Application Note

Practical Characterization of Lossy Transmission Lines Using TDR

Introduction

Losses in digital interconnects were not very important at the lower frequencies, but as the communications and computer system designs are moving into the gigahertz territory, this picture changes rapidly. High-frequency effects such as skin effect and dielectric loss begin to affect signal integrity in these high-speed digital systems in the most profound manner, and therefore must be understood and characterized.

Effect of Losses on Signal Propagation

DC losses, arising from the DC resistance of the conductor in the digital interconnect, will mainly affect the amplitude of the signal as it propagates through this interconnect. High-frequency losses, however, such as skin effect and dielectric loss, will result in smaller bandwidth for the interconnect system. This smaller bandwidth, in turn, will result in signal rise time degradation. If the 3dB bandwidth of the interconnect, that is the bandwidth at which the total signal attenuation reaches 3dB, is f_{3dB}, then the equivalent interconnect rise time can be estimated as:

$$t_{\text{interconnect}} = 0.35 / f_{3dB} \qquad (1)$$

and the rise time of the signal reaching the end of the interconnect can be estimated as:

$$t_{r\,final} = \sqrt{t_{r\,signal}^2 + t_{\text{interconnect}}^2} \qquad (2)$$

Figure 1. Rise time degradation is the result of limited bandwidth in the lossy interconnects

The measurement in Figure 2 below dramatically shows the impact on the signal rise time from the losses in an FR4 substrate. In this example, a step edge with a rise time of 50 ps was launched into a 36 inch long microstrip in FR4. This length is often found in backplanes that have daughtercards connected.

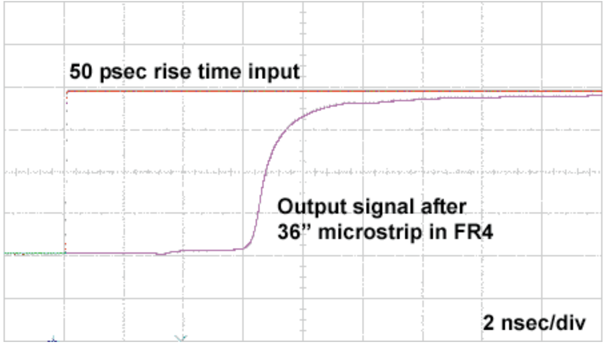

Figure 2. High-frequency losses result in significant rise time degradation and amplitude decrease in 36” FR4 trace

By the time the signal has exited the 36 inch run, the rise time has been degraded to longer than 500 ps. This rise time degradation will result in significant collapse of the eye-diagram. Overall, high-frequency losses, together with the delay dispersion due to crosstalk and pattern dependence, are the main reasons for eye-diagram collapse resulting from the system interconnects. This leads us to the conclusion that obtaining accurate crosstalk models for the interconnects, as discussed in [2], and loss models as proposed in this paper, allow the designer to predict the full effect of the digital interconnect performance on the jitter and the eye-diagram.

Therefore, when evaluating expected system performance, it is critical to take into account the lossy effects and their impact on SPICE or IBIS transient simulations. However, the difficulty arises from the fact that the losses are traditionally analyzed in frequency domain, while the performance of high-speed digital systems is evaluated in time domain. Time Domain Reflectometry and Transmission (TDR/T) measurements, coupled with IConnect(R) TDR modeling software from TDA Systems, come to the rescue to resolve this issue and provide a practical way of analyzing lossy lines and incorporating their properties in time domain simulations.

This application note is based in part on a presentation at DesignCon 2001 [1]

Loss Mechanisms

In presence of losses, the classic equation for the characteristic impedance of a transmission line:

$$Z = \sqrt{L/C} \tag{3}$$

where L and C are inductance and capacitance of the line per unit length, changes to:

$$Z = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{4}$$

where R and G are resistance of transmission line conductor and conductance of the dielectric per unit length, which may vary with frequency. The corresponding equivalent circuit can be described as follows:

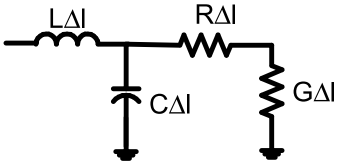

Figure 3. Equivalent circuit for a lossy transmission line segment includes conductor resistance and dielectric conductance, which may be frequency dependent. Δl is the length of the transmission line segment

Inductance may vary with frequency as well, but as we will see, one can account for it in the resistance term.

