Packaging in IBIS-AMI Technology

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Abstract

As serial links become faster and more complex, it is ever more challenging to model the silicon in an accurate and efficient manner. Traditional IBIS package models are simply not accurate enough and lack the bandwidth required for high-speed serial channels. The IBIS Algorithmic Modeling Interface (AMI) is a promising standard that is able to accurately model drivers and receivers that include equalizers and clock data recovery circuits. The introduction of the AMI modeling standard presents the opportunity to combine accurate driver and receiver models with high quality scattering parameter and W-element models of the passive IC, package, and PCB structures. In this paper we explore simulation with AMI models driving accurate high-bandwidth channel models of packages and printed circuit boards for robust simulation of high-speed serial systems. We also use these simulations to investigate the effects of variability in the manufactured channel.

Introduction

Over the past several years a number of different simulation techniques have been proposed for characterizing high speed serial links in low bit error rate (BER) systems. There are two areas of particular focus. The first involves taking advantage of the linear time invariant (LTI) nature of passive interconnect structures. By characterizing the channel with a step or impulse response [1] it becomes possible to use statistical and fast convolution-based transient analyses that allow for a combination of fast simulation speeds and accurate BER prediction. The second area of interest is the modeling of the equalizers that have become nearly ubiquitous in the transmit and receive circuitry of the integrated circuits driving the channel. Advanced equalizer technology has typically been omitted from transistor-level models due to intellectual property concerns.

For channels with data rates in the tens of gigabits per second it is typical to see designs that have a completely closed eye at the input of the receiver. It is only after on chip equalization has been applied that the received signal begins to resemble a traditional open eye diagram. Given this reality, signal integrity engineers wanting to simulate a given system must include more and more of the transmit and receive IC behaviors, in the form of these equalizers, in order to determine an accurate measure of system performance.

In this paper we will present the IBIS-AMI [2] methodology as a valuable tool for the simulation and analysis of semiconductor packaging with a focus on sensitivity analysis. A design kit for IBM's CU045 core technology will be used to enable a corner case analysis of different transmit and receive packaging and IC variations. Scattering parameters for different packages and IC models will be included in the linear channel and the AMI device front end. The various models may be selected in the channel simulation by changing a variable to the appropriate corner type. This channel study is intended to serve as an example of how the eventual adoption of high bandwidth IBIS-AMI package and IC models should work. Eye diagrams, BER, and frequency domain results will be shown to demonstrate the importance of modeling both the transmit/receive circuitry and the passive channel.

IBIS-AMI Background

The Algorithmic Modeling Interface (AMI) defined by the IBIS committee in version 5.0 of the IBIS Specification [2] provides a unique capability to address both the LTI and active transmit and receive circuitry, including but not limited to the equalizers, in a manner that is IC- and simulator-vendor agnostic as well as providing intellectual property protection and rapid simulation speeds.

The key feature of IBIS-AMI is that drivers and receivers can be modeled by algorithmic blocks rather than by individual transistors. Instead the macroscopic device behavior is described in a high-level programming language such as C. The motivation for this has multiple aspects. Modern transceivers incorporate sophisticated signal processing algorithms such as decision feedback equalization. The circuit models for these devices tend to have a higher transistor count compared to non-equalized devices. A full transistor based simulation using traditional SPICE transient analysis of equalized devices along with the passive interconnect structures will suffer from slow simulation times that make this approach impractical for simulating the long bit patterns required to adequately characterize the circuit's performance. An IBIS-AMI driver or receiver model is compiled into a library file (.dll or .so) which has far less numerical complexity and is therefore much faster to simulate than the transistor equivalent.

Additionally, IBIS-AMI offers inherent intellectual property protection. As the models are algorithmic in nature they do not contain any of the manufacturing process information that must be included with transistor models. Given that the models are compiled prior to distribution even the behavioral algorithms can be kept hidden. This allows the IP vendor to choose what level of detail to include in documentation accompanying IBIS-AMI models while still enabling accurate simulation by end users.

