An Overview of High-Speed Serial Bus Simulation Technologies

Asian IBIS Summit, Beijing, China September 11, 2007



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- **1.** Overview: Traditional vs. Emerging Approaches
- 2. Worst-Case Bit Sequence
- **3.** Validating Results, Summary
- 4. Equalization





Traditional TD Simulations and SerDes

- It is possible to generate eye diagrams and BER contours with normal Time Domain simulations
- Benefit:
 - all non-linear and time variant effects can be accounted for (with appropriate Tx/Rx models)
- Problem:
 - it usually takes a long time to simulate, especially with transistor level Tx/Rx models





Advanced Analysis Techniques

- Chip and CAD tool vendors developed numerous "fast" algorithms in recent years
- Benefit:
 - one can predict the eye and BER of huge number of bit transitions (millions) in a few seconds or minutes
- Problem:
 - most algorithms rely on some assumptions which are not always true or cannot always be satisfied
 - **•** for example: using Linear, and Time Invariant (LTI) models

• Note:

there are specialized linear time domain simulators (using LTI assumptions) which are orders of magnitudes faster than general purpose time domain simulators





How do These "Fast" Algorithms Work?

- Most "fast" algorithms use superpositioning and statistical techniques to get quick results
- Example:
 - a worst case eye opening can be obtained from a pulse response by superimposing UI-wide slices of the waveform and summing them appropriately
 - BER curves are obtained similarly but the probability of each cursor combination is also calculated using statistical techniques





Statistical Contours



Illustration:

The innermost contour corresponds to the worst case eye opening

The worst case contour alone doesn't tell us of the probability a trace may reach a particular region

The nested contours confine the areas a trace may enter with a certain probability: 0, 1e-30, 1e-27...1e-3, etc...

Statistical contours are what we'd get if we built the set of eye contours for increasingly longer sequences





Additional Effects

- Cross talk and jitter increases the complexity of the algorithms
 - is the aggressor signal synchronized with the victim?
 - deterministic and random jitter must be handled differently
 - etc...
- Multi-tap, equalization, clock recovery features require additional algorithms
- Encoded data needs special attention
 - 8b10b and similar encoding schemes eliminate certain data patterns and result in a more open eye naturally





Crosstalk Illustration

- Since crosstalk responses add to the self-response, the PDFs of the crosstalk responses and the self-response must be convolved
- However, the crosstalk PDFs must be defined differently depending on whether the signals of the victim and aggressor(s) are synchronized



For synchronous crosstalk (left), we need to define a PDF for each slice along unit interval. For asynchronous crosstalk (right), we define uniform PDF by averaging all the crosstalk PDFs



Jitter Illustration

- **Random jitter has unlimited Gaussian distribution. It may** close the eye (at low levels of probability)
 - we characterize random jitter by defining both statistical (sigma/bit interval ratio) and frequency properties (median frequency/bit rate ratio)
- **Deterministic sinusoidal jitter has 1/sqrt(1-x²) type PDF.** (Some use a double dirac delta function as a simplification). It may close the eye only if the magnitude is large enough
 - it is characterized by magnitude and frequency measure
- We account for jitter in statistical and time-domain simulation (eye-contour, traces and bathtub)





Further reading on jitter: http://www.tek.com/Measurement/scopes/jitter/55W_16146_1.pdf



Jitter Effects on Bathtub Curves



Red - no jitter

- Blue sinusoidal jitter, magnitude to bit interval ratio is 0.02
- **Green** gaussian random jitter, sigma to bit interval ratio 0.05
- **Black** both random and sinusoidal jitter



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Verification at Worst Case

How do we Know we Have the Correct Answers?

- We can find what data sequence generates the worst eye contour and then using the same sequence we can run time domain simulations to check whether we get the same eye contour
- Problem:
 - how do we find the "true" worst case?
 - LTI models used in "fast" algorithms may give a different worst case sequence from the actual worst case sequence we would get using non-LTI models





Worst Sequence (WS)

- The WS is *unique* for any combination of channel and pulse width
- For a given channel and pulse width, we can find a WS directly that generates the worst eye in a fraction of a second
- If WS contains 50 pulses, the probability to find WS & worst eye by applying a long random sequence would be 1 in 2⁵⁰, or less than 1 in 1e¹⁵
- We can also find the WS directly for encoded data sequences, such as 8b10b





Why are the tails of the PDF so important?





