Connector Model Quality Assessment Methodology

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Revision History

Revision Number	Description	Date
001	• Initial Release	September 2011
002	• Updated document title	November 2011

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1 Introduction

This quality assessment methodology document defines the type of models that are used to describe connector behavior and recommends how best to evaluate model accuracy and define the quality (qualification) levels for electrical models.

1.1 Scope

The scope of this document is limited to the quality assessment of connector geometric and electrical models. Via models are outside the scope of this document.

1.2 Reference Documents

This document follows the procedures outlined in ANSI Electronics Industry Alliance (EIA) standards documents.

- The Touchstone specification for s-parameter models is available for download at: http://www.eda.org/ibis/connector/touchstone_spec11.pdf.
- ASCII Text format description (US-ASCII 8-bit), ISO/IEC 8859-1:1998
- HSPICE* Signal Integrity User Guide, W-element modeling of coupled transmission lines
- *PCI Express* Connector Measurement Procedure Specification* (PCI-SIG)
- Miller, D. (2004), *Designing High-Speed Circuits, Advanced Signal Integrity Methods for Engineers*. Intel Press
- Johnson, H. W. & Graham, M. (1993), *High Speed Digital Design: A Handbook of Black Magic,* New Jersey, Prentice-Hall
- Brim, B. & Chitwood, S. (2008, June), *Electrical Modeling and Model Representations for Package Interconnects and Power Delivery Networks*, IBIS Summit Presentation, retrieved from http://www.eda.org/ibis/summit, March 18, 2009.

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2 Model Type, Application and Limits

2.1 Geometric/Material

These models are typically used by the most advanced designers and they are usually distributed only under carefully detailed non-disclosure agreements. The primary objective filled by use of these models is accurate 3D model combination also known as concatenation and electrical performance analysis of the connector+via stack.

A primary customer may want advanced information that enables the customer to optimize their own footprint designs to take advantage of the best characteristics of the connector being developed with custom via structures and board stack-ups. Such objectives can be achieved by use of software capable of analyzing the combination of connector, via and board geometric designs.

The geometric model often does not contain material properties, metal plating types and thicknesses. This information and the 3D models are both required to accurately model the electrical behavior of the structure.

2.2 Scattering Parameter

Scattering parameters provide very accurate and very wide-band details of the electrical performance of a device. They are considered the most accurate information about the electrical performance of the device that is attainable for circuit applications.

Scattering parameters are usually obtained in one of two ways: field solver analysis of a computer model of the mechanical device, and by direct measurement. The most desirable situation is when the field solver solution correlates to the measurements because this provides confidence that both are correct.

These models are typically shared to a broader audience than 3D models. The limitations on these models are more often related to labelling and level of communication as to what they represent and whether or not they correlate to measurements. These models typically run slower in simulations than Curve Fit or W models.

2.3 Curve Fit

Curve fit models, such as rational polynomial models, are typically derived directly from scattering parameters by use of any of several commercially available software products. They can be nearly as accurate as scattering parameters and sometimes enable use of circuit solvers that don't work quite as well directly with scattering parameter models.

These models are typically shared to a broader audience than 3D models. The limitations on these models are more often related to labelling and level of communication as to what they represent and whether or not they correlate to measurements. These models typically run slower in simulations than W models.

2.4 Fast Models (For example, Pole-Residue)

The fast model is preferred by most engineers doing high-speed interconnect circuit design exploring many different product concepts at once. It is not unusual for these designers to have to analyze hundreds of variations and they, the designers, are very sensitive to the time required to complete an individual simulation.

Designers exploring concepts are typically far more interested in a model that is moderately accurate but runs very fast, than a model that is very accurate but runs slow. Their strategy is to use the fast model in analysis searching for corner cases, and when corner cases are identified, use the slower, more accurate model for verification.

These models are typically shared to a broader audience than 3D models. The limitations on these models are that they provide estimates of performance at the cost of accuracy. The models sometimes are of questionable use in exploring and estimating crosstalk. Some information on fast model limitations can be found in the reference documents.

While belonging to the class of curve fit models, the pole-residue model is typically very accurate while remaining nearly as fast, sometimes faster than the W model. This property makes Pole-Residue Models preferred by signal integrity engineers doing SPICE* simulations of high-speed links.

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3 General Requirements

3.1 Geometric Connector Models

IP must be protected or in some way shareable with users of the model.

Model must be shown to be accurate through repeated physical measurements to assess accuracy and variability.

The Model must load correctly in a commercially available field solver without crashing the field solver and with a minimal use of healing algorithms.

The Model must have adequate traceability.

3.2 Connector Electrical Model and SPICE* Time Domain Model

Model must be IP protected and, in some way, shareable with users of the model.

Model must be shown to be accurate through electrical measurements according to the appropriate test specification to assess accuracy and variability.

Model must be causal and passive.

Model be stable and run in typical electrical model software tests:

1. Run with all ports connected to impedance other than nominal.
2. Run for at least 50 nsec of simulated time without crashing (a step size of 2 psec is adequate).
3. Must remain stable when three models are concatenated together and run for at least 50 ns.

The model must have adequate documentation explaining things like assumptions and limitations, and pin mapping the model.

The model must be accompanied by a Model Quality Factor plot showing the area between the measured and the modeled response (see Chapter 7), or some equivalent report showing modeled versus measured performance comparison. For models distributed in advance of hardware, the model must be accompanied at a minimum by a report indicating the the model's conformance to causality, passivity and stability requirements.

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4 Model-Specific Requirements

4.1 Geometric / Material

The geometric model format is ASCII Text

The model will include all elements of the physical structure in such a way as to allow separation of those structures by electrical property and electrical function.