Skin Effect: Series Resistance

Series resistance consists of the DC resistance term R_{DC} and the high-frequency skin effect term R_{AC} [3]. The DC resistance term can be calculated directly from the geometry of the conductor as:

$$R_{DC} = \frac{\rho}{tw} \tag{5}$$

where ρ is the DC resistivity of the conductor metal, *t* is the thickness and *w* is the width of the conductor.

R_{AC} increases with frequency due to the current crowding on the outside surface of the conductor at higher frequencies. The area close to the surface that continues to support the flow of the current at higher frequencies is called the *skin depth*, and is determined as:

$$\delta = \sqrt{\frac{1}{\sigma \mu f}} \tag{6}$$

where σ is the conductivity of the metal, μ is its magnetic permittivity, and *f* is the frequency at which the skin depth is calculated. If we now use equation (5) to compute the AC resistance, and substitute δ from equation (6) to calculate the cross-section of the conductor at higher frequency, we will discover that the skin effect resistance is proportional to the square root of frequency, and the total conductor resistance at frequency can be calculated as:

$$R(f) = R_{DC} + R_{AC} \cdot \sqrt{f} \tag{7}$$

For the same reasons that resistance changes with frequency, inductance will too. As the current crowds to the outside "skin" of the conductor at higher frequencies, the inductance at the same frequencies decreases as follows:

$$\begin{aligned} R(f) + j\omega L &= R_{DC} + R_{AC} \cdot \sqrt{f} \cdot (1 + j) \\ &= \left(R_{DC} + R_{AC} \cdot \sqrt{f}\right) + j\omega\left(L + \frac{R_{AC}}{2\pi\sqrt{f}}\right) \end{aligned} \tag{8}$$

Dielectric Loss: Shunt Conductance

Dielectric loss is due to the displacement current in the transmission line dielectric, such as FR4. If we describe the frequency dependent complex dielectric constant as:

$$\varepsilon(\omega) = \varepsilon'(\omega) + j\varepsilon''(\omega) \tag{9}$$

the current through the equivalent capacitor formed by the transmission line in the dielectric with dielectric constant $\varepsilon(\omega)$ can be described as:

$$I = C\frac{dV}{dt} + G_d V \tag{10}$$

where *I* is the current through the transmission line, *V* is the voltage applied to that transmission line, *C* is the transmission line capacitance per unit length, and G_d is the dielectric conductance per unit length.

The dielectric conductance can be described using a factor known as *dielectric loss tangent* or *tan*(δ):

$$G_d = \omega \tan(\delta) C \tag{11}$$

where *tan*(δ) is defined as:

$$\tan(\delta) = \frac{\varepsilon''}{\varepsilon'} \tag{12}$$

Typically, *tan*(δ) is constant vs. frequency within the frequency range of interest for common high-speed board materials today, such as FR4 or Duroid®, but the assumption of *tan*(δ) being independent of frequency must be tested for each material. It is important to note, however, that if *tan*(δ) is frequency independent, equation (11) indicates that the dielectric conductivity will be linearly increasing with frequency.

A typical *tan*(δ) value for Duroid®, as given in [4], is a very small factor, about 0.005. It is typically a small factor for most other dielectrics used today, even FR4. As a result, skin effect will dominate the loss and dispersion characteristics in the lower gigahertz range, whereas the dielectric loss will dominate in the upper gigahertz range. For example, for 1oz copper, 8-mil wide trace, ε_r of 3.5 and *tan*(δ) of 0.02 (typical FR4 trace of about 50 Ω impedance), the dielectric loss will begin to dominate near 1 Ghz, as shown in Figure 4.