IBIS-AMI Theory

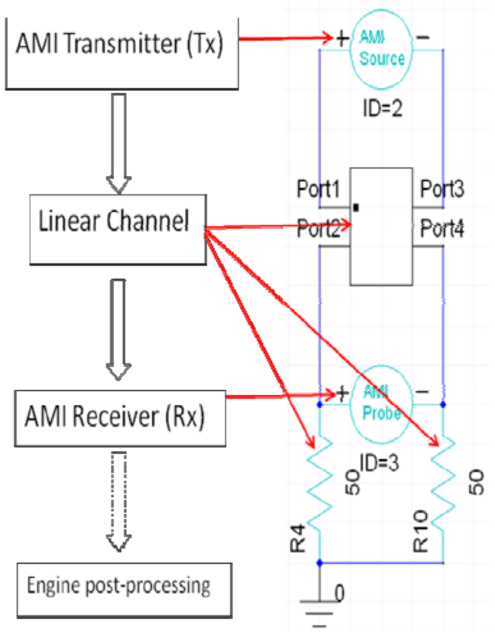

Figure 1: A typical setup for AMI Analysis.

The initial assumption for AMI analysis is that receiver and transmitter models are treated as black boxes on both intuitive and algorithmic levels. On the intuitive level, we assume that AMI devices are electrically isolated (buffered) from the rest of the circuit, which makes it possible to simulate the circuit based on the characteristics of the linear channel. On the algorithmic level, each AMI device is represented by a compiled library with three functions:

- AMI_Init() – initializes the model and often implements the "linear" part of the model's equalization schemes.
- AMI_GetWave() – implements the non-linear part of the model's equalization schemes for transient simulations
- AMI_Close() – allows the model to clean up any resources used during a simulation

The general setup for AMI transient analysis is shown in Figure 1. The typical structure of an AMI source is shown in Figure 2.

The base (and most limiting) assumption of AMI analysis is that the channel is linear and it can be characterized by an ideal impulse response. Usually simulators rely on some kind of transient analysis to generate this response. The general approach is to either approximate an ideal impulse with a finite pulse or differentiate the step response of the system to obtain the impulse response. Such discretization of the system is equivalent to an additional low-pass filter so the characteristics of the pulse or step should be chosen to ensure that none of the frequencies of interest are degraded.

During the initialization stage the simulator passes the impulse response of the channel and other simulation parameters through the AMI_Init() functions of the transmit and receive libraries. The other simulation parameters include bit period, time step, and vendor-defined model parameters. The libraries use this information to initialize the model and can also modify the channel impulse response to reflect the "linear" part of the model's algorithm.

The simulator then proceeds with the transient stage of the AMI simulation by passing a specified bit pattern through the system following these steps in a loop:

1. Generate a block of transmitted bits
2. Convert a list of bits into a piecewise-linear rise-fall signal
3. Push the signal through the transmitter's AMI_GetWave() function
4. Convolve the signal with the channel's impulse response
5. Push the signal through the receiver's AMI_GetWave() function
6. Post-process the results (eye and bit-error-rate plots)

The simulator loops until all bits in the specified pattern have been passed through the system. For multiple parallel channels, the contribution of aggressors is accounted for by convolving the input with the aggressor-victim impulse response and is added linearly to the victim signal.

It is also possible to use AMI models in statistical simulators of LTI (linear time-invariant) systems such as described in [1]. In this case, only the linear part of AMI model is taken into consideration, i.e. the simulator uses the channel response modified by AMI_Init() function and ignores AMI_Getwave().

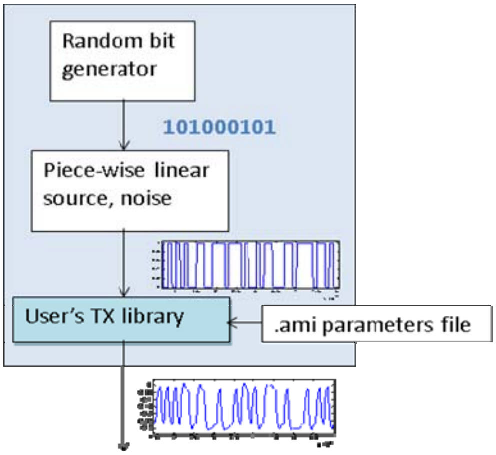

Figure 2: The structure of an AMI source.

