

Lossy Line Simulation and Analysis

Effect of Frequency Dependent Losses

The effect of frequency dependent losses on the interconnect link performance is primarily in degradation of rise time, amplitude, and eye diagram. The rise time for the signal transmitted through a link slows down as a result of losses, and the signal amplitude decreases. The amplitude, however, does not stay at a permanently lowered level, as it would in a case of purely DC loss. In fact, it gradually creeps up towards the incident signal amplitude. However, the losses can delay the signal to the point that it effectively looks as if it never reaches that incident signal level.

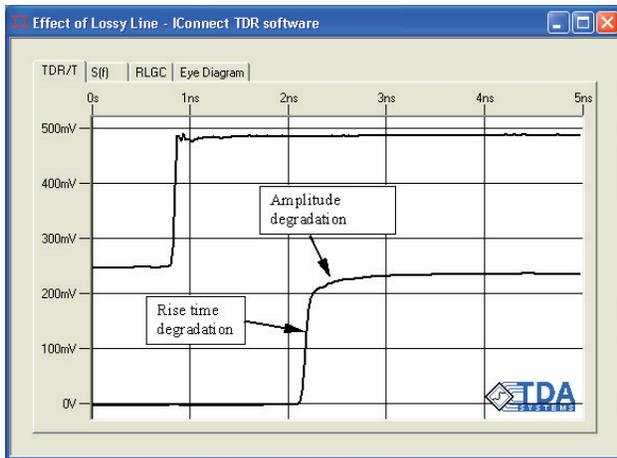


Figure 1. Effect of frequency dependent losses on the digital signal

The eye diagram degradation due to losses in the interconnects may result in a significantly more closed eye, with decreased eye diagram width due to rise time degradation, and decreased height due to amplitude degradation.

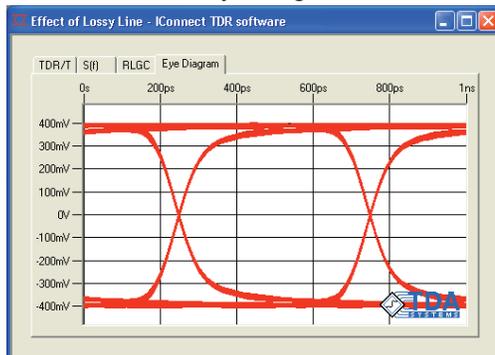


Figure 2. Effect of losses on the eye diagram degradation

Lossy Line Basics

Frequency dependent losses in transmission lines result mainly from skin effect (increasing resistance of copper or other metal conductor at higher frequencies) and dielectric loss (increasing conductance of dielectric at higher frequencies). A substantial amount of information on these effects can be found in the literature. Perhaps the most practical discussion about skin effect and dielectric loss can be found in [1]. In a typical FR4 board, the skin effect becomes important as the clock frequency reaches several hundred megahertz. At those frequencies, dielectric loss is low, but increases faster with frequency, becoming the dominant loss factor in the gigahertz regime, Figure 2, [2].

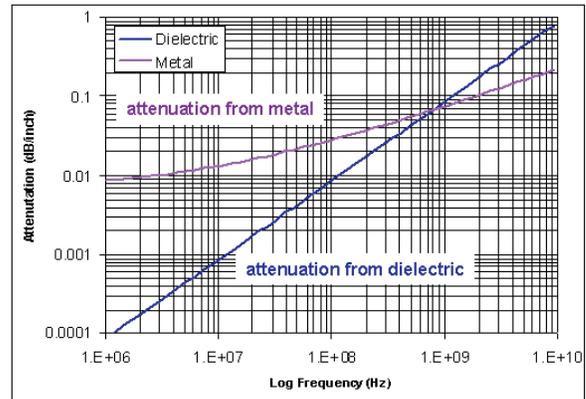


Figure 3. Dielectric loss is low around 100 megahertz, but increases with frequency faster, becoming the dominant loss factor in gigahertz regime [2].

Rise time and amplitude degradation can result in erroneous switching of the receiver, or a failure of the receiver to switch at all. Eye diagram degradation can result in the inability of an interconnect vendor to meet the required industry specification.

Simulating losses in a transmitter/receiver linear regime

Taking a clue from microwave design, the natural way to characterize and simulate losses is by using measured network parameters of the interconnect link. These network parameters can be Time Domain Reflection and Transmission (TDR/T) data or S-parameters (TDT or S21, the insertion loss and TDR or S11, the return loss) of the interconnect link.