This small red area contains all of the bit errors (BE), and the lower bound on the PDF (green line) is the worst case From here we can see how important it is to generate an accurate tail for the PDF.

The lower bound of the PDF is determined by the worst case sequence. Without knowing this bound, an accurate BER estimation is not possible.





What does a true PDF look like?

- Two PDFs with the same expected value and similar mean deviations may produce both under- (A) and over-estimation (B) of the BER.
 - * The central limit Theorem states that the sum of many independent and identically distributed random variables tends to have Gaussian distribution. However, the cursors typically have very different magnitudes therefore the associated values are not identically distributed.



Data Encoding and WS Prediction







Unconstrained worst case sequence results in a closed eye (*pessimistic*) A 100k-bit long <u>random</u> 8b10b input sequence results in an eye that is better than reality (<u>optimistic</u>) A 400-bit long <u>worst</u> 8b10b input sequence yields a <u>realistic</u> worst case eye while complying with the protocol





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Additional Checks and Tests

- We can check the effects of non linearity by
 - overlaying the waveforms of full transistor level models with the waveforms of behavioral models used in the "fast" tools
- Comparing the results of the various "responses" can help to find the amount of non-linearity
 - rising/falling step, pulse, impulse
- We can run a huge number of bit transitions with <u>fast time</u> <u>domain</u> simulations and correlate its results with the results of statistical algorithms
 - remember, there are fast time domain simulation techniques (using LTI assumptions) that make trillions of bits simulations possible (in the time domain)

Cross-Verification Flow

Worst-case solution imposes bounds on statistical measures such as PDF or BER. Those can be verified

Fitted vs. Convolution-Based Algorithms

Problem:

- convolution based algorithms use impulse/pulse/step response waveforms as input
- the length of the input waveform determines the length of the convolution and ultimately the accuracy and speed of the algorithm

Solution:

- use fitted functions
- accuracy is independent of input waveform's length
- no need to limit the waveform's sampling rate or length
- unlimited dynamic range (accurate accounting for low frequency effects)
- **—** about 100 times faster than competing approaches

Channel with Long Impulse Response

A 60 ns impulse response seems to settle after 5 ns

However, when zooming out, oscillations become visible

Convolution-based methods become inefficient with long responses

Menfor araphics Over

AC Analysis Reveals Low-frequency resonances

Sampled transfer function (from AC analysis with adaptive step) and fitted transfer function are in excellent agreement (error < 0.03%)

ISI May Propagate for Thousands of Bits

- Fitted data consists of 20 poles only vs. the thousands of points in the pulse response waveform that is used by the convolution based algorithm
- It is impossible to determine the required minimum length for the pulse response other than by trial and error

Eye opening vs. # of bits in the worst case sequence

Unconstrained WS: need a length in the hundreds

8b10b WS: need a length in the thousands

Eye opening vs. length of random sequence

Convolution with a 100-bit WS does not show eye closing (magenta, cyan)

BER Contours for Long ISI Propagation

Unconstrained sequence

8b10b protocol

Benchmarks (Normalized to 1e6 Bits)

Fit-based approach

- Cursor-based approach (4000 bit long response)

Summary:

- **—** The Ratio was 150 without and 400 with input jitter
- However, as we saw it before from the 8b10b worst sequence, the 4000 bit pulse response is still too short to cover all of the ISI effects in this particular channel

Simulation Technique Comparison Chart

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Tx and Rx Equalization

- There are two main types of equalization
 - Finite Impulse Response (FIR), also known as Feed-Forward Equalizer (FFE)
 - http://en.wikipedia.org/wiki/Finite_impulse_response
 - Infinite Impulse Response (IIR), also known as Feed-Back Equalizer (FBE)
 - <u>http://en.wikipedia.org/wiki/Infinite_impulse_response</u>
- Both of these can be implemented in Tx and Rx
- Decision Feedback Equalization (DFE)
 - similar to IIR (or FBE) but it has a decision block (comparator) in the loop
 - implemented in Rx only

A Typical DFE Block

In contrast to linear equalization, DFE cannot suppress pre-cursors. However, it is capable of completely removing a number of the post cursors

Opening the Eye with DFE

taps = 0

taps = 10

taps = 30

Bathtub Curves with FFE and DFE

FFE and DFE if applied together allow the best combined effect.

If necessary, we may add random jitter and build the combined eye/bathtub or investigate bit error propagation

Blue- no DFERed- 2 tap DFEBlack- 5 tap DFE and 3 tap FFE