Channel Modeling

Figure 3 shows the general signal flow for the IBM PCI-E channel that was used for the AMI simulations:

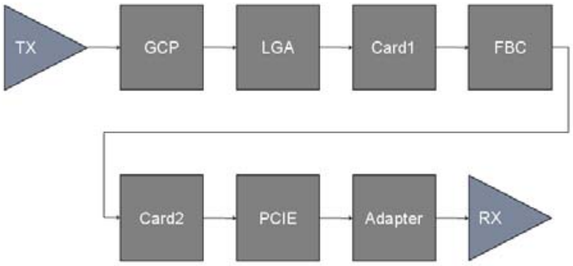

Figure 3: Channel Schematic

In this schematic the signal flow starts at the IBIS-AMI transmitter (Tx) and ends at the AMI receiver (Rx). The blocks between the driver and the receiver are a collection of Touchstone® S-parameter models and W-element models representing a Glass Ceramic Package (GCP), Land Grid Array (LGA) connector, Printed Circuit Board (PCB) card, Card Connector (FBC), PCI-E connector, and Adapter card. These blocks represent the LTI portion of the channel that is characterized by the impulse response of the concatenated models for IBIS-AMI simulations. The blocks include the details of the signal paths including traces, vias, connectors, and the reference paths for the return current.

Since the entire LTI portion of the channel will be characterized by an impulse response, the overall accuracy of the AMI simulation will be limited by the quality and accuracy of the models in the channel. To be an accurate model the components of the channel models need to represent the insertion loss, propagation delay, far- and near-end crosstalk, and characteristic impedance of the physical components. To be a quality model the accurate model also needs to be causal and passive [3] over the full frequency range of energy excitation in the simulation. This range is technically infinite, but it is common to explicitly model the frequency range from DC to the knee frequency of the signal rise time.

We establish the models according to the considerations presented in [4]. The impulse response for the channel is obtained via the numerical differentiation of a step response computed in a full SPICE transient analysis. The models need to be inherently passive and causal in order to provide for a stable simulation that converges. The frequency bandwidth must encompass the frequency content of the driving signals. This includes DC for establishing the correct voltage levels and it extends to a frequency high enough to accurately represent the edge rates of the driving signals. For this channel we are operating at 5 Gb/s with rise times at approximately 100 ps and modeled the interconnect from DC to 20 GHz. For the channel models that use scattering parameter models, we specify a step of 20 MHz to adequately address the overall channel delay of approximately 7 ns.

The need for stable models with adequate bandwidth is not new to the signal integrity community. One of the driving concepts behind the IBIS-AMI methodology is to be able to simulate bit patterns that are orders of magnitude longer than can be simulated with traditional transient circuit simulations. This leads to simulations that are pushing down to lower and lower bit error rates. What might be perceived as small changes to the impulse response can result in large changes to the circuit at lower BERs. For this reason it is all the more important for the channel models to be as high fidelity as possible.

Simulation Details

To illustrate the use of IBIS-AMI in a channel we chose the circuit represented by the high level description in Figure 3. The channel contains three parallel differential signal paths: a victim lane flanked by two aggressors.

To analyze the results of the simulations in this paper we will look at two key metrics: eye height and eye width. The eye height measurement will be made at the midpoint of the signal's unit interval, and eye width will be measured at 0V.

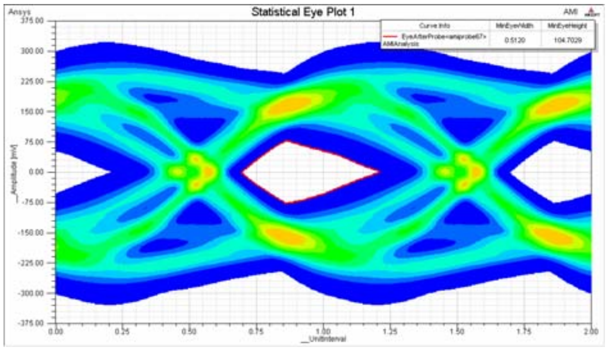

Figure 4: Nominal Channel Eye Diagram.

