ECE 546
Lecture - 24
Jitter Analysis
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Measuring Jitter
Eye Diagrams

- Eye diagrams are a time domain display of digital data triggered on a particular cycle of the clock. Each period is repeated and superimposed. Each possible bit sequence should be generated so that a complete eye diagram can be made.
Eye Diagram

- $t_{UI}$: Symbol Duration
- $V_{P,P}$: Differential Peak-to-Peak Voltage
- $t_{TJ}$: Total Jitter
- $t_{MJ}$: Marginal Jitter
- 300mV

Mathematical model of jitter and voltage in a communication system.
High-Speed Oscilloscope

8-bit flash ADCs provide 256 discrete levels along vertical axis
Interleaving Architecture

[Diagram of interleaving architecture with labeled components such as Input Signal, Variable Gain Preamp, T/H, A/D, MUX, Master Timebase, Clocks φ1, φ2, φ3, φN, and Samples Out.]
High-Speed Scope Digitizers

- **SiGe-Based Technologies**
  - Fastest ADCs run at 3.125 Gsamples/s
  - Typically 8-16 digitizers

- **CMOS Designs**
  - ADCs sample at lower rate
  - 80 digitizers or more
Timing Diagram

\[ T_{ADC} = \frac{T_{ADC}}{N} = T_{Samp} = \frac{1}{F_{Samp}} \]
Sampling Procedure

Once waveform samples have been reassembled into a representation of the waveform, they are stored to digital memory.

The maximum number of samples is the record length.

Record length are typically in excess of 100 million samples.
Frequency Interleaving

![Diagram showing a block diagram of frequency interleaving with components like splitter, filters, mixers, and local oscillators. The diagram illustrates the flow of signals through different channels: Channel 1, Channel 2, Channel 3, and Channel 4.](image-url)

- Filters: Lowpass, Bandpass 1, Bandpass 2
- Mixers
- Image Reject
- Local Oscillators
- Conventional High-Bandwidth Real-Time Scope

(For detailed analysis and understanding, refer to the full document or lecture notes.)
Nyquist Criterion

A signal of bandwidth $B$ that has been sampled at regular intervals $T$ can be exactly recovered if the sampling rate satisfies

$$F_N = \frac{1}{T} > 2 \times B$$

$F_N$ : Nyquist rate

$T$ : sampling interval

$B$ : bandwidth
High-Speed Oscilloscopes

• Oscilloscopes use DSP techniques to:
  - Extend their analog bandwidth
  - Flatten their amplitude

• Practice has benefits

• However, limitations should be understood
Scope Channel Equalization
Edge Triggering

\[ T_{\text{OFF}} \] is recorded with high resolution but is subject to noise.
Trigger Jitter

Trigger jitter is the amount of effective timing instability between the trigger path and the signal capture path.

In eye diagram construction, multiple waveform acquisitions are overlayed. Trigger jitter is then an externally introduced noise that cannot be distinguished from the true jitter.

Typical value: ~ 1 ps RMS
Trigger Jitter

- Waveforms from Different Trigger Events

- Trigger Position

- Time

- Voltage

$\sim 1$ ps RMS
Sample Jitter

Much of the timing instability in an oscilloscope is a combination of *phase noise* in the instrument’s time base and *aperture jitter* in the track-and-hold circuits.

They exhibit a Gaussian probability distribution.

*Interleaving errors* from the digitizers are another large source of errors. They are deterministic and are manifested as deterministic jitter can be calibrated out.
Oscillator Phase Noise
Sample Jitter

• **Gaussian Errors**
  - Phase noise
  - Aperture jitter in track-and-hold circuits

• **Deterministic Errors**
  - Interleaving mismatches
  - Can be calibrated out
Eye Diagram

An eye diagram is a time-folded representation of a signal that carries digital information.

Eye is horizontally centered on the ideal sampling instant.
Eye Diagram

• Unit interval (UI) of a bit sequence is typically independent of the waveform sampling interval of the measurement instrument.
  
