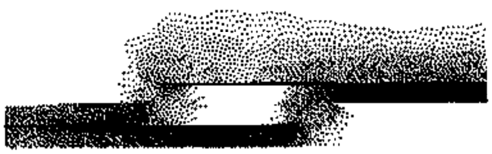
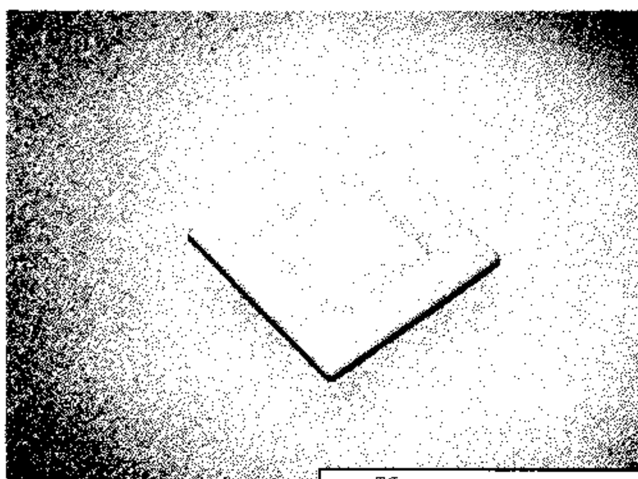
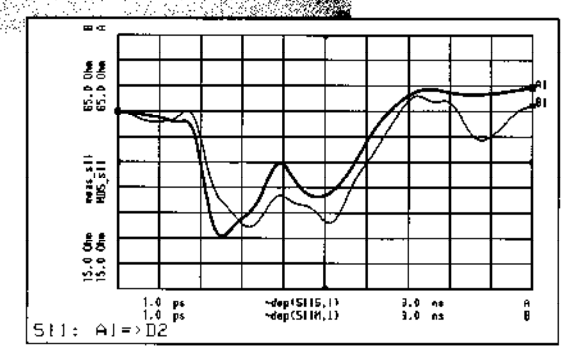
Modeling Passive High-Speed Digital Structures

Application Note 1203-1

Effective use of HP 85150B and HP 85180A high-frequency CAE products for leading-edge package design







Introduction

As clock speeds and edge rates increase in digital and mixed-mode circuits, signal integrity has become a primary concern. Parasitic effects in the packaging and interconnection of integrated circuits can degrade performance of a system until it literally malfunctions. Two software tools, the HP 85150B Microwave Design System and the HP 85180A High-Frequency Structure Simulator, help designers to characterize these parasitic effects and minimize performance degradation.

High-frequency analog designers have measured, modeled, and circumvented parasitic effects for years. Their design tools and measurement techniques can be used by designers of high-speed digital systems to help them understand the electrical performance of the passive structures of digital circuitry. These structures include IC packages, traces on and within printed circuit boards, backplanes, and connectors. Even though they are an integral part of digital or mixed-mode (digital and analog) circuitry, the structures themselves are considered analog designs.

Organization

This note demonstrates the practical use of the HP 85150B Microwave Design System (HP MDS) and the HP 85180A High-Frequency Structure Simulator (HP HFSS) in modeling passive, high-speed digital structures. Several topics are discussed, beginning with a comparison of frequency domain S-parameters and time-domain reflectometry data. Following this is a discussion of the HP MDS software using S-parameters from two sources, a network analyzer and the HP HFSS software. Finally, an appendix discusses the appropriate use of lumped and transmission line models.

Back to Basics

The passive structures of digital systems have electrical properties that betray the electromagnetic wave nature of the signals propagating through them. All physical structures can store and supply energy in the form of electric (capacitance) or magnetic (inductance) fields. All structures also have transmission delay, however meaningful, due to the finite speed of light.

Approximate models of structures as inductors, transmission lines, etc., are extremely useful within the bounds of their assumptions. Yet designers often mistake symbol for fact. The electromagnetic complexity of all structures, and therefore the measurement and modeling complexity needed to characterize them, increases with shorter risetimes (wider bandwidth). More sophisticated models are usually required when signals have less than one nanosecond risetime (above a few hundred megahertz). The HP Microwave Design System has an expanded library of sophisticated circuit elements based on geometric and material parameters.

Measurements and Models

There are as many ways to model a single, straight, PC board trace as there ways to measure one. First, one chooses a model for convenience and accuracy, and then one chooses the measurement equipment to supply the data/coefficients for the model. The technique applied here uses frequency domain S-parameters as its basis.

Alternatives to the S-parameter network analyzer include the impedance meter, the LCZ Meter, and the time-domain reflectometer (TDR) (see figure 1). In the hands of the modeling expert, these instruments "expect" to find a combination of resistances, inductances, capacitances, and transmission line impedances and delays. S-parameters are more abstract because they make few assumptions about what is "inside" a network. This allows S-parameter data to be used over the widest range of applications and frequency bandwidths.