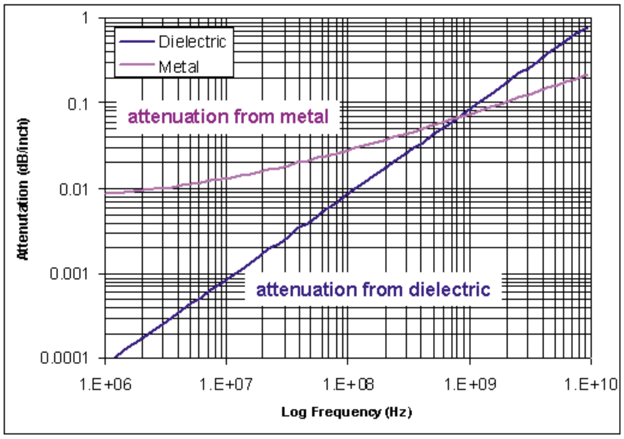

Figure 4. For 1oz copper, 8mil wide trace, ε_r of 3.5 and *tan*(δ) of 0.02 (typical FR4 trace of about 50 Ohm impedance), the dielectric loss will begin to dominate near 1Ghz

Transmission Line Loss Modeling in IConnect TDR Software

From the knowledge about loss mechanisms that we gained in the previous section of this paper, we conclude that if we can determine R_{AC} and G_d, we get the complete high frequency dispersion picture for our interconnect.

A simple approach appears to be to use the equations given in the previous section, or one of the many powerful electromagnetic field solvers on the market, and compute those parameters based on the theoretical data. The problem with this approach, however, is that we all know that accurate information about the dielectric constant, magnetic permittivity, resistivity and often the exact geometry of the transmission line on the board is not easily available. Without such information, any loss parameter extraction will provide inaccurate data and will not be useful for circuit simulations.

A more practical approach is to use TDR/T measurements and extract the loss parameters using IConnect TDR software lossy line modeling function. With IConnect lossy line model extraction, we start with TDR and TDT measurements on the test vehicle, and fit the value of characteristic impedance Z_0, time delay t_d, tan(δ), R_{DC} and R_{AC} to the measured data. IConnect software provides a direct integrated interface to simulation tools and allows the designer to run the SPICE or IBIS simulation on the extracted data, and obtain an automatic comparison between the simulation and the previously measured TDR/T data. This is an easier and more intuitive approach for a digital designer than extracting these parameters from frequency domain measurements.

The first step in the extraction process is to acquire a reference open waveform by taking a TDR of a test fixture or test probe disconnected from the Device Under Test (DUT). If the quality of the open reference is poor and losses in the fixtures, probes and cables are high, it may be difficult to extract the interconnect loss accurately. Therefore, a designer must pay careful attention to the fixtures, probes and cables used in the measurement process. These fixtures and probes ought to be either de-embedded or allow the designer direct access to the DUT. Such de-embedding is relatively easy to use with a TDR oscilloscope.

The next step is to measure TDR and TDT data for the DUT. Good repeatability between the reference measurement and the DUT measurement is very important when extracting losses.

The test vehicle DUT is a 42.5 inch long serpentine microstrip manufactured on FR4 substrate (Figure 5). The spacing between the meander legs was chosen so that the crosstalk is less than 1%.

It is important that the loss extraction must be performed on a DUT without significant changes in line impedance; otherwise, the energy losses due to reflection of the signal at discontinuities between transmission lines of different impedance will be overlayed on top of skin effect and dielectric losses and will make the extraction of skin effect and dielectric loss parameters difficult.