  ➢ Waveform sampling interval must be no more than one half the unit interval to avoid aliasing
  
  ➢ Rule of thumb for eye diagrams is to sample 5 to 10 times the bit rate
  
  ➢ For 2.5 Gb/s, the sampling rate should be 20 GSamples/s

Large eye openings ensure that the receiving device can reliably decide between high and low logic states even when the decision threshold fluctuates or the decision time instant varies.
Eye diagram construction in real-time oscilloscope is based on hardware clock recovery and trigger circuitry.
Eye Diagram Construction
Eye Diagram Construction

1. Capture of the Waveform Record

2. Determine the Edge Times
Eye Diagram Construction

3. Determine the Bit Labels
Eye Diagram Construction

4. Clock Recovery
Eye Diagram Construction

5. Slice Overlay

6. Display
Eye Diagram Measurements

- Rise/fall slope
- Eye top
- Eye base
- Best time to sample center of the eye
- Time of significant events i.e., edges
- Relative bit time
- Voltage
Eye Diagram Measurements
Reference Levels
Eye Height

Eye Height is the measurement of the eye height in volts

\[ \text{Eye Height} = (\mu_{PTop} - 3\sigma_{PTop}) - (\mu_{PBase} + 3\sigma_{PBase}) \]

- \( \mu_{PTop} \) : mean value of eye top
- \( \sigma_{PTop} \) : standard deviation of eye top
- \( \mu_{PBase} \) : mean value of eye base
- \( \sigma_{PBase} \) : standard deviation of eye base
Eye Width

*Eye Width* is the measurement of the eye width in seconds

\[
\text{Eye Width} = \left(\mu_{TCross2} - 3\sigma_{TCross2}\right) - \left(\mu_{TCross1} + 3\sigma_{TCross1}\right)
\]

*Crossing percent* measurement is the eye crossing point expressed as a percentage of the eye height

\[
\text{Crossing Percent} = \frac{\left(\mu_{PCross1} - \mu_{PBase}\right)}{\left(\mu_{PTop} - \mu_{PBase}\right)} \times 100\%
\]
Jitter Measurements

Jitter peak-to-peak is the peak-to-peak value for the edge jitter in the current horizontal units

\[ \text{Jitter pp} = \max(TCross1) - \min(TCross1) \]

Jitter root mean square is the RMS value of the edge jitter in the current horizontal units

\[ \text{Jitter RMS} = \sigma_{TCross1} \]

Jitter 6\(\sigma\) represents the same measurement reporting the 6\(\sigma_{TCross1}\) value
Noise Measurements

*Noise peak-to-peak* is the peak-to-peak value of the noise at the top or base of the signal as specified by the user

\[
\text{Noise pp} = \begin{cases} 
\max(PTop) - \min(PTop), & \text{or} \\
\max(PBase) - \min(PBase) 
\end{cases}
\]

*Noise root mean square* is the RMS value of the noise at the top or base of the signal

\[
\text{Noise RMS} = \begin{cases} 
\sigma_{PTop} & \text{or} \\
\sigma_{PBase} 
\end{cases}
\]
Noise Measurements

**Signal-to-noise ratio** is the ratio of the signal amplitude to the noise at either the top or the base of the signal

\[
S/N \text{ Ratio} = \frac{\mu_{P\text{Top}} - \mu_{P\text{Base}}}{\sigma_{P\text{Top}} - \sigma_{P\text{Base}}}
\]

**Duty cycle distortion** is the peak-to-peak time variation of the first eye crossing measured at the mid-voltage reference as a percent of the eye period

\[
\text{DCD} = \frac{T_{\text{DCD}}^{\text{p-p}}}{\left(\mu_{T\text{Cross}2} - \mu_{T\text{Cross}1}\right)} \times 100\%
\]
Eye Quality Factor

*Quality factor* is the ratio of the eye size to noise

\[
\text{Quality Factor} = \frac{\left( \mu_{PTop} - \mu_{PBase} \right)}{\left( \sigma_{PTop} + \sigma_{PBase} \right)}
\]
Margin Testing