The model will include material properties required for setting up an electrical analysis:

1. Dielectric constant of plastics.
2. Loss tangents.
3. Surface metal thicknesses and their electrical characteristics.

The model must include a reference to any associated non-disclosure agreement.

The model must contain the following traceability information:

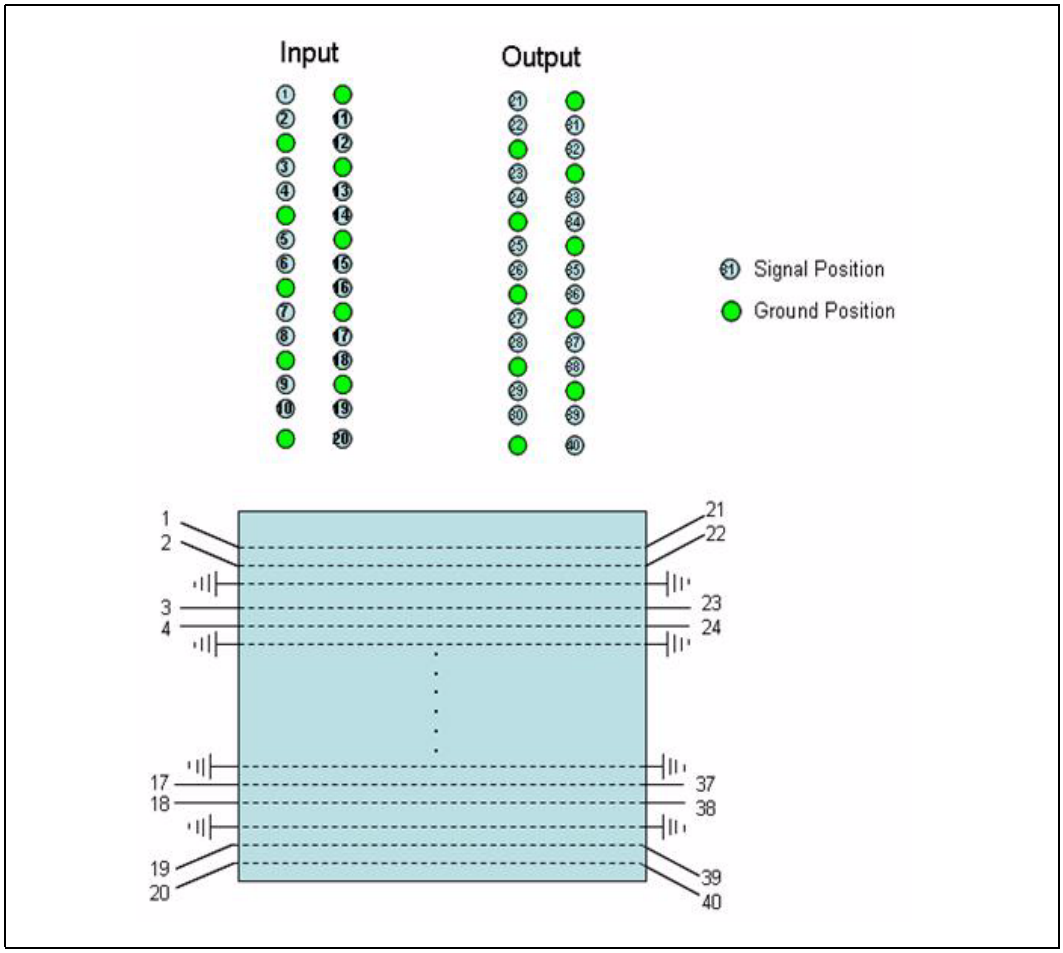
1. Header information (format, size, and revision number).
2. Identification of what is being modeled at Maximum Material Condition (MMC) and Least Material Condition (LMC).
3. A description of which ports of the model correspond to which physical pins.
4. Whether or not the model is correlated to actual measurements.

The files that make up the model will be incorporated into one zip file that may be encrypted as deemed appropriate by the supplier.

4.2 Scattering Parameter

If left side crosstalk aggressors are symmetrical with right side crosstalk aggressors with n pairs per wafer then size of the model should be 2 wafers with 4n input ports and 4n output ports (for example, 5 pairs per wafer requires a 40 port (S40P) model). Where n = number of pairs.

Figure 4-1. Illustration of Scattering Parameter Port Numbering with Symmetrical Pin-out



The file format for the model is Touchstone version 1.1 minimum.

The reference impedance of the Touchstone file will be 50 ohms.

The lower frequency bound of the file will be no more than 50 MHz.

The upper frequency bound of the file will be at least 20 GHz.

The range of frequencies will be covered by at least 400 frequencies and the preferred number of frequencies is 2000.

The format of numerical data can be any of the formats accepted by the Touchstone Specification. (for example, real-imaginary, magnitude angle).

Comments in the Touchstone file will include:

1. Identification of what is being modeled, for example, Right Angle Header.
2. Model revision number and date.
3. Identity of the device being modeled, that is, specific part number.
4. A map of which ports of the model correspond to which physical pin.

5. A description of where the reference planes were placed when the model was created.
6. Whether the model was created by simulation or by measurement and whether or not the model is correlated to actual measurements.
7. Any other information the vendor deems appropriate.

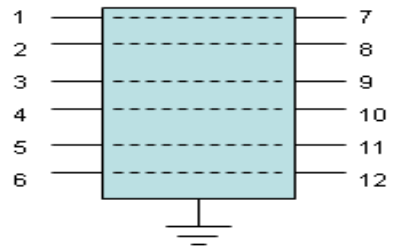
Model data will be defined in terms of single-ended ports; that is, it shall not be reduced to only the differential characteristics.