For those not familiar with S-parameters, they are simply the energy that is reflected off of, or transmitted through, a device under test. The measurement is performed under specific circuit conditions, one frequency at a time. While S-parameter

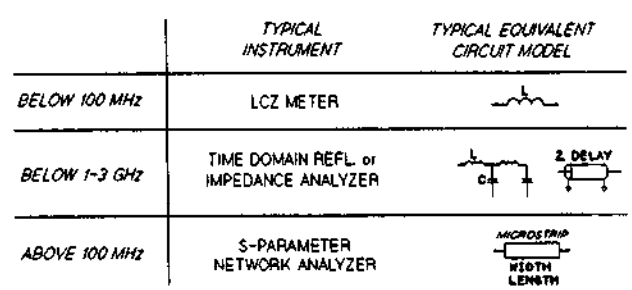


Figure 1
Models and their measuring instruments increase in complexity as the risetime decreases.

data is formatted differently than time-domain reflectometer data, the underlying information is the same. Indeed, S-parameter data can be converted to the TDR format inside most network analyzers.

In summary, one only measures what one expects to find. If the basis of a measurement is a model that is overly simplified, neither the measurement nor a simulation based on it can be accurate. S-parameters are very general. More practically, S-parameter measurements are accurate and readily available.

Packaging Applications of HP MDS

Package and interconnect designers can use HP MDS to create models for use in SPICE and other simulation tools. Of the capabilities of HP MDS, two are particularly useful in this context.

First, HP MDS can be used to refine an equivalent circuit model based on the S-parameter performance. Once the user has created the basic circuit, the "optimization" feature of HP MDS changes the component values until the performance of the model is the same as the measurement. The optimizer is also helpful in converting one kind of model into another model, such as a microstrip transmission line into a LC ladder network.

Secondly, HP MDS can be used to show model response to TDR, time domain, or frequency domain waveforms. HP MDS is an important link in the modeling process, shown in figure 2.

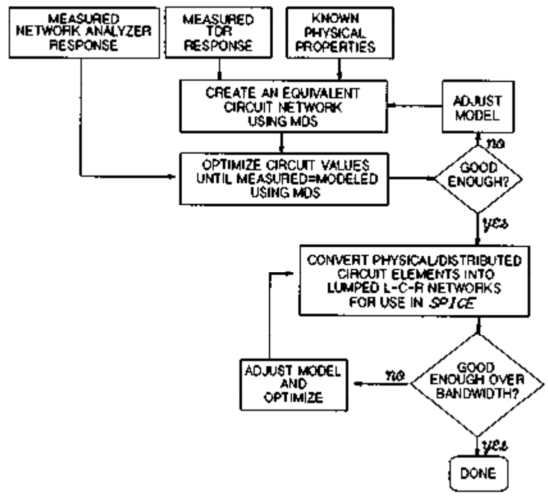


Figure 2
Flow chart of the package modeling process

Advantages of HP MDS

HP MDS has some important advantages over the current generation of SPICE and SPICE-derivative simulators when it comes to high-frequency/sub-nanosecond risetime modeling. HP MDS simulates "distributed" circuits (circuits with transmission lines and delays) very easily, including circuits whose characteristics change with frequency. HP MDS also allows S-parameter data to be used directly in a simulation, so stimulus/response simulations can be performed even before a model has been created.

Another advantage of HP MDS is its stripline, microstrip, and other dielectric-based circuit elements that allow the designer to enter geometric and material properties of the circuit directly. The user does not need to guess at parameter values (such as inductance or impedance) to obtain good agreement between measured and modeled.

Example 1: Modeling a signal Path in a PGA

The first modeling example involves characterization of a signal path through 169-pin Pin Grid Array (PGA) (Figures 3-6). This includes measuring the performance of the PGA and developing an equivalent circuit for it. The PGA was measured using an HP 8510B network analyzer and the coaxial fixture shown in figure 7. The measured S-parameter data were transferred into an HP MDS system, where HP MDS was used to refine an equivalent model.

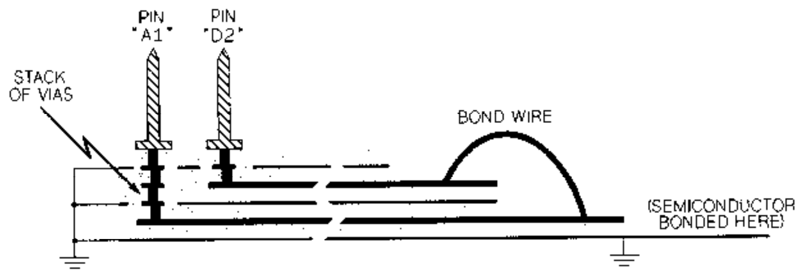


Figure 4
Cutaway side view - Signals encounter pins, vias, traces, and a bond wire along the path.

