PELE: Pre-emphasis & Equalization Link Estimator to Address the Effects of Signal Integrity Limitations

Names omitted

ABSTRACT- **This paper discusses a methodology employed to create a tool that quantifies the effects of signal integrity limitations particularly for high-speed applications. The tool is based on a platform of routines which predict performance over high-speed links. It contains routines that optimize transmitter pre-emphasis and receiver equalization that lead to superior BER performance. The tool is qualified against Agilent's ADS simulator and correlated with measurements.**

Keywords: **Transceiver, pre-emphasis, equalization, link simulation, behavioral model and optimization**

Category: **10/15/17**

I. Introduction

System-level design of high-speed links generally involves tradeoffs between cost, complexity, density and performance. A typical channel can consist of a transmit daughtercard, a PCB backplane, a receiver daughtercard with connectors in-between. As data rates increase, effects that degrade signal integrity such as trace skin effect, dielectric losses, connector and package discontinuities become more prevalent which often tips the balance of tradeoffs usually with unfavorable consequences [1],[2].

As a result, those customers who are faced with the task of designing higher data rate systems with legacy backplanes are concerned about the feasibility of such an undertaking and those customers who are designing new links want to avoid the high-cost route that help guarantee performance, such as employing back-drilled vias and the use of esoteric PCB materials. The whole question of link or backplane throughput can be difficult to answer without considerable effort spent by, at very least, modeling link attenuation followed by performing exhaustively long transient simulations.

SerDes vendors, fully aware of these signal integrity limiting factors, offer modern transceivers that include a multitude of pre-emphasis and equalization settings to combat what can be severe signal integrity (SI) degradation in the link. However, this comes at the expense of additional transceiver complexity. Consider for example the sheer number of combinations associated with increased number of pre-emphasis settings, number of pre- and post-taps, number of equalization gain and pole/zero settings in the latest generation of transceivers. Exercising each option could take several man-months of effort alone to eliminate settings that won't offer any solution.

Clearly, signal-integrity issues and the additional sophistication associated with the transceivers used to combat them, coupled with the customers' desire to minimize BER in the system makes the entire design process and pre-emphasis/equalization setting selection difficult. For this reason, we created "PELE", our tool name which is an acronym for Pre-emphasis and Equalization Link Estimator.

PELE is built upon a modular and expandable framework. Central is its ability to optimize pre-emphasis and equalization settings and predict near- and far-end eye diagrams for any given link. It is designed to offer fast results which are not only afforded by the methodology to process the signal path, as discussed later, but by also modeling the transmitter and equalizer which avoids transistor-level depth. In essence, circuit-level simulations are run as a pre-processing step to model the transmitter and receiver accurately so they don't need to be included as part of PELE simulation overhead. The mathematical methodology and driver/receiver modeling are the two main tenets which offer significant speed-up without significant loss of accuracy.

To the user, in its most fundamental application, PELE accepts S-parameters of the customer's end-to-end link which encompass components such as daughtercards, the backplane and connectors. If such S-parameters can not be measured (say from an existing legacy backplane) they can be generated during the design process with SI tools such as Agilent's ADS that contain libraries of non-ideal or solver-based models of microstrips, striplines, vias and other SI-related elements. Momentum, HFSS or other EDA tools can be used to generate S-parameters from more esoteric structures where need be, such as the package.

PELE incorporates each packages' S-parameters as well as the SerDes's intrinsic pre-emphasis and equalization capabilities on a per-device basis as tied to those products supported. The package is important to include since they can contain impedance discontinuities which show up as multi-path reflections between the transmitter and output package pin, as well as in between the input package pin and the receiver. PELE is then made available to be subjected to the

customer's link for either feasibility or as part of the design process.

Given all the available transmitter and/or equalizer settings coded within PELE, the tool runs through optimization routines to choose those transceiver settings which suggest the best combination. This step is not only key to eliminating the time necessary to run the gamut of possibilities that weed out solutions that will not work, but also quickly converges on an initial best setting which will lead to the best BER performance.

It is interesting to note that the Optical Internetworking Forum (OIF) supports a transceiver modeling program called "StatEye", used to support compliance testing of backplane channels. It too was designed to support fast simulation speed. One differentiator of our platform is the inclusion of precision transmitter and receiver models that can be correlated with measurements. A second differentiator is input pattern dependence, again key for correlation of PELE simulations against simulations and measurements.