These S-parameters can be measured directly using a vector network analyzer (VNA), a time domain reflectometry oscilloscope (TDR) with IConnect® TDR software, or computed using one of the numerous electromagnetic field solver tools. In the latter case, when the S-parameters are computed numerically, their accuracy must be verified using either TDR or VNA. If the driver and receiver can be assumed to be linear, then it is a fairly straightforward task to evaluate the performance of the interconnect link using the IConnect linear interconnect link simulator. A designer can also include in the IConnect simulations the effect of the equalization and pre-emphasis, connectors and vias, IC packages and sockets that reside in the signal path.

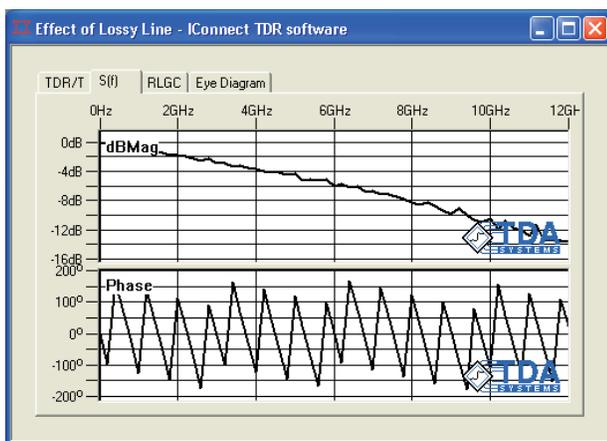


Figure 4. Interconnect losses in frequency domain

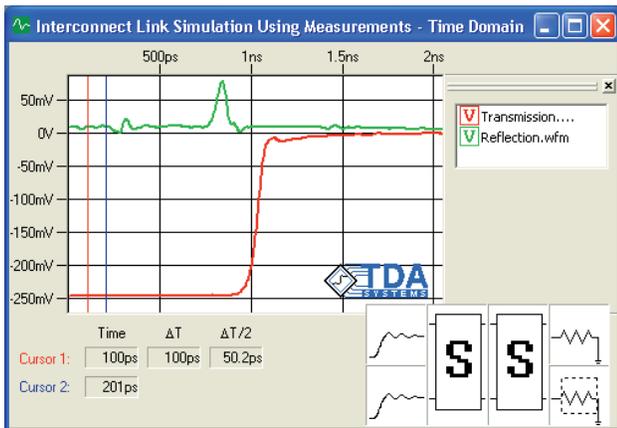


Figure 5. Simulation of interconnect losses in IConnect Link Simulator

However, it is not always possible (rarely possible, as a matter of fact) to assume the linearity of the transmitter and receiver in the interconnect link. If the transmitter/receiver are non-linear, we need to simulate the link performance in traditional signal integrity analysis tools, such as SPICE or IBIS. Because digital design has traditionally been done using time domain simulators, a dichotomy emerged between the time domain approach for digital

system simulations and frequency dependent loss analysis. As a result, at the current level of SPICE or IBIS simulation technology, it has been either impossible or impractical to attempt to simulate measured data directly. Where it is possible, such simulation is not sufficiently efficient to simulate a large backplane-style system. The currently existing alternatives for simulating the effect of losses are:

- Parametric models
- Frequency dependent RLGC data tables
- Behavioral models

Using Parametric Models

Parametric models utilize certain assumptions about the nature of the losses. For example, the W-element in HSpice, which has been thoroughly discussed in the industry, and has equivalents in other major SPICE simulators, assumes square root dependence of the skin effect with frequency and linear dependence of the dielectric loss with frequency.

$$R(f) = R_{DC} + R_{AC}, \quad G(f) = G_d \cdot f \quad (1)$$

where R_{dc} and R_{ac} are the DC and high-frequency resistances of the conductor, G_d is the dielectric loss parameter related to material losses, and f is frequency.

As long as these assumptions hold, the model will be simulated accurately. One advantage of this model is that making the parametric assumptions allows the designer to extract the skin effect and dielectric loss from a single measurement, requiring no exact knowledge about the geometry or material properties that a typical electromagnetic field solver might require. For example, these losses can be extracted from TDR/T or S-parameter measurements using the lossy line extraction routine in IConnect TDR software. The extracted model is listed below, and the correlation between the measurement and the simulated data in time and frequency domains are also shown.