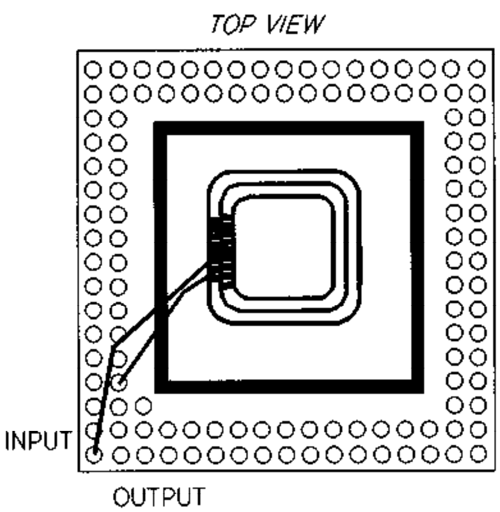


Figure 3
Top view - Signals travel inward to the bonding cavity and return along a different trace.

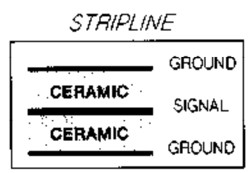


Figure 5
Cutaway view of a "stripline" transmission line, as modeled by HP MDS.

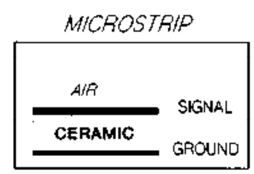
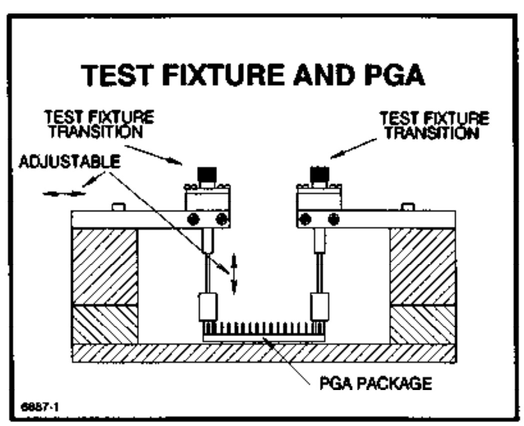


Figure 6
Cutaway view of a "microstrip" transmission line, as modeled by HP MDS.

Figure 7
The Pin Grid Array was measured with an Intercontinental Microwave fixture and a HP 8510B network analyzer.



The first task in the modeling exercise is to establish the range of usage of the model. If the model will be used only at long risetimes (low frequencies), considerable effort can be saved by simplifying the model. Three separate models were derived using the same S-parameter data to demonstrate that different models with different limitations can be used to model the same network.

Given the physical dimensions, range of usage, and other design information, the engineer creates an equivalent circuit for a structure. Models that do not use constant geometric or material parameters, such as a pure inductance or a transmission line impedance, must then be estimated. TDR and TDT (time domain through) information are excellent sources of these parameter values. Having a high-quality initial network and parameter values saves a lot of effort later in the process.

Once the circuit has been entered into HP MDS, the software can then "optimize" the circuit. Optimizers iteratively change the parameter values, such as a capacitance value, until the response of the circuit is the same as the measured response. Optimizers add a degree of automation to the modeling process.

If the measured and modeled responses remain too different after an optimization, there are two potential reasons why the optimizer may not have been able to find suitable parameter values. First, the initial guesses may have been very inaccurate. Second, the circuit may be incapable of the desired performance. No optimizer can make a passive network exhibit gain, for example.

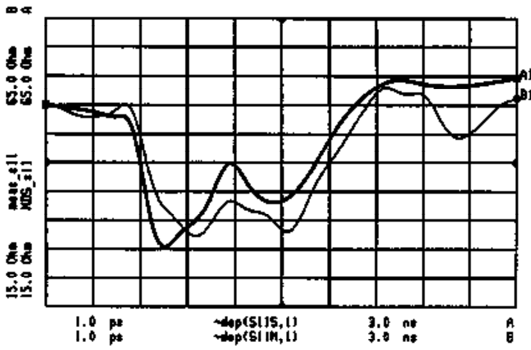


Figure 10. Reflection vs. time [TDR]

The equivalent circuit shown in figure 8 is the most literal of the three shown. It is based exclusively on geometric dimensions and material parameters. Its performance was verified against measurements to several gigahertz. Measured vs. modeled for reflection (S11, TDR) and transmission (S21, TDT) are shown (figures 9-13).