The organization of this paper is as follows: First, a behavioral modeling methodology of the high-speed transceiver is presented. Secondly, the framework surrounding the mathematical processes and the optimization of FIR filter-based pre-emphasis and equalization is discussed. Agilent ADS and/or measurements are shown that demonstrate good correlation. Finally, a summary is presented.

II. MATLAB BEHAVIORAL MODELING

As mentioned earlier, the first thrust in the creation of a fast simulation platform was the use of behavioral models that represent the transmitter and receiver. Generally, transceiver drivers/receivers are represented by either IBIS or Hspice models. IBIS models are not suitable for high-speed serial I/O due to some constraints and are not always recommended or supported by high-speed IC vendors. Hspice models can reflect fairly accurately the transistor-level characteristics of transceivers used in high-speed designs; however they are still fairly complex and time consuming. The resulting simulation time, in the context of a serial link, can take hours or days to accomplish a single simulation run.

Recently, some EDA tool suppliers in partner with IC vendors provide proprietary behavioral I/O models in their board design tool which can be used to validate links with faster results. However, the approaches used result in the use of modeling devices through language representation [3]. Our approach has been to not restrict ourselves to the limitations of a language and keep the full mathematical flexibility as needed to guarantee good correlation.

Effects such as on-chip parasitics and package bump-to-ball trace characteristics, and how they terminate, can largely influence the results due to band limitation, reflections and skew which need to be included in the overall modeling for accurate results. Good correlation at this level is a necessary requirement in order for overall link correlations to be successful.

A. Tx Pre-emphasis Behavioral Modeling

Transmitter pre-emphasis is a widely used technique to help overcome ISI. However it is always possible to find an optimum pre-emphasis level that will lead to best-possible performance at the far end. The process of creating the transmitter's behavioral model is made easier by utilizing established matrix manipulation routines [4]. These computations take place in both the frequency and time domain.

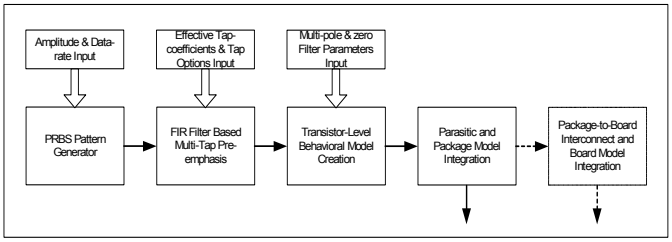


Figure 1 Transmitter behavioral modeling flow chart

Figure 1 shows the flowchart that graphically describes the creation of these models. The pseudorandom bit sequence (PRBS) data patterns can be generated with arbitrary bit width at any specified data-rate and amplitude.

Transmitter pre-emphasis is first generated using a discrete Z-domain FIR filter. For accuracy, the model created uses tap-coefficients extracted from either transistor-level simulations or measurement data. This reflects the actual behavior of a transmitter necessary for accuracy in the behavioral model. This approach allows a straightforward implementation of multi-tap pre-emphasis.

A multi-pole filter is then employed to model the transistor switching behavior, parasitic and output loading conditions. Taking for example the transmitter, the actual amplitude seen is limited due to finite supply voltage. The latter has to be extracted from either circuit simulation or measurement data and must account for headroom limitations, transistor charge-sharing effects as well as parasitic from routing on the silicon, ESD and bump pads. These factors also limit the edge-rate of output signal and need to be accounted for in the behavioral model. On a per-amplitude setting basis, these effects can be encompassed as a synthetic multi-pole filter, which can be represented by the following transfer function

$$H(\omega) = \frac{1}{(1 + j\omega / p_1)(1 + j\omega / q_n)^n}$$

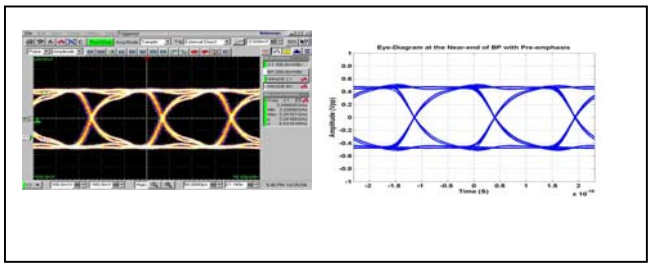
where p_1 and q_n are poles and n is the order.