An example eye diagram for the channel is shown in Figure 4 and shows that the eye has a height of 104.7mV and a width of 0.512 UI or 102 ps.

There are a number of channels or paths in the system that are topologically represented by Figure 3, but which vary from each other in physical placement. This impacts some key parameters such as the length of traces, connector pin location, and trace layer. Typically, we pick the channel for which our experience leads us to expect the worst case eye: for example, the one with the longest trace length or longest via stubs. In fact, for our eye analysis we may create an artificial worst case channel which has the superset of the longest lengths of any channel on each segment of the model and the longest via stubs. We expect that if this somewhat artificial channel meets our minimum eye height and eye width requirements then all the channels in the system will meet the eye requirements. Figure 5 shows the insertion and return losses for the LTI portion of such a worst case channel in the system being analyzed here.

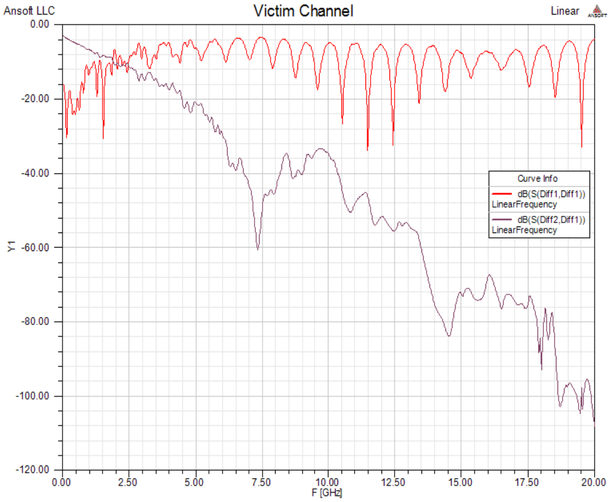

Figure 5: Insertion and return loss S-parameters for the simulated channel.

Transient simulation of the full channel is used in order to create a step response, which is then differentiated to get the initial channel impulse response. The IBIS-AMI models in turn use the AMI_Init functionality to modify the linear impulse response to account for whatever equalization that the AMI model writers have chosen to model in that fashion. The initial and final impulse responses of the victim channel are shown below in Figure 6.

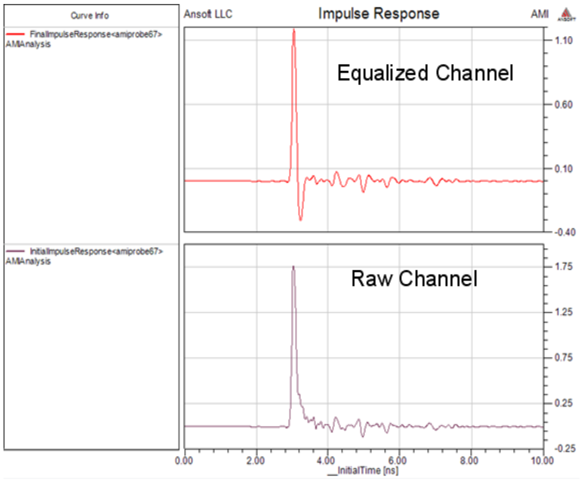

Figure 6: Impulse Responses

Sensitivity Analysis

With the channel described as a collection of discrete components it is possible to easily set up a parametric analysis to sweep individual model variables in order to examine the circuit's overall sensitivity to different kinds of process variations.

The channel analysis is used to establish the key design parameters and determine the range of eye size for the variation of channels in this system. We are interested in the variation of lengths and via stubs from one channel to the next in the system. It is also of interest to characterize the impact of manufacturing variations which will change the impedance and attenuation of the traces on a particular channel from system to system. We are also interested in the value of applying manufacturing improvements to the channel, such as introducing backdrilling of the PCB vias at the connectors.