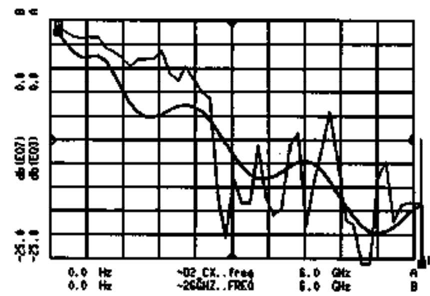


Figure 11. Transmission vs. frequency [dB(s21)]

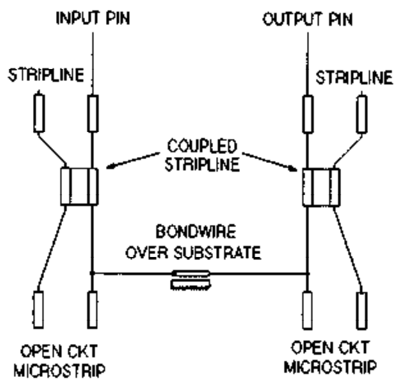


Figure 8. Model of signal path, based primarily on stripline transmission lines.

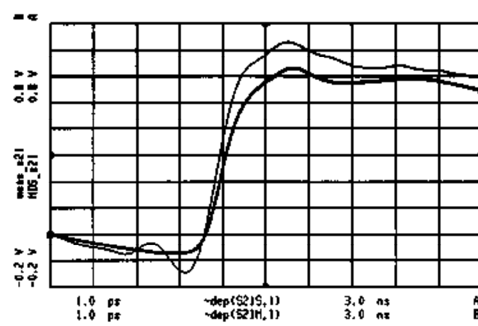
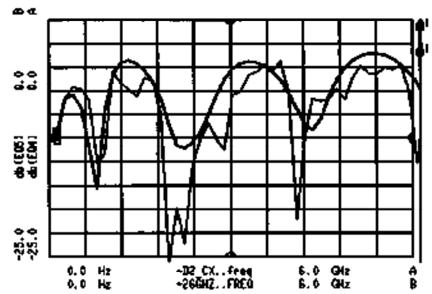


Figure 12. Transmission vs. time [TDT]

Figure 9. Reflection vs. frequency [dB(s11)]



The second equivalent circuit, shown in figure 13, is a simpler circuit based on ideal transmission lines characterized by impedance and delay. A simple inductor has been used for the bond wire. The initial parameter values for this circuit were obtained by interpreting the measured TDR trace, then refined using the HP MDS optimizer. Its performance was verified against measurements to below 0.2 ns (approx. 2 GHz). Measured vs. modeled for reflection (S11, TDR) and transmission (S21, TDT) are shown (figures 14-17).

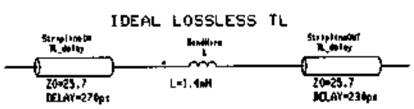


Figure 13.
Model of signal path, based primarily on ideal transmission lines with delay.

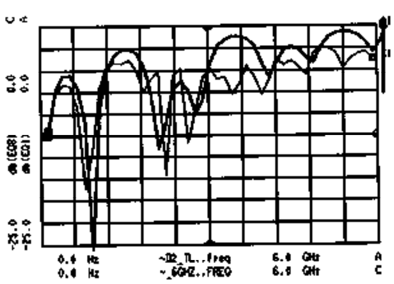


Figure 14.
Reflection vs. frequency [dB(s11)]

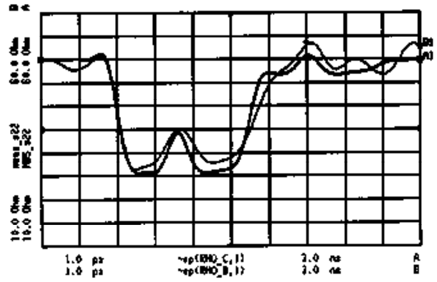


Figure 15.
Reflection vs. time [TDR]

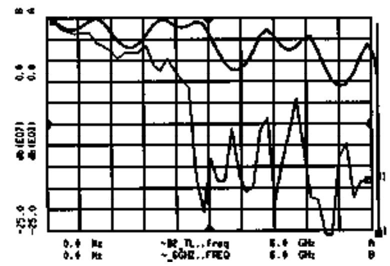


Figure 16.
Transmission vs. frequency [dB(s21)]

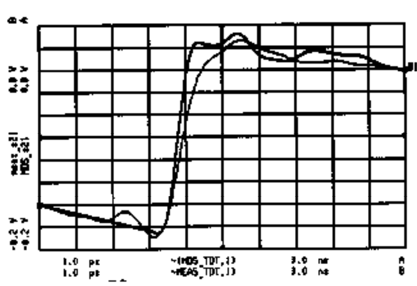


Figure 17.
Transmission vs. time [TDT]

The third equivalent circuit, shown in figure 18, is the most simplified circuit. The model is based on a lumped inductance-capacitance (LC) ladder with no transmission lines. It is a further evolution of the circuit in figure 13. Each of the transmission lines was converted to an LC ladder equivalent using the HP MDS optimizer. A final, fine adjustment to the values was obtained by optimizing the coarse LC ladder values directly to the measured data. The performance was verified against measurements below 0.4 ns (approx. 1 GHz).

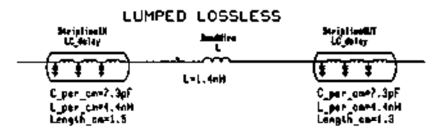


Figure 18.
Model of signal path, based on lumped, repeated LC ladder networks.

