ECEN689: Special Topics in High-Speed Links Circuits and Systems
Spring 2010

Lecture 23: Jitter

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Announcements

• HW6 due Wednesday April 7 (in class)
• Exam 2 will be either April 28 or 30
• Reading
  • Will post some jitter application notes
  • Majority of today’s material from Hall reference
Agenda

• Noise Budget Example

• Jitter
Noise Source Classifications

- Determining whether noise source is
  - Proportional vs Independent
  - Bounded vs Statistical
- is important in noise budgeting

![Noise Source Classifications Diagram]
Noise Budget Example

- Peak TX differential swing of 400mV\textsubscript{ppd} equalized down 10dB
  - ±200mV → ±63mV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>K\textsubscript{n}</th>
<th>RMS</th>
<th>Value (BER=10^{-12})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Differential Swing</td>
<td></td>
<td></td>
<td>0.4V</td>
</tr>
<tr>
<td>RX Offset + Sensitivity</td>
<td></td>
<td></td>
<td>5mV</td>
</tr>
<tr>
<td>Power Supply Noise</td>
<td></td>
<td></td>
<td>5mV</td>
</tr>
<tr>
<td>Residual ISI</td>
<td>0.05</td>
<td></td>
<td>20mV</td>
</tr>
<tr>
<td>Crosstalk</td>
<td>0.05</td>
<td></td>
<td>20mV</td>
</tr>
<tr>
<td>Random Noise</td>
<td>1mV</td>
<td></td>
<td>14mV</td>
</tr>
<tr>
<td>Attenuation</td>
<td>10dB = 0.684</td>
<td></td>
<td>0.274V</td>
</tr>
<tr>
<td>Total Noise</td>
<td></td>
<td></td>
<td>0.338V</td>
</tr>
<tr>
<td>Differential Eye Height Margin</td>
<td></td>
<td>62mV</td>
<td></td>
</tr>
</tbody>
</table>

- Conservative analysis
  - Assumes all distributions combine at worst-case
- Better technique is to use statistical BER link simulators
**Eye Diagram and Spec Mask**

- Links must have margin in both the voltage AND timing domain for proper operation.
- For independent design (interoperability) of TX and RX, a spec eye mask is used.

![Eye Diagram](image)

- **Eye at RX sampler**
- **RX clock timing noise or jitter (random noise only here)**
Jitter Definitions

- Jitter can be defined as “the short-term variation of a signal with respect to its ideal position in time”

- Jitter measurements
  - Period Jitter ($J_{PER}$)
    - Time difference between measured period and ideal period
  - Cycle to Cycle Jitter ($J_{CC}$)
    - Time difference between two adjacent clock periods
    - Important for budgeting on-chip digital circuits cycle time
  - Accumulated Jitter ($J_{AC}$)
    - Time difference between measured clock and ideal trigger clock
    - Jitter measurement most relative to high-speed link systems
Jitter Statistical Parameters

- **Mean Value**
  - Can be interpreted as a fixed timing offset or “skew”
  - Generally not important, as usually can be corrected for

- **RMS Jitter**
  - Useful for characterizing the random component of jitter

- **Peak-to-Peak Jitter**
  - Function of both deterministic (bounded) and random (unbounded) jitter components
  - Must be quoted at a given BER to account for random (unbounded) jitter
Jitter Calculation Examples

![Diagram of jitter calculation examples]

<table>
<thead>
<tr>
<th>n</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Mean</th>
<th>RMS</th>
<th>PP</th>
</tr>
</thead>
<tbody>
<tr>
<td>J_{PER}</td>
<td>-0.06</td>
<td>0.02</td>
<td>-0.06</td>
<td>0.12</td>
<td>0.005</td>
<td>0.085</td>
<td>0.18</td>
</tr>
<tr>
<td>J_{CC}</td>
<td>0.08</td>
<td>-0.08</td>
<td>0.18</td>
<td>-</td>
<td>0.06</td>
<td>0.131</td>
<td>0.26</td>
</tr>
<tr>
<td>J_{AC}</td>
<td>-0.07</td>
<td>-0.05</td>
<td>-0.11</td>
<td>0.01</td>
<td>-0.055</td>
<td>0.05</td>
<td>0.12</td>
</tr>
</tbody>
</table>
Jitter Histogram

- Used to extract the jitter PDF
- Consists of both deterministic and random components
  - Need to decompose these components to accurately estimate jitter at a given BER
Jitter Categories

- **Total Jitter**
  - **Random Jitter (RJ)**
    - Characteristics:
      - Unbounded, Gaussian distributed
      - Key parameters: $\mu = 0$, $\sigma_{\text{RMS}}$
      - Sources: Device noise (shot, flicker, thermal)
  - **Deterministic Jitter (DJ)**
    - Characteristics:
      - Bounded, peak-to-peak
      - Key parameters: Maximum pk-pk jitter
      - Sources: Losses, reflections, $t_f/t_r$ mismatch, spread spectrum clocking, crosstalk
  - **Sinusoidal Jitter (SJ)**
  - **Data Dependent Jitter (DDJ)**
  - **Intersymbol Interference (ISI)**
  - **Duty Cycle Distortion (DCD)**
  - **Bounded Uncorrelated Jitter (Crosstalk)**
Random Jitter (RJ)

- Unbounded and modeled with a gaussian distribution
  - Assumed to have zero mean value
  - Characterized by the rms value, $\sigma_{RJ}$
  - Peak-to-peak value must be quoted at a given BER
- Originates from device noise
  - Thermal, shot, flicker noise

$$RJ(t) = \frac{1}{\sqrt{2\pi}\sigma_{RJ}} e^{\frac{-t^2}{2\sigma_{RJ}^2}}$$
Deterministic Jitter (DJ)