4.3 Curve Fit

The preferred configuration is a 12-port model in which three pairs are included:

1. The central pair will be intended for use as the signal pair in circuit analysis.
2. The two outside pairs will be the two most significant crosstalk aggressors associated with the central pair.
3. The port arrangement of the model is:

Figure 4-2. Curve Fit Model Port Numbering Illustration



Curve fit models are to be accompanied by documentation that quantifies the location and magnitude of the worst deviations between the model and the source data used in creating the model. Graphs of source and model differences are acceptable for this.

These models are to be stable under the range of conditions that will be found in their typical SPICE application:

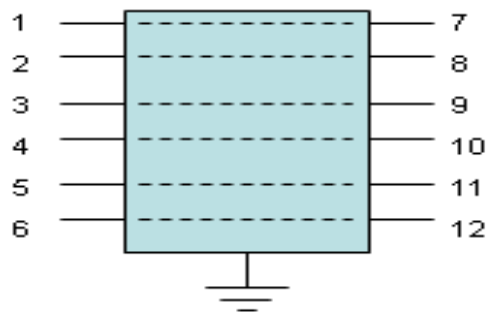
1. At the nominal trace impedance (Zo) of the environment where they are intended to be used.
2. Over a reasonable range of deviations from the nominal environment impedance, at least Zo ±10%.
3. When subjected to a reasonable range of reflections in their intended environment, at least reflection coefficients up to ±0.2.
4. When exposed to a voltage step with a rise time equal to the maximum at which they are intended to operate.
   a. Differential or single-ended.
   b. On any port.

The size of the model should be 2 wafers with 4n input ports and 4n output ports if the crosstalk aggressors on the left side are symmetrical with right side, where n = number of pairs per wafer. For example, 5 pairs per wafer requires a 40 port (S40P) model.

4.4 Fast Models (For example, Pole-Residue)

Fast models are to be 12-port models plus ground return (3 pairs plus ground return) using the port arrangement shown below:

Figure 4-3. Fast Model Port Numbering Illustration



Nodes 1 through 6 are to be one end of the connector, nodes 7 through 12 are the other end of the connector. Node 13 is the ground return.

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5 Quality Metrics

5.1 Geometric/Material

Function and Stability

Must be loadable in Computer Simulation Technology Microwave Studio* or ANSYS HFSS* field solvers without crashing the application.

Accuracy

Geometry must accurately represent the actual part at nominal mated conditions.

If component geometry models are specified at other than nominal condition (that is, nonminal un-mated condition), the geometry must accurately represent the part in that condition.

Content

Separable model consisting of full geometry of the metal contacts ending at the contact-to-PCB interface and the geometry of the thermoplastic housing in which the metal contact resides. Connector geometric models exclude all PC board elements (that is, pad, via structures, and so forth).

Material Characteristics

Contacts – base metal, plating types and thicknesses.

Housing – dielectric constant and loss tangent at 1 GHz.

Other components (that is, ground contacts, shielding) same characteristics as the housing or the contact depending on whether it is metal or plastic.

Identification

Include NDA or other applicable IP identification.

Identify the part as to its size relative to the tolerance band (that is, nominal, max, min) and actuation condition (mated, unmated).

Field solver that was used to test functionality.

Include the date code for the model.

Format

The ASCII formatted (zipped) file contains all elements of the connector model.

5.2 Scattering Parameter

Function and Stability

S-parameter model must be stable, passive and causal (see Chapter 6).

Accuracy (Correlation to Measurement)

S-parameter models must accurately correlate to measured response.

Impedance

Impedance is not applicable for Scattering Parameter models.

Insertion Loss Measurements

When making insertion loss measurements, calibrate the measurement system once and conduct all board tests with this calibration. Measurement variations due to board manufacturing should not exceed the limits outlined in Table 5-1:

Table 5-1. Expected Maximum Board Measurement Variation (Insertion Loss)

Frequency	Measurement Correlation	Sample Spec (Intel® QuickPath Interconnect - 85Ω)
0 - 1 GHz	±0.2 dB	±0.5 dB
1 - 5 GHz	±1.0 dB	±2.5 dB
5 - 10 GHz	±5.0 dB	±10.0 dB

Far-End Crosstalk (FEXT) Measurements

When making FEXT measurements, calibrate the measurement system once and conduct all board tests with this calibration. Measurement variations due to board manufacturing should not exceed the limits outlined in Table 5-2:

Table 5-2. Expected Maximum Board Measurement Variation (FEXT)

Frequency	Measurement Correlation
0 - 5 GHz	±3.0 dB
5 - 10 GHz	±10.0 dB

Near-End Crosstalk (NEXT) Measurements

When making NEXT measurements, calibrate the measurement system once and conduct all board tests with this calibration. Measurement variations due to board manufacturing should not exceed the limits outlined in Table 5-3:

Table 5-3. Expected Maximum Board Measurement Variation (NEXT)

Frequency	Measurement Correlation
0 - 5 GHz	±2.0 dB
5 - 10 GHz	±3.0 dB

Content

- S12P Models: 2 models (3 longest pairs through the connector and the 3 shortest pairs through the connector). This requirement is not applicable to mezzanine connectors.
- Range: 50 MHz to 20 GHz, minimum 400 steps, preferred 2000 steps.

- Location of signal reference plane.
- The models should not include the mounting vias.
- Model should include a report showing MQF and modeled vs measured response (error area A2 as shown in Chapter 7) at a minimum.