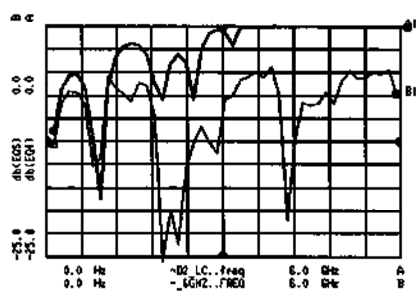


Figure 19.
Reflection vs. frequency [dB(s11)]

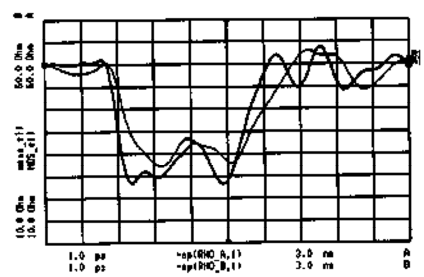


Figure 20.
Reflection vs. time [TDR]

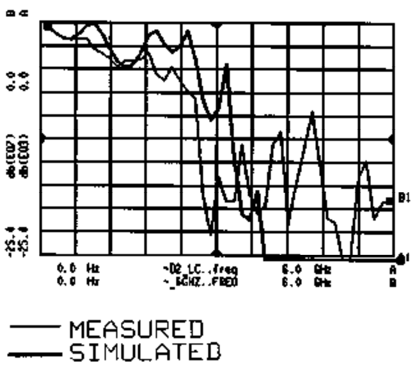


Figure 21. Transmission vs. frequency [dB(s21)]

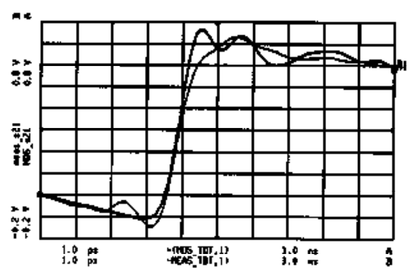


Figure 22. Transmission vs. time [TDT]

Studying Circuit Response & Risetimes

Many designers feel more comfortable specifying parameters in terms of the time domain rather than the frequency domain. This is especially true when examining simulation results. IC packages and interconnections are usually characterized by how they degrade the time domain information passing through them. HP MDS allows the user to stimulate a circuit with time domain waveforms and view the response in the post-processor. The HP MDS post-processor is also able to transform S-parameter data into the familiar Time Domain Reflectometer (TDR) and Time Domain Through (TDT) formats.

Time-domain Waveform Sources

Although HP MDS operates primarily in the frequency domain, it contains several useful time-domain voltage waveform sources that can be used as stimuli in circuit simulations. These sources include common analog functions as well as some specifically designed for characterizing digital circuits. These may be found in the standard **mwlib** library of HP MDS and in the user-contributed **application-lib** library. A square wave source with a specifiable risetime, shown in figure 23, is just one of the many waveforms available.

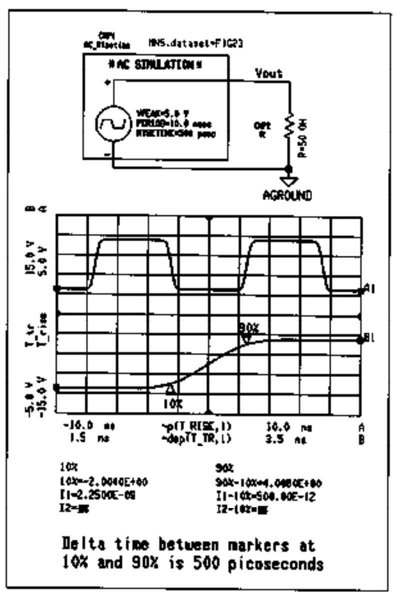


Figure 23. A square wave voltage source with finite risetime.

Using an Oscilloscope with HP MDS

In addition to the pre-defined waveforms available in the component libraries of HP MDS, it is also possible to use a waveform captured on an oscilloscope as a stimulus in a simulation. HP MDS is able to read trace data from the HP 54000-series of digital sampling oscilloscopes in real time. The trace data is stored in a **Dataset**. There it can be converted to the frequency domain using the Fourier Transform, and the Fourier coefficients used to specify harmonics of a frequency domain source.

In practice, measured waveforms can be used in a simulation, thereby increasing its realism. This could be used, for example, to inject an IC's output driver waveform into the measured S-parameter response of a proposed package. The designer could examine the risetime of the combination without ever having connected them together. A model for the package is not necessary; the measured S-parameters can be used directly in a simulation.

Using HP HFSS with HP MDS

The HP Microwave Design System(HP MDS) is able to model a great variety of circuits and structures using built-in circuit elements. However, no circuit simulator can account for all of the electro-magnetic effects within an IC package or connector. The HP 85180A High-Frequency Structure Simulator(HP HFSS) calculates the true S-parameter response of arbitrarily-shaped transmission lines and other structures.