- Bounded with a peak-to-peak value that can be predicted
- Caused by transmission-line losses, duty-cycle distortion, spread-spectrum clocking, crosstalk
- Categories
  - Sinusoidal Jitter (SJ or PJ)
  - Data Dependent Jitter (DDJ)
    - Intersymbol Interference (ISI)
    - Duty Cycle Distortion (DCD)
    - Bounded Uncorrelated Jitter (BUJ)
Sinusoidal or Periodic Jitter (SJ or PJ)

- Repeats at a fixed frequency due to modulating effects
  - Spread spectrum clocking
  - PLL reference clock feedthrough
- Can be decomposed into a Fourier series of sinusoids
  \[ SJ(t) = \sum_{i} A_i \cos(\omega_i t + \theta_i) \]
- The jitter produced by an individual sinusoid is
  \[
  PDF_{SJ}(t) = \begin{cases} 
  \frac{1}{\pi \sqrt{A^2 - t^2}} & A > |t| \\
  0 & A \leq |t| 
  \end{cases}
  \]
Data Dependent Jitter (DDJ)

- Data dependent jitter is correlated with either the transmitted data pattern or aggressor (crosstalk) data patterns.
- Caused by phenomena such as phase errors in serialization clocks, channel filtering, and crosstalk.
- Categories:
  - Duty Cycle Distortion (DCD)
  - Intersymbol Interference (ISI)
  - Bounded Uncorrelated Jitter (BUJ)
Duty Cycle Distortion (DCD)

- Caused by duty cycle errors in TX serialization clocks and rise/fall delay mismatches in post-serialization buffers
- Resultant PDF from a peak-to-peak duty cycle distortion ($\alpha_{DCD}$) is the sum of two delta functions

$$PDF_{DCD}(t) = \frac{1}{2} \left[ \delta \left( t - \frac{\alpha_{DCD}}{2} \right) + \delta \left( t + \frac{\alpha_{DCD}}{2} \right) \right]$$
Intersymbol Interference (ISI)

- Caused by channel loss, dispersion, and reflections
- Equalization can improve ISI jitter

![Histograms showing probability distribution of jitter with and without equalization](image)
Bounded Uncorrelated Jitter (BUJ)

• Not aligned in time with the data stream
• Most common source is crosstalk
• Classified as uncorrelated due to being correlated to the aggressor signals and not the victim signal or data stream
• While uncorrelated, still a bounded source with a quantifiable peak-to-peak value
Total Jitter (TJ)

- The total jitter PDF is produced by convolving the random and deterministic jitter PDFs

\[ \text{PDF}_{JT}(t) = \text{PDF}_{RJ}(t) * \text{PDF}_{DJ}(t) \]

where \( \text{PDF}_{DJ}(t) = \text{PDF}_{SJ}(t) * \text{PDF}_{DCD}(t) * \text{PDF}_{ISI}(t) * \text{PDF}_{BUJ}(t) \)
Jitter and Bit Error Rate

- Jitter consists of both deterministic and random components.

- Total jitter must be quoted at a given BER:
  - At BER=10^-12, jitter ~1675ps and eye width margin ~200ps.
  - System can potentially achieve BER=10^-18 before being jitter limited.
Dual Dirac Jitter Model

- For system-level jitter budgets, the dual Dirac model allows for the budgeting of deterministic and random jitter components.

\[
RJ(t) = \frac{1}{\sqrt{2\pi} \sigma_{RJ}} e^{-\frac{t^2}{2\sigma_{RJ}^2}}
\]

\[
DJ(t) = \frac{\delta(t - DJ_{\delta\delta} / 2)}{2} + \frac{\delta(t + DJ_{\delta\delta} / 2)}{2}
\]

\[
JT(t) = RJ(t) \times DJ(t) = \frac{1}{2\sqrt{2\pi} \sigma_{RJ}} \left[ e^{-\frac{t-DJ_{\delta\delta}/2}{2\sigma_{RJ}^2}} + e^{-\frac{t+DJ_{\delta\delta}/2}{2\sigma_{RJ}^2}} \right]
\]
Dual Dirac Jitter Model

- Jitter at a given BER is computed considering both leading and trailing edges

\[ BER_{\text{lead}}(t) = 0.5 \left[ \text{erfc} \left( \frac{t - DJ_{\delta \delta}}{2 \sigma_{RJ}} \right) + \text{erfc} \left( \frac{t + DJ_{\delta \delta}}{2 \sigma_{RJ}} \right) \right], \quad BER_{\text{trail}}(t) = 0.5 \left[ \text{erfc} \left( \frac{UL - t - DJ_{\delta \delta}}{2 \sigma_{RJ}} \right) + \text{erfc} \left( \frac{UL - t + DJ_{\delta \delta}}{2 \sigma_{RJ}} \right) \right] \]

where \( \text{erfc}(t) = \frac{2}{\sqrt{\pi}} \int_{t}^{\infty} e^{-x^2} \, dx \)
Dual Dirac Jitter Model Example

- Plot measured jitter PDF vs Q-scale

\[ Q_{BER}(BER) = \sqrt{2} \text{erf}^{-1} \left( 1 - \frac{BER}{\rho_T} \right) \]

where \( \rho_T \) is the transition density, typically 0.5

- Tails are used to extract \( \sigma_{Rj} \)

- Extrapolate to Q(0) to extract DJ bounds

![Graph of Jitter Distribution and Extracted Values](image)
Dual Dirac Jitter Model Example

- Extracted dual Dirac model matches well with measured jitter PDF
Next Time

- Statistical BER Analysis Tool Overview
- Timing Circuits