* Time Domain Analysis Systems: IConnect

* Type: Lossy Line

```
.subckt Effect_of_Lossy_Line port1 port2 gnd_
W1 N=1 port1 gnd_ port2 gnd_
RLGCMODEL=Effect_of_Lossy_Line_Model L=1
.MODEL Effect_of_Lossy_Line_Model W MODEL-
TYPE=RLGC N=1
+ Lo=6.96e-008
+ Co=2.50567e-011
+ Ro=0.787
+ Go=1e-9
+ Rs=3.07e-006
+ Gd=6.62667e-012
.ends
```

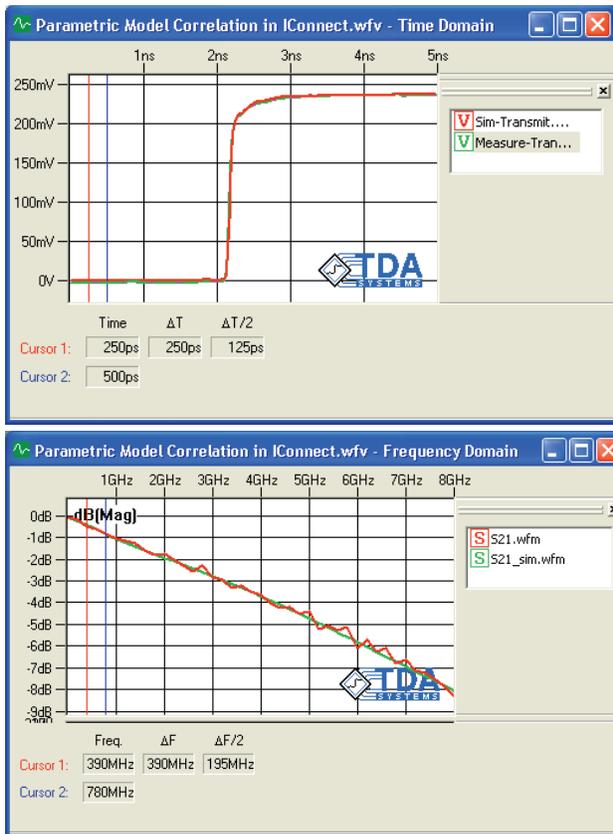


Figure 6. The parametric model extracted in IConnect can provide excellent correlation with measurements for both time and frequency domains

Another advantage of this model is that it can be extracted rapidly, and that it can enable the simulator to simulate losses quite quickly. The disadvantage is that the parametric assumptions do not always hold. Moreover, there have been a number of discussions in the industry about the issue of how accurately a W-element or other parametric model implementations in SPICE can simulate the dielectric loss effects. Even though we find that the accuracy of these simulations is adequate for most applications, when the accuracy of the model is questioned or clearly insufficient, one is forced to consider other alternatives.

Using Frequency Dependent RLGC Tables

Frequency dependent RLGC tables do not make the assumptions that a parametric model might make, but instead provide a table with RLGC values for a number of frequency points. The advantage of this approach is the increased accuracy, but the disadvantages are many. First, it typically takes longer to simulate. Second, unless the same assumptions as for parametric model are made, it is impossible to separate the frequency dependent R from G

directly from measurement, making it necessary to first run a field solver analysis, and then validate it using measurements. Finally, because the simulator is sometimes forced to interpolate the frequency dependent values, which lie between the table data points, it can produce data that make the simulation unstable, violating causality, passivity and stability constraints which must be imposed on the normally causal (does not respond before the time 0), passive (does not amplify signal or generate energy), and stable (does not oscillate) interconnect link.

IConnect TDR software offers a frequency dependent RLGC table output for its lossy line model extractor. To be able to separate the series R and L components from shunt C and G components, however, IConnect is forced to make the same assumption as for its parametric model extraction method. A typical output is shown below. Note that the fact that the dielectric loss parameter G varies with frequency forces the capacitance to vary with frequency as well.

Frequency	R	L	G	C
0.0000E+00	7.8700E-01	6.9960E-08	2.2100E-09	2.9339E-11
4.1100E+07	8.0822E-01	6.9670E-08	1.9028E-04	2.7912E-11
8.2200E+07	8.1517E-01	6.9648E-08	4.0699E-04	2.7574E-11
1.2300E+08	8.2057E-01	6.9639E-08	6.0625E-04	2.7339E-11
...
7.9400E+09	1.0555E+00	6.9605E-08	3.8924E-02	2.5412E-11
7.9800E+09	1.0563E+00	6.9605E-08	3.9145E-02	2.5410E-11
8.0200E+09	1.0572E+00	6.9605E-08	3.9366E-02	2.5407E-11
8.0600E+09	1.0580E+00	6.9605E-08	3.9587E-02	2.5404E-11
8.1000E+09	1.0588E+00	6.9605E-08	3.9807E-02	2.5401E-11
8.1400E+09	1.0596E+00	6.9605E-08	4.0027E-02	2.5398E-11
8.1800E+09	1.0604E+00	6.9605E-08	4.0247E-02	2.5395E-11
8.2200E+09	1.0612E+00	6.9605E-08	4.0467E-02	2.5392E-11
...

Behavioral modeling

Behavioral modeling, as the name implies, aims to reproduce the time and frequency domain behavior of the interconnect link, without paying any attention to the actual topology of the extracted model. Different approaches can be used in behavioral modeling; some examples are discussed in paper, for example [3].