Identification

Include the following in a comment field inside the model itself:

- Device type, revision number, and revision date.
- Description of the position of the reference planes.
- Clear indication as to whether the model is based on measurements or simulation.
- Clear indication that the model has been or has not been correlated to measurement.
- Include NDA or other applicable IP identification.

Format

- Touchstone, version 1.1

5.3 Curve Fit Models

Pole Residue is the preferred curve fit model.

Function and Stability

SPICE time domain model must be stable, passive and causal as defined in Chapter 6.

Accuracy (Correlation to Measurement)

Model accuracy is assessed with a Model Quality Factor (MQF) for Impedance, Insertion Loss, and Crosstalk.

$$XX = \log_{10}\left(\frac{X1}{X2}\right)$$

Where “XX” = the Model Quality Factor (MQF) for either Impedance, Insertion Loss, or Crosstalk. The larger the model quality factor, the more accurate the model is deemed to be. A more complete description of Model Quality Factor is provided in Chapter 7.

For curve fit accuracy:

1. The Peak impedance of the Curve Fit model must be within 2.5 ohms of peak measured impedance.
2. The Minimum impedance in the Curve Fit model must be within 2.5 ohms of the minimum measured impedance.
3. The Average Curve Fit model impedance must be within 1 ohm of the measured average impedance.

Content

SPICE Models: 2 models (3 longest pairs through the connector and the 3 shortest pairs through the connector).

The model should include lines labelled ".prot" and ".unprot" to bracket the model body and prevent unintentional printing out the model itself. The subcircuit call should be positioned in the model body so that it is printed.

The models should not include the mounting vias.

The model should include a report showing MQF and modeled vs measured response (error area A2 as shown in Chapter 7) at a minimum.

Identification

Format: Model interface shall be a sub-circuit call, node 1-6 input side of 3 pair, node 7-12 output side of 3-pair, node 13 ground return.

Identification (Include in a comment field inside the model itself):

1. Device type, revision number, revision date,
2. Description of the position of the reference planes,
3. Clear indication as to whether the model is based on measurements or simulation,
4. Clear indication that the model has been or has not been correlated to measurement.
5. Include NDA or other applicable IP identification.

Format

SPICE, accessible as a sub-circuit call.

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6 Prerequisite Model Tests

6.1 Passivity

A passive component is a component that is incapable of energy or power gain and may either refer to a lossy component that consumes but does not produce energy, or to a lossless component that conveys energy with no loss. For a lossy connector model, the power out of the model should be less than the power into the model. Only transmitters should be non-passive.

1. **Polar Plots:** There are many different tools available for checking the passivity of a model. Those that produce a polar plot provide a quick, initial test of model passivity. Passivity is likely when all points lie within the unit (1.0) data circle of the plot as shown below in Figure 6-1, and Figure 6-2. Results should remain below 1.0 for all frequencies under all reasonable variations of impedance and reflections in adjacent components. Spikes/step discontinuities in the polar plot also indicate potential model issues.
2. **dB Loss Plots:** dB Loss plots must remain negative for all frequencies, under all reasonable variations of impedances and reflections in adjacent components.

