Presentation on Serial Link Simulation using ADS

This document is owned by Agilent Technologies, but is no longer kept current and may contain obsolete or inaccurate references. We regret any inconvenience this may cause. For the latest information on Agilent’s line of EEsof electronic design automation (EDA) products and services, please go to:

www.agilent.com/find/eesof
Serial link Simulation using Advanced Design System
Serial Link Challenge

• Analog Components in a Serial Link
  – Interconnects  *Best represented in frequency domain*
    • Modeling impedance mismatch, crosstalk, dispersion, dielectric losses
      – Frequency domain models derived from simulation or measurements
  – I/O Models  *Best represented in time domain*
    • IBIS and non-linear transistor level models

• Digital Components in a Serial Link
  – SERDES Models  *Best represented in numeric domain*
    • De-emphasis
    • Decision Feedback Equalizer
    • Feed Forward Equalizer
    • Clock and Data Recovery
    • Gain Controls

Accurate representation of RF, analog, and digital components using ADS

Agilent Technologies
Agenda

- High-Speed Serial Link: Design Flow
- Transmitter: Jitter Modulation, De-emphasis Modeling
- Analog Passive Channel: Interconnect Modeling
- Receiver: Jitter Modulation, Equalization Modeling
- Post-Processing: Statistical Eye, BER/Bathtub
- Validation of Results and Examples

Paper contributed by:
Huang Chunxing (huangchunxing@huawei.com),
Cory Edelman (cory_edelman@agilent.com), &
Sanjeev Gupta (sanjeev_gupta@agilent.com)
High-Speed Serial Link Design

Transmitter

Data Signal → FEC & Coding → Pre-emphasis (RJ, DJ, DDJ, PJ) → Tx

Receiver

Rx → Feed Forward Equalizer → Decision Feedback Eq. → CDR

1. Component designer – Ensures that components meet jitter budget specifications
2. Link Architect – Link jitter analysis, BER, De-emphasis, FFE, DFE

Analog Passive Channel

Statistical post processing
High Speed Serial Link - Design Flow

Transmitter

MATLAB Co-simulation in ADS

Analog Channel

Receiver

MATLAB Co-simulation in ADS
Why Huawei used ADS?

- A *time-domain simulator* that *accurately* finds the response of frequency-domain measurements and models – *how channels are characterized*
  - ADS 2006 Update 1 has a new, exclusive, patent-pending simulator that accurately predicts time domain response directly from multi-port S-parameter models

- A *link-level tool* that can model equalizers and pre-emphasis, analog channel, and verify performance by analyzing jitter
  - ADS Ptolemy supports RF and DSP co-simulation. (mixed signal simulation)
  - Deterministic jitter is bounded and may be simulated within an acceptable time

- **Co-simulation with external tools**
  - ADS supports MATLAB co-simulation

- **Able to use fast behavioral driver, buffer and receiver models**
  - ADS 2006 Update 1 supports IBIS models
Transmitter - Jitter Component

ISI: largest of the difference between the earliest falling/rising edge and latest falling/rising edges.

DDJ: difference in the position of the earliest edge (rising or falling) and the latest (rising or falling) edge.

DCD: amplitude of nominal eye crossing is other than the 50% level.

TJ(t) = RJ(t) + PJ(t) + DDJ(t) + ...

Data Correlated

Data Un-Correlated
Transmitter Modeling - Jitter Modulation

- Using Voltage Controlled Delay to add jitter
- Transmitted jitter includes Periodic Jitter or PJ, and Duty Cycle Distortion or DCD
- Random Jitter or RJ will be considered in statistical post-processing

\[ PJ_{total}(t) = \sum_{i=0}^{N} A_i \cos(w_i t + \theta_i) \]

- Sinusoidal Source
- DCD

\[ DCD = 0.5 \left[ \delta(x - W/2) + \delta(x + W/2) \right] \]
- Pattern Generator
- Voltage Control Delay
- Signal with jitter
Transmitter Modeling – De-emphasis

- Pre-distortion of a digital signal to compensate for high frequency losses in a channel
- Both pre-emphasis and de-emphasis could be expressed as Finite Impulse Response or FIR filter

![Frequency Response Graph](image)
High-Speed Serial Channel Components

- Connectors
- Line-cards
- Backplane
Serial Link- Channel Representation

- Measurement-based models – Network Analyzer
- Physical models – EM solution of Maxwell’s equations
- Analytical models – closed form representation
Channel Models

- Channel models, including forward response and crosstalk, are usually best expressed using S-parameters.
- ADS provide accurate time domain simulations directly from S-parameter/Touchstone files obtained from Network Analyzer measurements or EM solvers.

