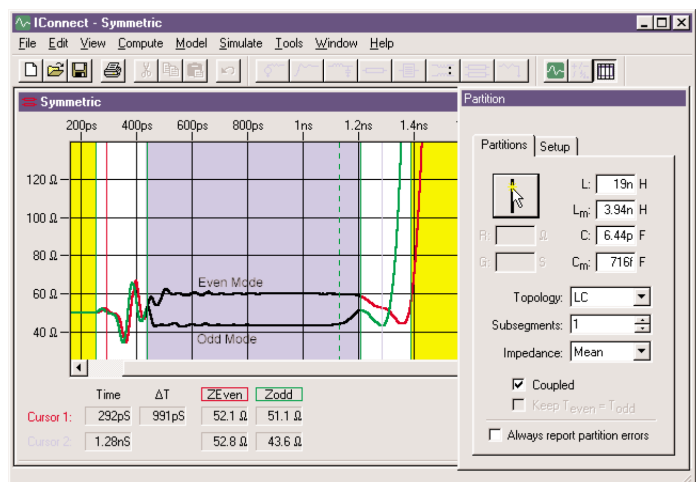

Figure 9. Applying the even and odd analysis to compute L-C matrices for the coupled lines in IConnect software. Note that for long lines a large numbers of subsegments must be used to accurately model the line

coupled structure are easily computed (Figure 9).

Conclusions

We have demonstrated a technique for extracting a distributed coupled line model from Time Domain Reflectometry (TDR) measurements. This model can be easily used in any standard time domain simulator (SPICE or IBIS), and can accurately predict the propagation of a digital signal through a differential transmission line pair. As a result, the digital system simulation will predict the system behavior more accurately, resulting in higher performance system design.

Appendix I. Sample SPICE circuit listing

```
* Name: Automatically Generated
.subckt Symmetric 1 2 3 4 5
****** Partition #1
  t1  1  5  6  5 Z0=49.7 TD=92.3p
  t2  3  5  7  5 Z0=49.7 TD=92.3p
****** Partition #2
  l1  6  8 19n
  c1  8  5 6.44p
  l2  7  9 19n
  c2  9  5 6.44p
  c3  8  9 716f
  k1 l1 l2 207m
****** Partition #3
  t3  8  5  2  5 Z0=49.7 TD=87.5p
  t4  9  5  4  5 Z0=49.7 TD=87.5p
.ends
```

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