The S-parameters can then be imported into HP MDS as if they had been measured on a network analyzer.

HP HFSS can tell the package designer whether a connection or trace will perform well at high frequencies before prototypes are built. Early in the design process, HP HFSS can perform the function of a network analyzer. However, HP HFSS can go beyond a network analyzer in its ability to identify specific problems in a design.

Contrasting HP HFSS and HP MDS

HP HFSS analyzes passive structures at their most fundamental, electromagnetic level. It requires significant computer resources to perform these analyses on real-world structures. As such, it yields results that have a high level of confidence and are often superior to measurements.

The HP Microwave Design System operates at the circuit level. Its simulations are very efficient, taking seconds or minutes instead of minutes or hours. When used within the realm of its target application, it is also accurate. Outside its intended usage, the models of HP MDS are less useful.

There is therefore a compromise between the accuracy of HP HFSS and the design capacity and speed of HP MDS. In practice, this compromise is implemented by breaking a design into the portions that are well understood and easily modeled by existing analytical equations (HP MDS) and those that are less understood and are not modeled by analytical equations (HP HFSS). The latter are simulated into S-parameter blocks that are imported into HP MDS, where the entire structure or design is then combined into a single circuit model.

Contrasting HP HFSS Results and S-parameter Measurements

Measurements will continue to be the keystone of the modeling process. Without accurate measurements connecting the modeling process to reality, simulation is a purely intellectual exercise. There are two occasions, however, when accurate S-parameters are simply unavailable. HP HFSS can often fill this gap.

S-parameters are rarely available early in the design process before anything has been built. *HP HFSS (and HP MDS) furnishes the designer with a good estimate of the performance of missing structures.*

The second advantage of HP HFSS relative to measurements lies in the content of the data. *Using HP HFSS, the user is able to simulate very specific combinations of structures without interference or distortions caused by unrelated structures, such as a test fixture.* The user does not need to be concerned with the performance of a measurement system or its calibration.

Nevertheless, one should correlate one's model with measured results at the earliest possible opportunity. When a model accurately predicts the output of one's production process, the modeling process is complete.

Example 2: Modeling a Package Via

An example that shows how HP HFSS fits into the larger modeling process is shown here. It is a "via" that connects traces on different layers in a multichip module. After simulation in HP HFSS, the S-parameters were brought into HP MDS. Two equivalent circuits were optimized to match the "measured" (HP HFSS) performance so that the via model could be used in a SPICE simulation.

Only a portion of the entire chip carrier was modeled; more specifically, the via and the traces that connect to it. The input port was a "microstrip" transmission line on the top dielectric layer. The output port was a "stripline" transmission line between the second and third layers. Other structures that may have been present in the actual package were not represented because previous experience showed that they had no effect on the performance.

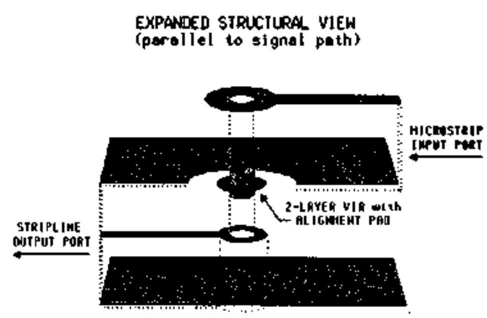


Figure 24. The via connects traces on two different layers.

HP HFSS simulated the electromagnetic performance of the structure in figure 24 in 0.5 GHz steps up to 10 GHz, corresponding to a risetime below 30 ps. The magnitude of the electric field is shown in several cross sections of the structure in figures 25-27.
The EM field distributions of common digital structures are certainly not familiar to most designers. However, important modeling information can obtained from qualitative observations of the electric field, for example.

First, note the size of the wavelength relative to the size of the structure. This ratio is single most important consideration when developing a model because shorter wavelengths (shorter risetimes) cause the electromagnetic complexity to increase. Knowing when to use a lumped element (RLC) or a transmission line model (or neither) can save the designer a great deal of time. The meaning of this ratio is discussed more fully in a later section.

Another useful piece of information can be obtained by looking at the electric field strength. Where the fields are stronger in the vicinity of another object (typically a ground plane or an adjacent trace), one can usually assume that a capacitance exists between the two.

Physically, a capacitance means that a voltage difference between two points causes charge (and therefore an electric field) to collect at their faces. By observing where the electric fields are "bunched" in a simulation, the designer can make educated guesses about the placement and magnitude of parasitic capacitances. These capacitances almost always occur where the trace changes direction or is close to another trace.

Examining field distributions can be helpful to the experienced designer, but is certainly not necessary to achieve good modeling results.