Channel Impulse response:
Derived from direct S-parameter simulation using ADS High Frequency SPICE.

Comparison of S-Parameters derived from the impulse response of ADS SPICE simulator with original data.
Co-Simulation in ADS (Analog/Digital Mixed Signal Simulation) (Molex 10Gb Backplane)
Receiver Modeling - Equalization

The Impulse Response $h(t)$ embodies all of the information contained in a circuit element.

To obtain the optimum tap coefficients, we need to invert the process:
“Taps” are the corrections the equalizer uses to open the eye

- A weight is applied to \( N-1 \) preceding bits to correct the current bit...

\[
e(n) = \sum_{k=0}^{N-1} T_{ap_k} r(n - k)
\]

\[
e(n) = \sum_{k=0}^{N-1} f(k) r(n - k)
\]
LFE taps are tuned to
1. remove ISI over N pre-cursors and
2. to minimize noise gain, $f^*f$

The $M$ feedback taps, $b(n)$, cancel the residual post-cursor ISI after the LFE.
Decision Feedback Equalizer

\[ r(n) \rightarrow T \rightarrow r(n-1) \rightarrow T \rightarrow r(n-2) \rightarrow \ldots \rightarrow r(n-(N-1)) \]

\[ f(0) \times f(1) \times \ldots \times f(N-1) \times \]

\[ + \rightarrow \]

\[ e(n) \rightarrow \]

Feedback filter

\[ s(n) \rightarrow T \rightarrow \hat{s}(n-1) \rightarrow T \rightarrow \hat{s}(n-2) \rightarrow \ldots \rightarrow \hat{s}(n-(M-1)) \]

\[ \times \times \times \times \times \]

\[ + \rightarrow \]

Delay, \( \tau \)

Symbol Detector

\[ ADS \]

\[ \text{time, psec} \]

\[ 0.4 \]

\[ 0.2 \]

\[ -0.2 \]

\[ -0.4 \]

\[ 0 \]

\[ 0.15 \]

\[ 0.1 \]

\[ 0.05 \]

\[ 0 \]

\[ -0.05 \]

\[ -0.1 \]

\[ -0.15 \]

\[ -20 \]

\[ -10 \]

\[ 0 \]

\[ 10 \]

\[ 20 \]

\[ 30 \]

\[ 40 \]

\[ 50 \]

\[ 60 \]

\[ 70 \]

\[ 80 \]

\[ 90 \]

\[ 100 \]

\[ 110 \]

\[ 120 \]
Equalizer- Algorithms

Algorithm calculates the optimal sampling point and equalizer coefficients

- **LMS adaptive algorithm**
  - The LFE taps are set to maximize the eye-opening.
  - Optimization techniques seek to determine the maximum of a function…
    - The problem:
      \[ \sum_n (s(n) - e(n))^2 = \sum_n \left[ s(n) - \sum_{k=0}^{N-1} f(k)r(n-k) \right]^2 \]
    - Find values for \( f_n \) to minimize the function

- **Zero Forcing algorithm**
  - Solve the following N-equations
    \[
    s(0) - \sum_{k=0}^{N-1} f(k)r(0-k) = 0 \\
    : \\
    s(N) - \sum_{k=0}^{N-1} f(k)r(N-k) = 0
    \]

But zero forcing
- does not give the best SNR
- is not unique

See William Press,
*Numerical Recipes*, Chapter 10
Equalization Type

- **Non-adaptive Equalizers**
  - Taps coefficient are fixed

- **Adaptive Equalizers**
  - Adaptive equalizers adjust their taps on the fly
  - Argument for including a known training pattern in the protocol
    - Training pattern \( \Rightarrow \) the ideal decision assumption is true
    - There are many proprietary adaptive equalizers without training sequences: “blind equalizer.”

\[
e(n) = \sum_{k=0}^{N-1} f(k)r(n-k)
\]
Decision Feedback Equalization (Non Adaptive)
Decision Feedback Equalization - Adaptive
DFE – 1 Sample per Bit

DFE is decision feed-back equalizer.
Continuous-Time Equalizer

CTE stands for continuous time equalizer. A CTE model is an ideal circuit that can adjust zeros and pole positions to get the desired frequency response. As with FFE, CTE has a noise gain problem. CTE with only one pole and one zero can be expressed by the following equation:

\[ H_{CTE}(f) = a \frac{p_0}{z_0} \frac{(s + z_0)}{(s + p_0)} \]

This is typically implemented in the analog domain.
Determining Link Performance – Statistical Post Processing

Why statistical post processing?