Figure 6-1. Polar Plot Showing all Points Within 1.0 - Passivity Likely

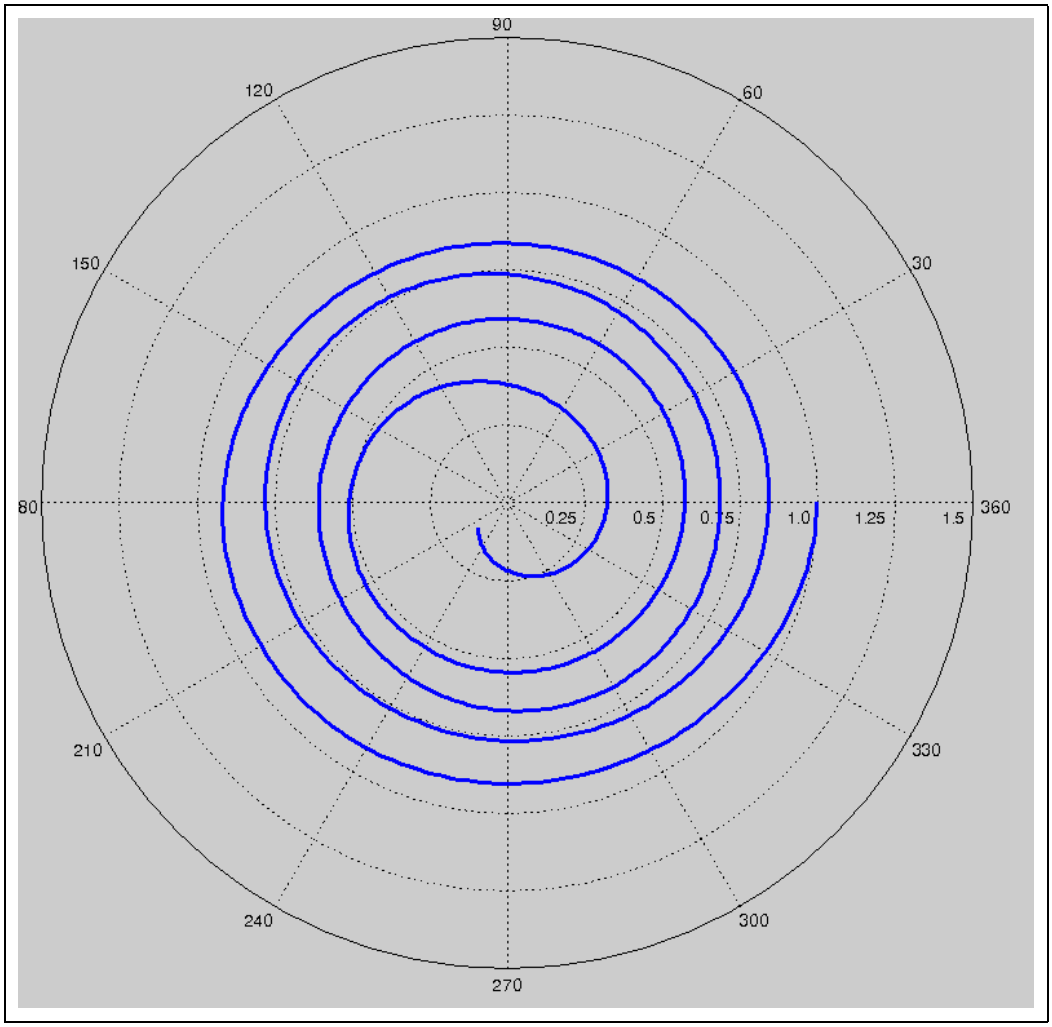
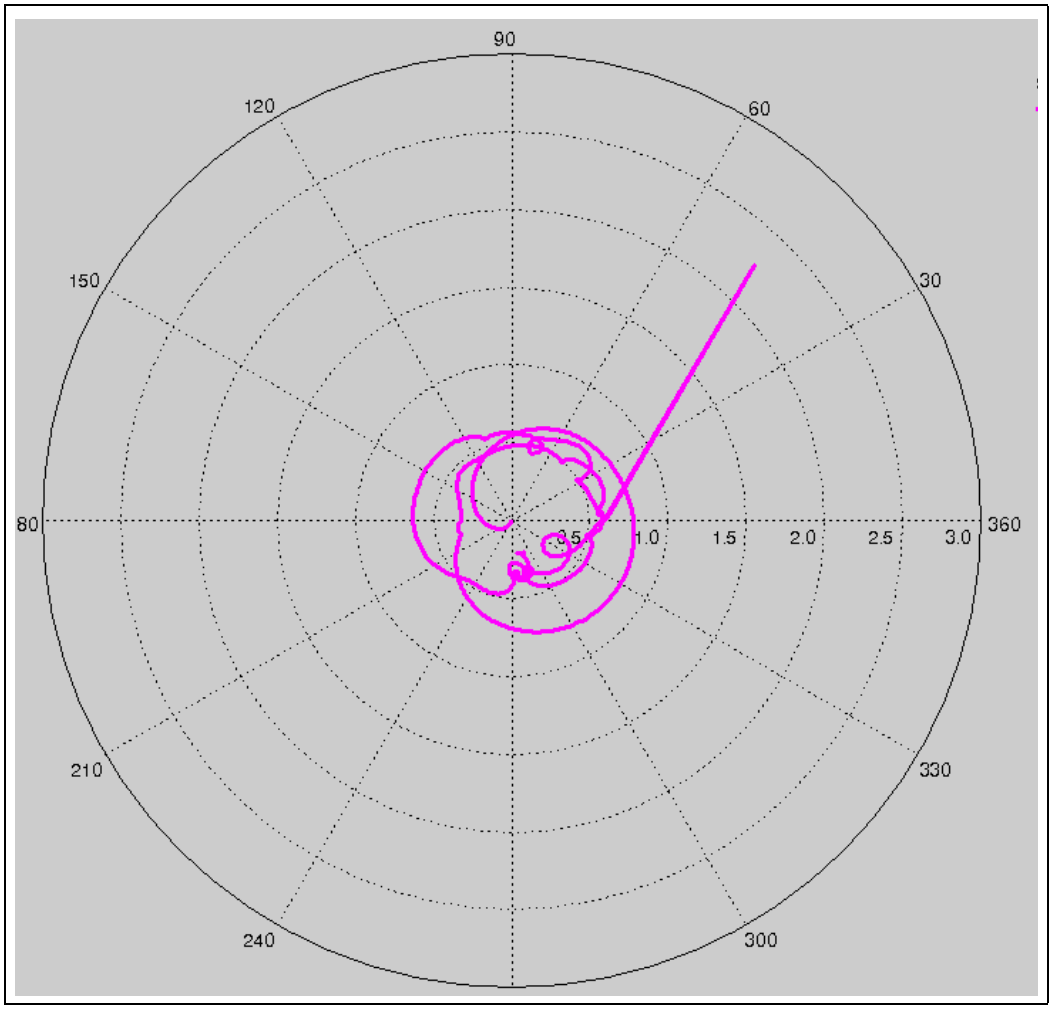


Figure 6-2. Polar Plot Showing Points Outside 1.0 - No Passivity



6.2 Stability

To test for stability, do an additional test using 3 copies of the models concatenated together. To concatenate the models, take the output pins of the first instantiation of the model and connect them to the input pins of a second instantiation of the model, and similarly connect the output of the second instantiation of the model to the input pins on a third instantiation of the model. Terminate all remaining signal pins to an appropriate impedance to keep them from becoming resonant

Run this combined model for 50 nanoseconds of simulated time, using a pulse rise time (Tr) at least as great as the bandwidth the model is claimed to accommodate.

$$Tr = \frac{0.35}{Bandwidth}$$

Where:

- Tr = rise time expressed in ns

- Bandwidth = model bandwidth expressed in GHz

The output response should settle to a stable DC voltage.