Recently, behavioral modeling received substantially much more attention, because of its potential to extract a model that will reproduce the frequency dependent behavior of the interconnect link exactly. They essentially allow the designer to include the TDR/T or S-parameter measured data for the interconnect into a SPICE or IBIS simulation -something that a signal integrity engineer would very much like to do. In addition, one is not required to de-embed any of the discontinuities in the signal path - they can be included in the model without any extra effort. Despite the fact that for a long

interconnect, such models can contain large number of components, this is a very attractive approach to evaluating the critical link in the digital system.

TDA Systems recently introduced a novel behavioral modeling approach, named MeasureXtractor™, which bases the extraction on measured data, and extracts the model automatically. This measured data can be either TDR/T or S-parameter measurements, and extraction, which is not an optimization algorithm, is quite fast - in some cases nearly as fast as the parametric model extraction. The correlation of such model to the S-parameter data is illustrated in the figure below. Note that it is difficult to distinguish between the model simulation results and the measured data.

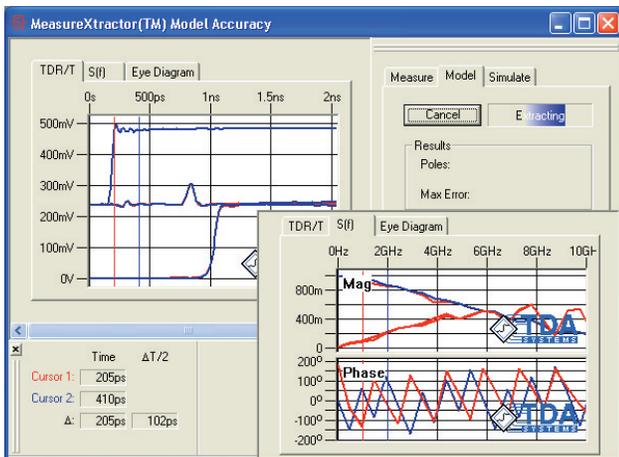


Figure 8. The correlation of measured and simulated TDR and TDT (S11 and S21) data. Simulated data is based on behavioral model extracted by MeasureXtractor™. Note that it is difficult to distinguish between the model simulation results and the measured data.

Clearly, when using a model with this exact level of frequency domain correlation, we essentially are achieving the desired goal that we started with - using our measurement data in evaluating the signal integrity performance of the interconnect. A sample of this model is shown in the table below.

* TDA Systems: IConnect	c35 36 gnd_ 7.15572e-12
* Automatically extracted	r93 37 gnd_ 3932.13
.subckt DUT port1 gnd_	c36 37 gnd_ 7.15572e-12
r1 port1 2 24977.9	r94 38 gnd_ 2488.86
r2 port1 3 23982.9	c37 38 gnd_ 3.07009e-11
r3 port1 4 12111	r95 39 gnd_ 5982.67
r4 port1 5 3124.2	c38 39 gnd_ 2.49077e-11
etc...	.ends

Summary and Comparison

We have presented a number of techniques for simulating frequency dependent losses in interconnect links. **S-parameters**, while being exact representation of frequency dependent, requires forced linearization of inherently non-linear transmitter and receiver, or other complex mathematical techniques, and is not effective for large backplane-style system simulations. **Parametric model** simulates quickly and efficiently and can be efficiently extracted from measurements, whereas its accuracy is sufficient for most applications. However, parametric assumptions do not always hold, and in some applications the accuracy of simulating parametric models in current SPICE implementations may not be sufficient. **RLGC tables** are more accurate than parametric models, but without the parametric model assumptions, could not be extracted from measurement directly. The RLGC table approach results in longer simulation times, and simulator interpolation between and extrapolation beyond frequency points can result in stability and passivity issues. **Behavioral modeling** is exact if implemented properly; effectively, it can be an S-parameter substitute. Models can also include other features embedded into the transmission line structure, such as vias or connectors. However, this approach results in longer simulation times, and passivity, stability, and causality of models must be ensured.

Given this summary, a designer can make a selection of the approach that best suits his or her needs based on the accuracy, extraction efficiency, and simulation speed of the model.

Bibliography

- [1] H.W.Johnson, M. Graham, "High-Speed Digital Design, A Handbook of Black Magic"-Prentice Hall, 1993
- [2]] E. Bogatin, S. Corey, M. Resso, "Practical Characterization, Analysis and Simulation of Lossy Lines," - DesignCon 2001, Santa Clara, CA, January 2001 (TDA Systems Application Note loss-0601)
- [3] S.D. Corey; A.T. Yang, "Automatic netlist extraction for measurement-based characterization of off-chip interconnect," - IEEE Transactions on Microwave Theory and Techniques, Volume 45, Issue 10, Oct 1997, pp 1934 -1940



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