We model the coupled traces in the packages and printed circuit boards as tabular W-element models. The tabular W-element traces are parameterized by length and the sensitivity to length can be easily analyzed by stepping the parameter of length in a design of experiments (DoE) analysis. However, individual tabular W-element models must be built to represent the low and high impedance corners or the low and high attenuation corners. We can also set up the DoE to sweep through the models to calculate the eye height and eye width for these cases [5].

The portions of the channel containing the PCB vias was modeled using a full-wave 3D electromagnetic extraction tool [6]. An S-parameter file using the Touchstone® SnP format [7] was used to capture the channel's behavior. There are several variations of this structure which impact the via stub lengths that we want to include in the sensitivity analysis. The stub lengths are determined by the wiring layer in which the trace intersects the via. If backdrilling is done, the via length also changes which impacts the behavior of the via structure. Backdrilling removes reflections due to the discontinuity caused by the stub of the via. These reflections cause mismatch in the interconnect and deteriorate the signal to noise ratio resulting in eye closure. Using [5] and [6], the geometrical shapes of the model can be parameterized to create the set of Touchstone® models needed for performing the sensitivity analysis.

To illustrate the results of this sensitivity analysis, we present sweeping of two of the variables: the impedance of the traces on the backplane and the length of the via stub. The impact of these variations is shown in Table 1.

Table 1: Eye Variation Table

Stub Length (um)	Impedance Corner	Eye Width (UI)	Eye Height (mV)
1021	low	0.790	174
1021	nominal	0.798	172
1021	high	0.778	165
2716	low	0.760	162
2716	nominal	0.774	161
2716	high	0.760	156
4739	low	0.690	150
4739	nominal	0.712	150
4739	high	0.708	141

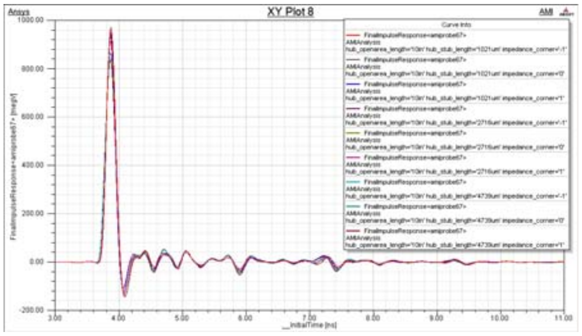

Figure 7: The sensitivity analysis impulse responses of each interconnect.

Additionally we can use a statistical analysis to observe how the channel will perform at low bit error rates. The impulse responses shown in Figure 7 are used for the statistical analysis, which produces the bathtub plot shown in figure 8. Table 2 shows the eye heights and widths measured at a BER of 1e-12.

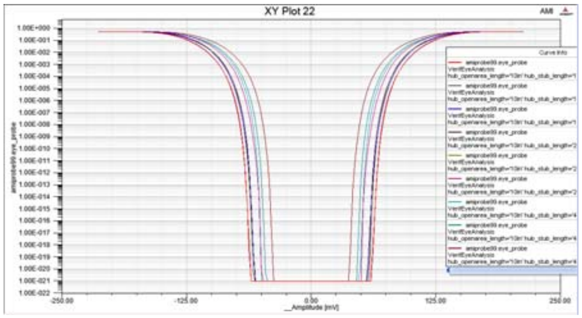

Figure 8: The eye height bathtub curves from the statistical eye analysis.

Table 2: Statistical eye variation at 1e-12BER

Stub Length (um)	Impedance Corner	Eye Width (UI)	Eye Height (mV)
1021	low	0.553	131
1021	nominal	0.551	131
1021	high	0.549	123
2716	low	0.624	123
2716	nominal	0.630	125
2716	high	0.630	108
4739	low	0.601	106
4739	nominal	0.609	100
4739	high	0.595	84.0

Passivity and Causality

In the process of performing the analyses presented in this work, the authors encountered S-parameter models that were non-passive and non-causal. These issues manifest in the form of non-convergence due to unstable models, or more subtly as unanticipated results.