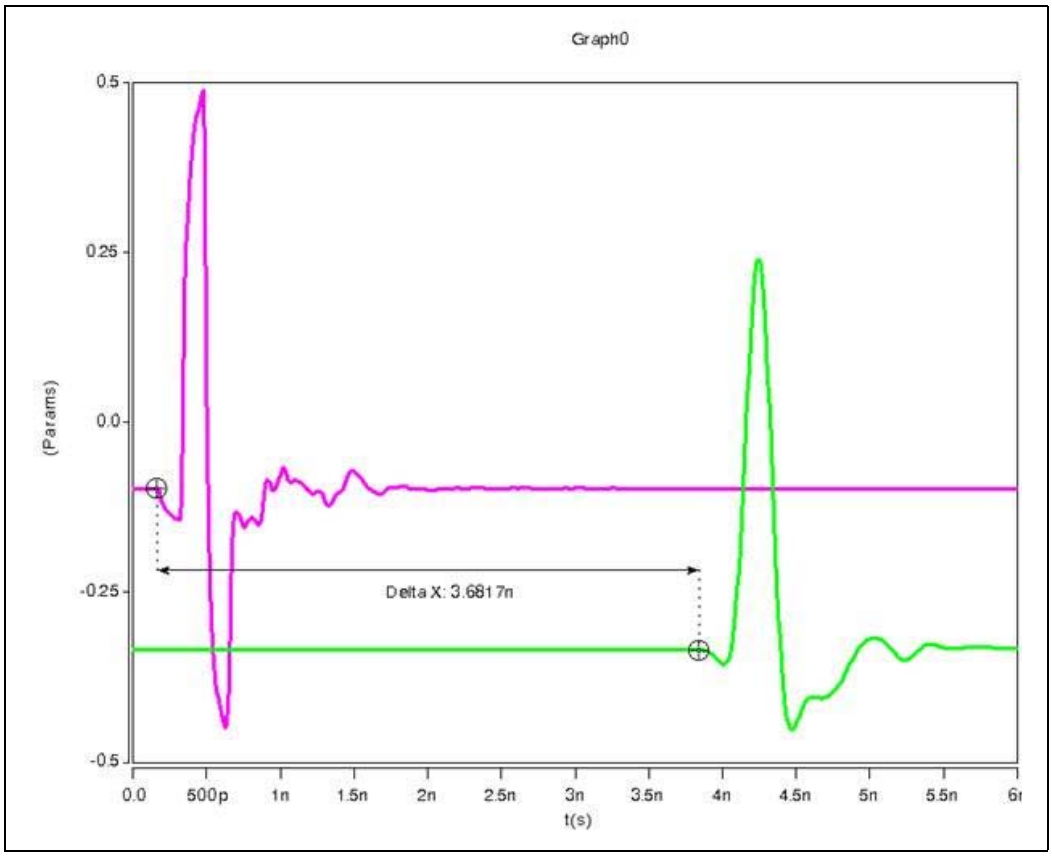
6.3 Causality

Causality simply means that the response at the output occur after the input. No event should occur at the output at a time before the stimulus at the input plus the time it takes the stimulus to travel from input to output. This is real world behavior, but some transmission line models can actually be "non-causal" in that the time-domain output changes before the input should have arrived. This is most commonly seen where high frequency loss modeling was done improperly.

Causality can be expressed in three domains: physical domain, frequency domain, and time domain. Mathematics can prove non-causality, but mathematics cannot prove causality.

1. The modeled insertion loss waveform (rise time and wave shape of the toe) must match the actual measurement at the output port of the device.
2. In the physical domain, dielectric constant changes as a function of frequency.
3. In the frequency domain, causality translates to a required relationship between the real and imaginary parts of a data set. All poles have to remain on the left side of the Laplace Transform plot.
4. In the time domain, an effect cannot precede its cause.

Figure 6-3. Causality Failure: In the time domain, signal arrives 1.0 ns after passing through a transmission line with 1.1 ns delay (delay proportional to interconnect length of about 21")



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7 Measurement and Verification

Although the most accurate information about electrical components comes from direct measurements, such measurements are often not suited for direct application in circuit simulations, and thus, measured results often must be translated into other formats for use in system simulation and performance analysis tools.

Unfortunately, such translations usually inject some level of inaccuracy into the model. It is desirable therefore to minimize this inaccuracy to improve the model, but when faced with different formats and numerous represented parameters, recognizing an improvement can be difficult. To improve electrical models, a metric for measuring the accuracy of the electrical models of components is required

An acceptable model quality metric should include he following characteristics:

- The metric should produce a numeric result, a number whose value clearly distinguishes a "better" from a "poorer" model. This number should be dimensionless and independent of such things as driver signal amplitude.
- The result should be easy to understand and to calculate.
- The metric should encompass all major electrical characteristics relevant to circuit simulations of the device. That is, the quality factor should represent impedance profile, insertion loss, and crosstalk.
- Since circuit simulators that are themselves well suited to DOE and Monte Carlo simulations typically do not handle frequency domain models well, this metric should evaluate model quality using the time domain.
- The metric needs to be useful for qualifying the impedance profile, the insertion loss, and the crosstalk characteristics of the model.

One suitable metric can be based on comparison of areas, specifically, a reference area established by the electrical measurements, verses the area between the model and the measurement. This satisfies the first requirement listed above: as the area between model and measurement decreases, the numeric value increases. It also satisfies the second requirement: as a ratio it becomes dimensionless. Area is easy to calculate and can be determined with virtually any mathematical tool such as MathWorks MATLAB*, Parametric Technology Corporation Mathcad*, or even Microsoft Excel*. A script could even be written in a SPICE simulator to calculate this value.