• Predict BER performance with minimal bit pattern

Calculate Forward channel PDF:

1. Interpolate through response to sufficiently small time interval

2. Overlap each bit in one Unit Interval (UI) range

3. At each UI sampling point, compute PDF of Overlapping data.
Statistical Post Processing - Random Jitter Effects on Link Performance

Random Jitter distribution

\[ P_{RJ} = \frac{1}{\sqrt{2\pi \sigma}} e^{-\frac{t^2}{2\sigma^2}} \]

Overall PDF

\[ P(ISI, \tau) = \int_{-\infty}^{\infty} P(ISI, \tau + \nu) \cdot P_{RJ}(\nu)d\nu \]
Statistical Post-Processing Using MATLAB® Co-simulation in ADS

Statistical Eye “StatEye”

- Statistical eye is a set of probability contours
- Horizontal axis is with respect to sampling point
- Vertical axis is with respect to signal amplitude
- Different colored lines represent BER
Bathtub

- Intercept through statistical eye along horizontal axis to get horizontal Bathtub at definite voltage
- Intercept through statistical eye along vertical axis to get vertical Bathtub at definite sampling time
Simulated vs. Measured

Validation of Simulation Results

- Using Agilent N4903 J-BERT signal generator; 86100C Infinium wideband scope
- N4903 internal random jitter (RJ) used in all cases shown

0.010 Unit Interval RJ

0.015 Unit Interval RJ
Simulated vs. Measured

Validation of Simulation Results (2)

0.05 Unit Interval PJ, .011 RJ

0.015 Unit Interval PJ, .018 RJ
Example - Channel pre-simulation

Assumed conditions:

10Gbps NRZ, PRBS 23, 100000 bits, amplitude 800mvpp, Tr(f) = 24ps

0.15UIpp DJ = 0.05UI DCD+0.1UI PJ, 0.15UIpp RJ @10^{-12}BER

BER = 1e-12 (2*Q=14.069)

3-tap de-emphasis, 5-tap DFE

Slice voltage: 10mV

Forward Channel Insertion Loss:

Eight crosstalk channels:
Example - Channel pre-simulation

- Simulation results:
  - 28mv eye-height
  - 0.222UI eye-width

- This indicates that the channel could support 10Gbps data transmission
ADS2006 Update 2 will provide root cause analysis of jitter problems

• Provides confidence that the BER simulation results will match the measured performance.
• Provides jitter diagnosis, which can reduce the product development cycle from weeks to hours.
• Allows the designer to systematically tweak the link for best performance by understanding the underlying issues

“ADS is the only commercially available EDA product that provides jitter diagnosis and results that can be trusted”
Jitter Analysis Capability in ADS2006 Update 2
Bathtub and Q Plots ADS2006 Update 2

<table>
<thead>
<tr>
<th>BTMdl</th>
<th>BTData</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TJpp</th>
<th>RJrms</th>
<th>DJdd</th>
<th>PJdd</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.319E-11</td>
<td>2.057E-12</td>
<td>3.860E-12</td>
<td>3.799E-12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PJrms</th>
<th>ISIpp</th>
<th>DCD</th>
<th>DDJpp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.635E-12</td>
<td>3.248E-13</td>
<td>3.458E-14</td>
<td>3.248E-13</td>
</tr>
</tbody>
</table>
Overcoming the Serial Link Design Challenge Using ADS

• Analog Components in a Serial Link
  – Interconnects **Best represented in frequency domain**
    • Modeling impedance mismatch, crosstalk, dispersion, dielectric losses
      – Frequency domain models derived from simulation or measurements
  – I/O Models **Best represented in time domain**
    • IBIS and non-linear transistor level non-linear models

• Digital Components in a Serial Link
  – SERDES Models **Best represented in numeric domain**
    • De-emphasis
    • Decision Feedback Equalizer
    • Feed Forward Equalizer
    • Clock and Data Recovery
    • Gain Controls

**Accurate representation of RF, analog, and digital components using ADS**
Summary:

- Introduced: Serial Link Design and Verification Design Flow
- The basic methodology of statistical eye simulation in ADS has been presented
- ADS is shown to be an ideal platform to realize statistical eye simulation:
  - Jitter Modulation at transmitter
  - Forward channel, crosstalk channel models
  - Include pre-emphasis or de-emphasis
  - Equalizers: Adaptive LFE, DFE
  - Statistical post-processing: StatEye, Jitter separation, BER bathtub
- Presented: A brief overview of new jitter analysis capabilities in ADS