The need for causal, passive models in time domain simulation has been well established in works such as [3] and [4]. There are a number of options available in simulation tools for detecting and further correcting S-parameter models that violate these fundamentals of stability. Care needs to be taken when addressing detected violations because modifying the original Touchstone® model requires changing either the real or imaginary part of the model to obtain a consistent Hilbert transform [12].

If a given model shows a passivity violation that is an indication of a limit on the accuracy of the extracted model. As passivity and causality are fundamental requirements for proper physical behavior, violations represent a known error in the behavior of the model. Correction techniques are certainly valuable for ensuring stable behavior, but do not necessarily provide a more accurate solution. When known stability violations are present in a model the best solution is to try to address them in the tool that produced the model. Passivity and causality violations are not limited to simulation; without proper setup and care violations are very common during measurements. A model without a DC operating point provides another significant challenge when trying to obtain accurate circuit analysis. It requires an extrapolation to DC for proper behavior and is one of the most commonly encountered causality violations. If the model has come from an electromagnetic field solver it is better to re-extract the model by adjusting options available to the field solver. A common error is the usage of frequency independent materials during model extraction with field solvers using the finite element method to extract Touchstone® models. Circuit analysis results using a causal, passive model produce highly accurate results, but when the original model undergoes a Hilbert transform to recreate a causal passive model the design engineer must ensure magnitude and phase of the modified model meet the desired accuracy constraints otherwise the circuit analysis results are highly suspect.

Future Considerations for the LTI Model

To develop standards for the modeling and simulation of the channel and its packaging components we must also consider future demands and address the bottlenecks we expect to encounter.

There are three such considerations that we have encountered in this effort that need future investigation and standards flexible enough to address the potential developments in modeling, simulation, and measurements that can impact how simulations are done. One consideration is the frequency bandwidth of the models. As data rates increase the upper limit of the required model frequency range increases. Our expectation is that the models need to be accurate to 40 GHz for channels operating in the 10 – 20 Gb/s range. Extraction techniques may need to be improved to efficiently mesh and solve structures in this frequency range. Measurement techniques need to be developed [8,9] to verify the extracted models and ensure the measured Touchstone® files contain a DC point, maintain Hilbert consistency, and are passive. In addition the variability and uncertainty of our models must be acknowledged [10]. The complexity of the structures, the range of the frequency content, and the difficulty of measurement at these frequencies are contributors to the uncertainty of the overall accuracy. A second consideration is the size of the files that need to be created, stored and operated upon. An S-parameter model in Touchstone® format can easily become 100 MB or larger. Factors contributing to this large size are the small frequency step needed to perform convolution-based transient simulations of the relatively long-delay channels; the number of ports required to model the crosstalk from nearby aggressors; and the significant digits needed to ensure stability, passivity, and causality are maintained. Any standard needs to support the use of other model representations as well. In this paper we used tabular W-element models for traces that can be accurately modeled with per-unit-length R, L, C, and G parameters. For structures that cannot be represented with per-unit-length parameters models with state space models, rational functions or macromodels such as in [11] should be supported.

The third consideration is the robustness of the models. We have already addressed the passivity and causality of the models. The requirements here will become more stringent as the eyes become smaller and errors must be minimized to obtain usable simulations for design and characterization.

Conclusions

The IBIS-AMI standard provides the methodology necessary to represent the transmit and receive circuits in simulations of high-speed channels. We have illustrated the modeling of a channel using IBIS-AMI models for the transmit and receive circuits with S-parameter and tabular W-element models of the packaging components of the channel. These models enable us to characterize and optimize a channel using a sensitivity analysis of the variations that are encountered in a system implementation.

Accurate models for the linear-time-invariant part of the channel are very important. The key elements of these models are that they represent the frequency bandwidth of the signals on the channel from DC to at least the knee frequency indicated by the signal rise time. Currently S-parameters are the standard format for the models we use. Model representations other than S-parameters such as W-elements and rational functions will need to be considered to maintain the accurate representation of the physical structures while maintaining passivity, causality, and flexibility for future applications.

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