Three major electrical characteristics critical to most interconnect circuit simulations include insertion loss (or for a driver, amplitude), crosstalk, and impedance profile. In this chapter, these factors are described as:

AA - the model's quality with respect to impedance

BB - the model's quality with respect to insertion loss

CC - the model's quality with respect to crosstalk

The three values are determined separately and the three results are reported as a concatenated value delimited by colons (for example, AA:BB:CC).

7.1 Impedance Model Quality Factor (AA)

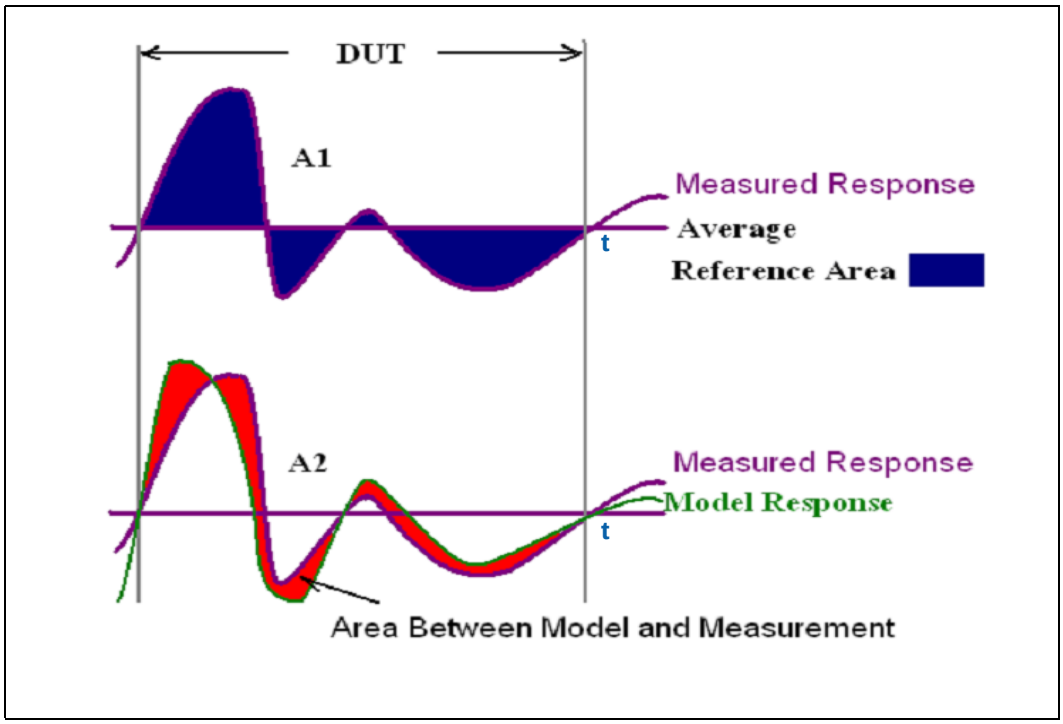
Using a TDR, (Time Domain Reflectometer) data set, calculate the average impedance of the device being modeled. Calculate the area between the measured response and the average impedance. Call this the reference area, A1.

Calculate the area between the measured response and the modeled response to a simulated TDR. Call this error area, A2. These areas are shown in Figure 7-1.

The impedance model quality factor, AA, equals the logarithm of A1 divided by A2, rounded to two digits.

$$AA = \log_{10}\left(\frac{A1}{A2}\right)$$

Figure 7-1. Impedance Loss Model Quality Factor (AA) - "x" axis is time



7.2 Insertion Loss Model Quality Factor (BB)

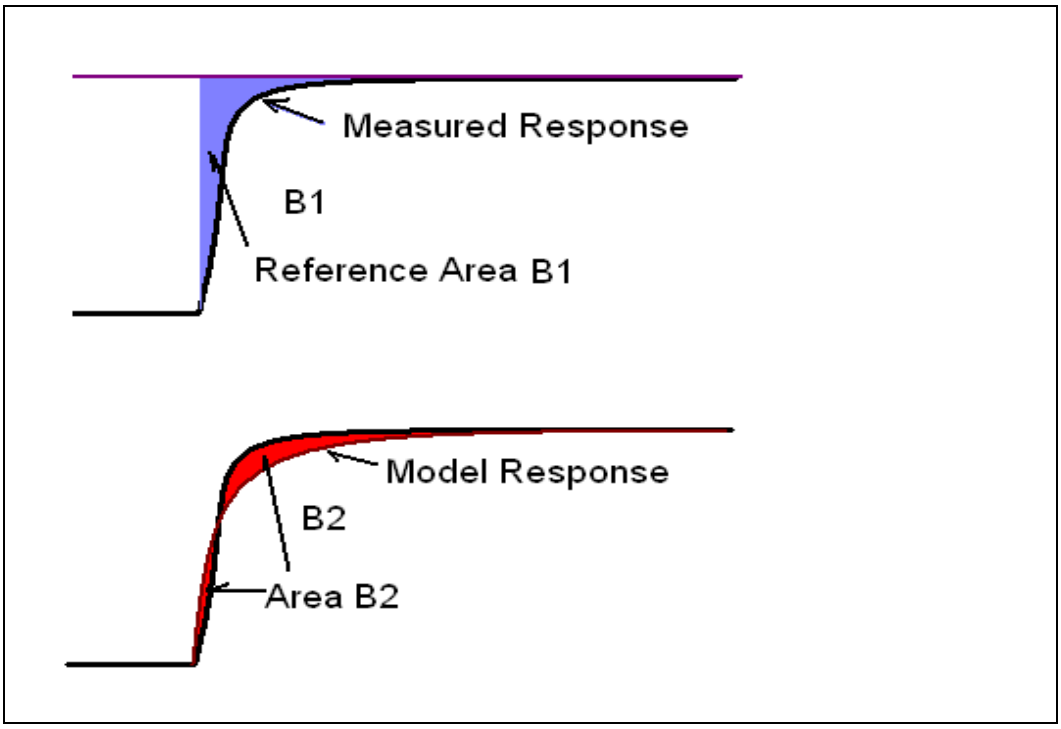
Using a VNA (Vector Network Analyzer) data set or a TDT (Time Domain Transmissionometer) data set, examine the output response profile produced by a step input, the measured response.