B. Rx Equalizer Modeling

Equalization techniques are commonly used to compensate for ISI in addition to, or as a replacement for, Tx pre-emphasis. The equalizer is represented, in its simplest form, by a continuous-time transfer function which has programmable gain, zero and pole locations. Again, the transfer function is generated from extracted transistor-level simulations of the actual equalizer.

C. Behavioral Model Correlation

Validation of behavioral models is performed by correlating them with both extracted circuit-level simulations and measurements.



(a) (b)

Figure 2 Tx output eye-diagram correlation: (a) measurement; (b) simulation from behavioral model

An example of an eye-diagram seen at the output of our transmitter (near-end) at 6.5Gb/s is shown in Figure 2. As seen, the amplitude and shape match fairly well. It is important to note that the measurement has a component of RJ and other DJ components on it that accentuates the measured curve over the simulated one. Jitter separation is employed to deembed the RJ, and other DJ components, thus confirming the ISI component for any given PRBS input pattern.

Good overall link correlation can only be achieved when a high-degree of precision in the behavioral models is obtained. As a result, considerable effort goes into modeling non-idealities of each component so as to avoid loss of accuracy.

III. Simulation Platform And Applications

A. Overall Framework

A high-level diagram of the overall platform that shows how the link is modeled and driven is shown in Figure 3.

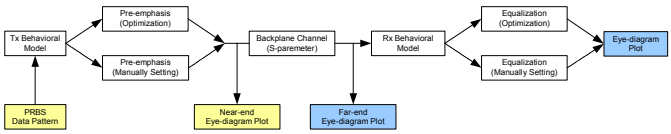


Figure 3 Block diagram of a full link simulation platform

The platform shown has the link represented by S-parameters and offers options to minimize the effects from ISI through the different signaling techniques, optimization algorithms and/or manually setting those options available to the customer. Once the tap coefficients and equalization settings are obtained, the eye diagrams can be plotted at specified locations (as shown in the figure) and parameters associated with the eye-diagram (e.g. eye opening width and height) can be extracted for any given input data pattern.

For ease of use, a user interface is added that guides the process of data entry. As shown in the flowchart of Figure 4, the user is requested to load the backplane S-parameter data file and then choose the Altera transceiver product and one of four-optimization modes. Available choices at this time include

1) Tx is manually set, with Rx automatically optimized
2) Rx is manually set, with Tx automatically optimized
3) Both Tx and Rx are automatically optimized and
4) Both Tx and Rx are manually set.

Depending on the optimization mode selected, as in the example shown in Figure 4, users need to specify the transmitter output amplitude, data rate, and pre-emphasis setting. The simulator then automatically searches for the optimal equalization setting for this particular backplane.

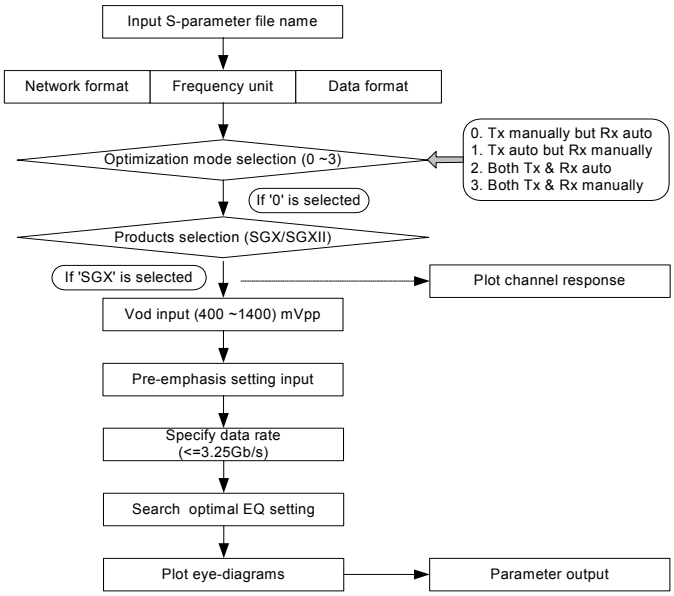


Figure 4 Link simulation platform user interface example

PELE will plot the S-parameter characteristics of the link as a function of frequency with an option to plot the impulse response with and without transmitter pre-emphasis. All eye-diagrams are shown with and without pre-emphasis and/or equalization. Eye opening characteristics are generated textually as well.