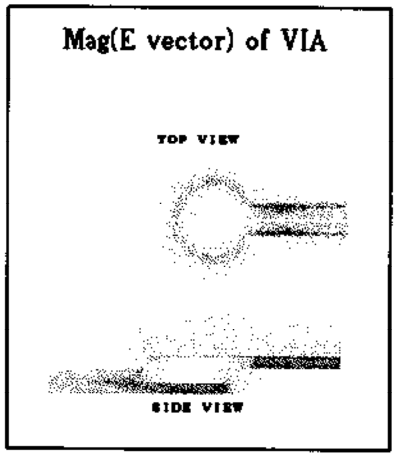


Figure 25.
Mag(E vector) in symmetry plane.

The HP HFSS software automatically calculated the S-parameters and stored them to disk. They were then read into the HP Microwave Design System, where two equivalent circuits were developed. The first was optimized to fit the frequency response data, resulting in a series inductance value of 0.144nH.

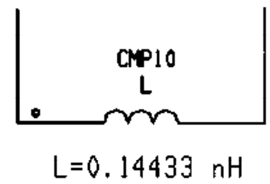


Figure 26.
One equivalent circuit for the via.

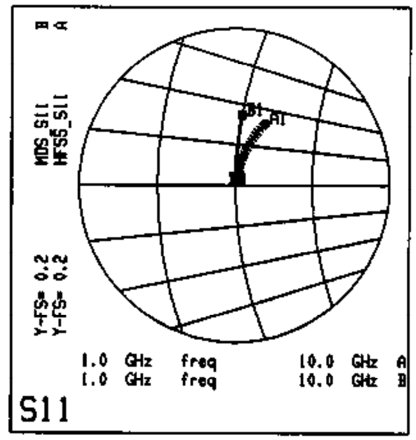


Figure 27.
HP HFSS calculation vs. modeled frequency response.

The second model reflects more of the physical character of the actual structure. The one inductor was split into two series inductors while three shunt capacitances were added. The inductances account for the self-inductance per unit length of the via. The capacitances account for charge accumulating on the top and bottom of the via, and also on the "catch pad" as the via passes through one of the ground planes. Additional circuit detail is possible, but would not add significantly to the accuracy or risetime of the model.

Nominal values for the parameters were estimated and then refined using the HPMDS optimizer. Results are shown in figure 29.

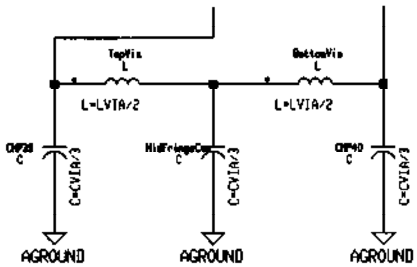


Figure 28.
An equivalent circuit with more detail.

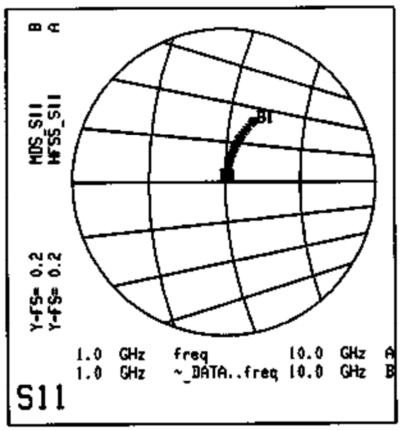


Figure 29.
HP HFSS calculation vs. modeled frequency response.

Once an acceptable model for the via has been obtained, the circuit can be entered into the appropriate transient or logic simulator for integration into a larger system. Subcircuits and "macro" functions of most circuit simulators are well-suited for this task.

Summary

High-frequency analog instruments and CAE software are not usually found in the tool kit of the digital package designer. Yet many high-speed digital systems are unwittingly troubled by analog problems, such as crosstalk, reflections, loss, and ground bounce.

The HP Microwave Design System and the HP High-frequency Structure Simulator can be used to characterize these analog problems. They help the package and system designer stay one step ahead of the IC performance. Both software programs speak the same language, S-parameters, that is the standard of the high-frequency analog community. AdditionJ10 ally, HP MDS allows the non-analog designer to stimulate circuits and format results in terms of more familiar time domain terminology.

APPENDIX: Effect of Wavelength on Modeling Approximations

It should be apparent that model and measurement complexity are related to decreasing rise-time (increasing frequency bandwidth). One of the underlying factors in this complexity is the size of the wavelengths relative to the structures through which they pass. The following discusses this relationship, how it affects the electrical performance, and the repercussions on modeling.

Wavelength >> Largest Structural Dimension

In the lower limit of frequency, the wavelengths of energy passing through the circuit are much, much longer than the structures themselves. Energy storage does not vary much with distance, so entire structures or traces can be said to have one capacitance (electric field storage) or inductance (magnetic field storage). Combinations of lumped circuit equivalents (i.e. - inductors, resistors, and capacitors) are adequate to model structures in this frequency range.