Determine the voltage to which the step response eventually settles. Calculate the area between the measured step response, and the final voltage level, starting at the time that the response has reached one percent of its final value and ending when it has fully settled to it's final value. Call this the reference area B1. Now calculate the area between the measured response and the model's response to the same size step and time, and designate that area B2.

The insertion loss model quality factor, BB, equals the logarithm of B1 divided by B2, rounded to two digits.

$$BB = \log_{10}\left(\frac{B1}{B2}\right)$$

Figure 7-2. Insertion Loss Model Quality Factor (BB) - "x" axis is time

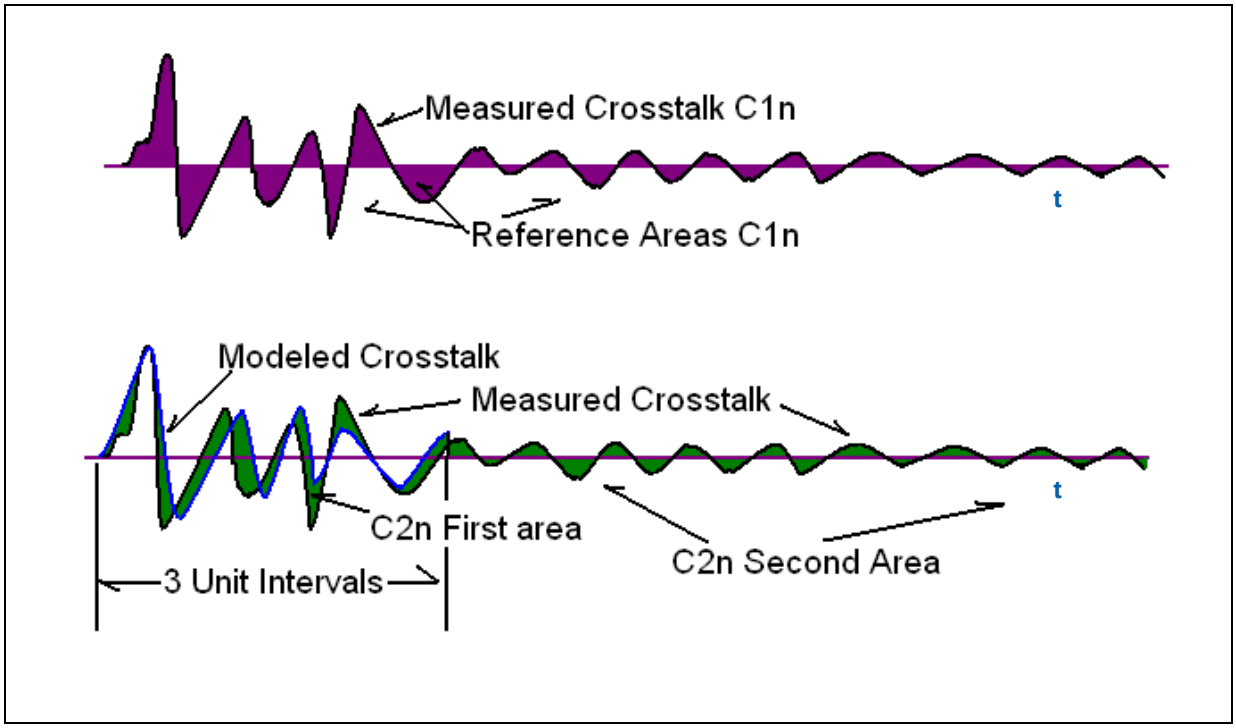


7.3 Crosstalk Model Quality Factor (CCn)

Using a TDT, (Time Domain Transmissionometer) data set, examine the crosstalk profiles for the aggressor patterns of interest. For each aggressor pattern of interest, calculate the reference area, beginning where a crosstalk voltage is first detected in the response and until the voltage reaches steady state. The area between the measured data and the line that defines the steady state voltage is called C1n, the reference area.

Very small phase differences can make the decay profile of the crosstalk shift enough that even minor variations make the areas in the decay region correlate poorly. The modeled vs measured area, C2n, to be calculated is foreshortened in light of this, and divided into two sections as shown in Figure 7-3.

Figure 7-3. Crosstalk Model Quality Factor (CC) - Voltage Settles to Zero



In the first area of C2n, the area between the model and the measured response is calculated for 3 unit intervals beginning where a crosstalk voltage is first detected.

In the second area of C2n, starting at 3 unit intervals after the first crosstalk voltage is detected and extending to the time where crosstalk is fully settled in the measured response, calculate the area between the model response and the steady-state voltage. These two areas are added together to form the total C2n.

The crosstalk model quality factor, CCn, is the logarithm of C1n divided by C2n.

$$CCn = \log_{10}\left(\frac{C1n}{C2n}\right)$$

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