B. Link Signal Processing

The second point made earlier which allows for fast simulation is the mathematical, signal processing approach used in PELE. PELE relies on considerable manipulation between time- and frequency-domains in order to process signals through the link. Referring to Figure 5, the transmitter accepts ideal data symbols and pre-distorts them according the behavioral model. Naturally, the output is subsequently degraded when passed through the link. This degradation is determined by first obtaining the channel impulse response by applying the Inverse Fast Fourier Transform (IFFT) to the S-parameters representative of the link. The transmitter's output is then convolved with the impulse response yielding the distorted data seen at the far-end of the channel.

Determining the quality of the signal at the output of the receiver (i.e. seen at the input of a clock/data recovery circuitry) can be approached in a couple of manners. The easiest and perhaps a logical extension would be to take existing, distorted signal and perform an IFFT and multiply it with the receiver's transfer function. This approach would complicate our ability to later perform optimization and easily account for the package's S-parameters. To overcome this, our approach was to first perform an FFT on the Tx behavioral model and multiply that with the channel frequency response and equalizer's behavioral model in the frequency domain. Once done, an IFFT is performed to see the time-domain output of the receiver.

C. Optimization

It was mentioned earlier that such a large number of transceiver settings at the customer's disposal implies considerable effort to explore through all the combinations. Not only is this true from a conventional transient simulation perspective (ie. Spice, etc), but also it is true of PELE as well. For that reason, an algorithmic approach is used to help converge on suggested solutions.

When optimizing transmit amplitude and pre-emphasis settings, the far-end distorted data and the error signal, as defined by the difference between the delayed training data and the input data, go into the convergence engine [5], [6] whose algorithm is given by

$$C(n+1) = C(n) + \mu \cdot u \cdot e \qquad (2)$$

where C is the tap coefficient, μ is the step size, u is the distorted signal, and e is the error signal. The convergence of error drives the pre-emphasis tap coefficients to their optimal values shown in Figure 5. The tap coefficients are variable, quantized to the available settings in the product. At the end of this process, time-domain simulations are performed with the resulting eye-diagrams displayed.

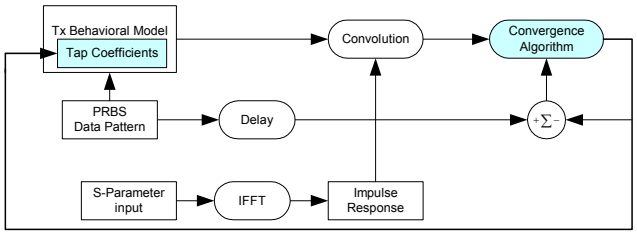


Figure 5 Tx Signal Path & Optimization Flowchart.

Similarly, equalizer performance can be optimized leading to suggested settings for a given link. As shown in Figure 6, the Tx output data pattern is first converted to the frequency domain, then multiplied by both the channel frequency response and the Rx equalization model represented by its transfer function. The product of the above three parts is converted back to time domain through an IFFT process. Finally an optimization algorithm is repeatedly applied to this process to seek for an optimal equalizer setting.

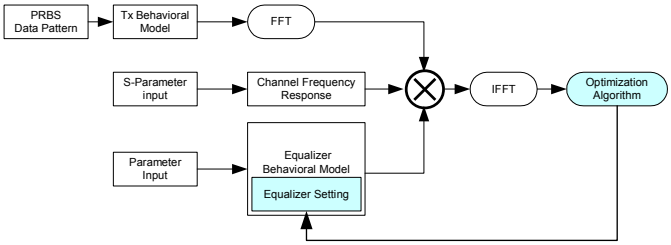


Figure 6 Rx Signal Path & Optimization Flowchart

D. Results

Correlation between PELE, transient simulation and measurements is accomplished using a suite of backplanes available to us. Three backplanes were selected to represent the worst-, typical- and best-case customer scenarios.