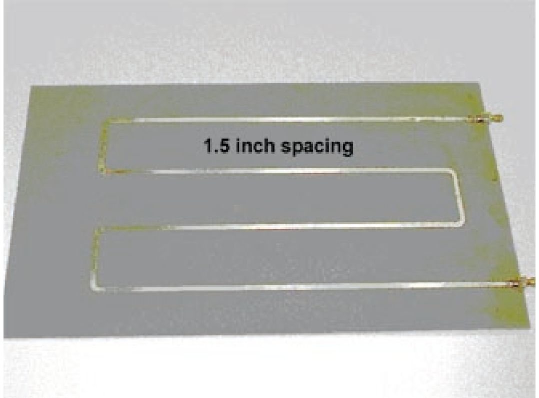

Figure 5. Test vehicle. Specific DUT characteristics were: t=30µm (1oz), w=120mils, ε_r~4.6, tan(δ)~0.02, Z_0~50 Ohm

The parameters extracted by IConnect for this test vehicle are:

R_{DC} = 0.2 Ω/m G = 0 S/m (fixed at 0)

L = 284 nH/m C = 123 pF/m

R_{AC} = 6.9e-5 Ω/(m·Hz$^{1/2}$)), G_d = 1.39e-11 S/(m·Hz)

These values of L and C correspond to impedance of 46.5 Ω and delay of 6.55 ns. Delay of 6.55 ns for 42.5 inch traces gives us an effective dielectric constant of 3.4. This effective dielectric constant value is lower than the typical one for the FR4 bulk dielectric constant, because our test vehicle conductor is on the outer board layer, forming what is known as microstrip line. G_d correlates to tan(δ) of 0.018. The correlation between simulation using these results and TDR/T measurements is shown in Figure 6.

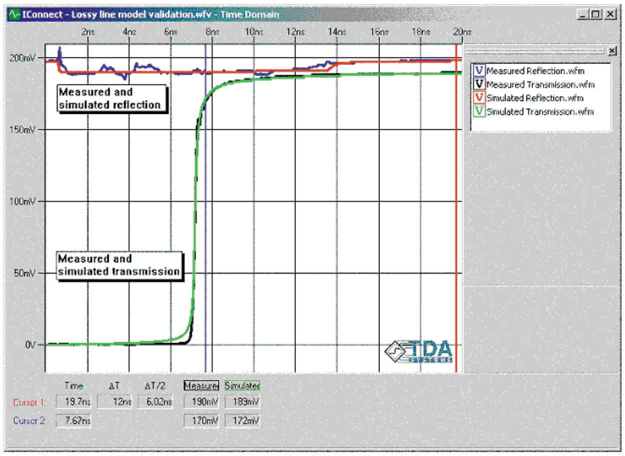

Figure 6. Correlation between the lossy line simulation and TDR/T measurement in IConnect. Lossy line data extracted in IConnect are: Z_0=48 Ω, t_d=6.36 ns, R_{DC}=0.2 Ω/m, R_{AC}=6.9e-5 Ω/(m·Hz$^{1/2}$)), G_d = 1.39e-11 S/(m·Hz), tan (δ)= 0.018. Excellent correlation results are achieved for both reflection and transmission measurements

The additional advantage of the IConnect TDR software lossy line modeling algorithm is that the correlation of the modeling results to measurement is performed in time domain, providing the digital designer with the transient time domain information he or she needs for validating the model. The comparison of simulated and measured data in time domain provides an accurate visual confirmation of the model accuracy to the designer.

It is worth noting that the effect of skin effect resistance on the overall high-frequency loss is small for this test vehicle. It is small due to the large test vehicle trace width, resulting in larger surface area in the conductor where the current can continue to flow even at higher frequencies. The dielectric loss, on the other hand, is independent of the conductor geometry, and depends only on the dielectric material properties. As a result, such a test vehicle is more amenable to characterization of dielectric loss. For a more real-world trace width of 5 mils, the skin effect would have a more profound effect on the overall loss in the interconnect, and we would extract a higher value for R_{AC} in IConnect.

The extraction process may be applied to obtain the differential loss characteristics of the interconnect. In that case, all the reference open, TDR and TDT of the DUT must be acquired with the TDR oscilloscope in differential mode.

Bibliography

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