Wavelength ~ Largest Structural Dimension

The first transition occurs when the length of the structure is more than approximately one-tenth of a wavelength long. Transmission lines and finite delays are required for full accuracy. Inductance-capacitance ladder networks can be used to approximate short lengths of delay. At the high end of this frequency band, the transmission line parameters become frequency-dependent (dispersive), and may require use of a microstrip transmission line instead of an ideal delay, for example.

Current flow changes in this frequency range, making traces lossier. The skin effect pushes current out to the extreme edges of the trace, reducing the effective cross-sectional area of the conductor and adding resistive losses beyond the DC ohmic loss. Moreover, when a PC board trace becomes much more than a wavelength long, it becomes an increasingly efficient antenna. At best, radiative losses are mistaken for resistive losses, meaning that voltage pulses get smaller as they travel away from their source. At worst, radiative losses cause EMI problems and interference with other circuitry.

Ground planes that are comparable to a wavelength in at least one of their dimensions can support voltage differences along their length. One must consider whether a conductive plane is actually functioning as a "ground plane."

Wavelength < Smallest Structural Dimension
The second threshhold is crossed when the width of the structure is more than about one-tenth of a wavelength wide, with gross effects beyond half of a wavelength wide. When the structure becomes too wide, higher order modes of propagation are possible. This means many different impedances and delays may be present on the same line, causing extreme pulse distortions. In the limit, microstrip and stripline circuits become waveguides or inter-coupled resonant cavities, unable to be represented by circuit theory because of the complex electromagnetic interactions. The HP HFSS software is therefore the most appropriate tool at the very highest frequencies.

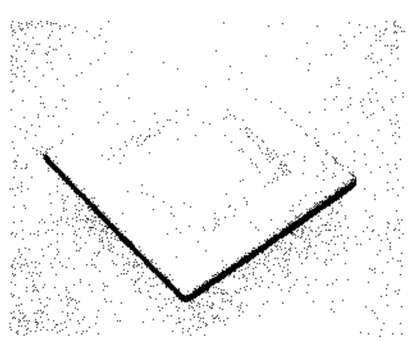
The preceding discussion is obviously a simplification of a rather advanced topic. Two real-world examples should make the concepts easier to understand.

Case Study: A PC board
If one encounters the problems described above, they are likely to occur first on a large structures such as printed circuit boards. A typical example is the demonstration PC board that is used with the HP 54000 series of oscilloscopes/TDRs. It is 80mm wide, 200mm long, and 1.59mm thick. It is made of copper on a substrate having a dielectric constant of about 4.3. Traces range from 1mm to 12mm in width. Feature size (in this case, the distance between changes in trace width) is roughly 20mm-50mm.

At about 3ns risetime (100 MHz), the shortest wavelength is approximately 1600mm. The series equivalent of the PC board traces can be safely modeled with a simple inductance, perhaps with small parasitic shunt capacitors.

At about 300ps risetime (1 GHz), the shortest wavelength is approximately 160mm. This is less than the length of the board, and only a couple of times longer than the distance between the trace discontinuities. Transmission lines with delays or microstrip transmission lines should be used.

Below 12ps risetime (25 GHz), the wavelength shrinks to about 6mm. This is very close to the trace widths on the PC board. The substrate thickness is nearly equal to the quarter-wavelength. "Moding," the spontaneous conversion of one transmission line propagating mode to another, is likely to occur at seemingly random frequencies in and above this frequency range. To make matters worse, the PC board is a few dozen wavelengths in length, making it an excellent antenna.



Case Study: A Pin Grid Array
The exercise is repeated for the PGA studied in an earlier section. It is a 44mm square ceramic package made from ten layers of 0.25mm thickness alumina, each having a dielectric constant of approximately 10. Line widths vary from 0.1mm to 0.3mm. Line lengths vary from 3mm to over 20mm.

At about 3ns risetime (100 MHz), the shortest wavelength in the ceramic material is over 1000mm, 25 times the longest dimension of the package. There is no added accuracy in modeling traces with transmission lines.

At about 300ps risetime (1 GHz), the shortest wavelength is approximately 100mm, and the majority of traces are more than 0.1 wavelengths in length. Skin effect is pushing trace currents into the lossy edges of metallization in the co-fired ceramic. Ideal transmission lines are useful, but the "skin effect" loss mechanisms of microstrip and stripline models may be more accurate than lumped resistances. Crosstalk and risetime degradation are severe enough that actual circuit application is doubtful, even though accurate measurements and models can be created.

Below 12ps risetime (25 GHz), the wavelength is only 4mm and the PGA has been reduced to a measurement curiosity. Standing wave patterns and resonances occur on all planes, in the IC cavity, and perhaps among the pins. The crosstalk and electromagnetic interactions are so severe that an equivalent circuit for this 169-pin PGA might contain thousands of elements, if one were able to create an equivalent circuit.

Printed in U.S.A. 1/91
5091-0971E