A full correlation process requires each and every setting to be exercised and compared. This is doable as the measurement process can be automated so that all eye diagrams can be captured and compared. As the output of the equalizer is not easily seen off-chip, BER is predicted and compared as part of the measurement correlation process.

Furthermore, as regards equalization, we qualify our optimization approach by comparing transistor-level ADS simulation results for tap settings surrounding the optimized result. One example has been given in Figure 7, which demonstrates the predicted optimal setting of the analog equalizer after receiving data across a 56 inch FR4 backplane. Here, PELE found a setting for the equalizer for this particular backplane as shown. Clearly, one setting higher or lower shows poorer performance.

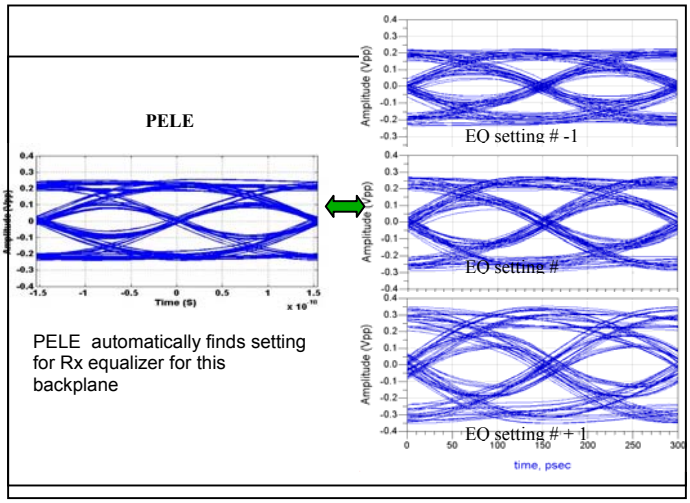


Figure 7 One qualification example of link simulation platform against ADS - Equalizer Output

An example of far-end correlation between PELE and measurement can be seen in Figure 8. Good correlation is seen which validates accuracy.

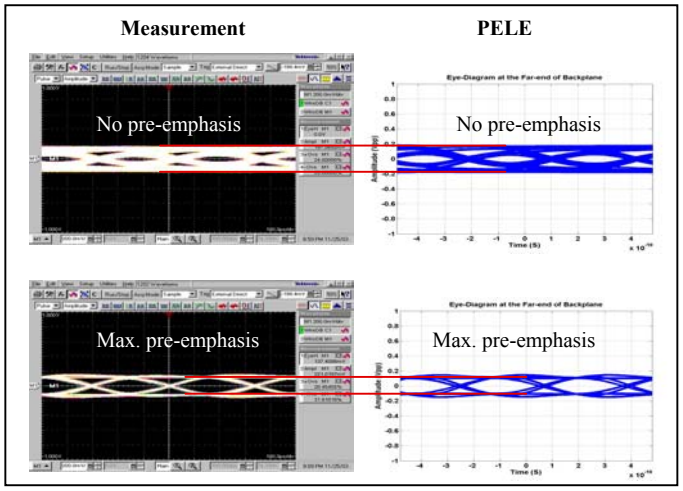


Figure 8 Far-end eye-diagrams correlation between the link simulator and measurement (3.125Gb/s data across 34" FR4 backplane)

Since the objective of any system is to achieve a minimum BER, we need to look at and include total jitter. This is particularly necessary when helping to qualify the equalizer as regards measurement, vs. predicted results. Conventional transient simulations generally yield DJ-related values. The RJ component is obtained from either transmit phase noise or jitter measurement. Armed with the DJ simulated through the link within PELE, and the RJ supplied, the BER becomes predictable through known methods [7] and is used to help overall correlation.

V. SUMMARY

PELE was originally created to address and quantify signal integrity limitations and then demonstrate the ability to overcome them. This tool enables us to quickly incorporate an arbitrary link and ascertain the viability of employing and varying the different signaling techniques available. An example application of PELE would be to consider minimizing power consumption by reducing transmit amplitude, vary pre-emphasis, then rely on equalization to maintain a BER specification.

A secondary application of PELE has been instrumental in assessing the types and levels of signaling required in next-generation transceiver products. This is achieved by allowing a version of this platform to be unlimited in its transmitter and equalizer's abilities.

This tool allows quick turn-around time when undergoing feasibility and performing design and is meant to help reduce time-to-market times for product development.

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