Eye diagram with low margin
Eye Diagram Specifications

PCI Express 2.0 eye diagram specification for full and deemphasized signals
Eye Pattern Analysis

Diagram:
- Pseudorandom sequence generator
- Transmitter
- Receiver
- Fiber
- Scope
- Data
- Clk
- Trig Vert

Eye Pattern Image:
Bit Error Ratio

- Bit error ratio (BER) is the fundamental measure of the overall transmission quality of the system
  - A single number that counts how many bits got right and how many errors were made
  - The BER is a measure of the percentage of bits that a system does not transmit or receive correctly
  - Instead of viewing the BER as a percentage, we can also consider it as a probability for a single bit to be received in error.

\[ N_{Err} = N_{bits} \cdot BER \]

- \( N_{Err} \): Average number of errors
- \( N_{bits} \): Number of transmitted bits
Bit Error Rate

- Bit error rate relates the number of errors to the test time
  - Different from bit error ratio
    \[ BERate = \frac{N_{Err}}{t} \]
    \( N_{Err}: \) Number of errors
    \( t: \) Test time

- Bit error rate can be calculated from bit error ratio using the data rate
  \[ BERate \left[ \frac{\text{Errors}}{s} \right] = BER \left[ \frac{\text{Errors}}{\text{Bits}} \right] \cdot \text{Datarate} \left[ \frac{\text{Bits}}{s} \right] \]

For PCI Express, \( BER=10^{-12}, BERate=0.025 \) Errors/s
Bit Error Ratio

Mean Time between Errors as a Function for Multigigabit Data Rates

<table>
<thead>
<tr>
<th>BER</th>
<th>1 Gbit/s</th>
<th>2.5 Gbit/s</th>
<th>5 Gbit/s</th>
<th>10 Gbit/s</th>
<th>40 Gbit/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-8}$</td>
<td>100 ms</td>
<td>40 ms</td>
<td>20 ms</td>
<td>10 ms</td>
<td>2.5 ms</td>
</tr>
<tr>
<td>$10^{-9}$</td>
<td>1 s</td>
<td>400 ms</td>
<td>200 ms</td>
<td>100 ms</td>
<td>25 ms</td>
</tr>
<tr>
<td>$10^{-10}$</td>
<td>10 s</td>
<td>4 s</td>
<td>2 s</td>
<td>1 s</td>
<td>250 ms</td>
</tr>
<tr>
<td>$10^{-11}$</td>
<td>1.66 min</td>
<td>40 s</td>
<td>20 s</td>
<td>10 s</td>
<td>2.5 s</td>
</tr>
<tr>
<td>$10^{-12}$</td>
<td>16.67 min</td>
<td>6.67 min</td>
<td>3.33 min</td>
<td>1.67 min</td>
<td>25 s</td>
</tr>
<tr>
<td>$10^{-13}$</td>
<td>2.78 h</td>
<td>1.11 h</td>
<td>33.3 min</td>
<td>16.67 min</td>
<td>4.17 min</td>
</tr>
<tr>
<td>$10^{-14}$</td>
<td>1.16 d</td>
<td>11.11 h</td>
<td>5.56 h</td>
<td>2.78 h</td>
<td>41.67 min</td>
</tr>
<tr>
<td>$10^{-15}$</td>
<td>11.57 d</td>
<td>4.63 d</td>
<td>2.31 d</td>
<td>1.16 d</td>
<td>6.94 h</td>
</tr>
<tr>
<td>$10^{-16}$</td>
<td>3.86 mo</td>
<td>1.54 mo</td>
<td>23.15 d</td>
<td>11.57 d</td>
<td>2.89 d</td>
</tr>
<tr>
<td>$10^{-17}$</td>
<td>3.17 y</td>
<td>1.27 y</td>
<td>7.72 mo</td>
<td>3.86 mo</td>
<td>28.93 d</td>
</tr>
<tr>
<td>$10^{-18}$</td>
<td>31.7 y</td>
<td>12.7 y</td>
<td>6.34 y</td>
<td>3.17 y</td>
<td>9.64 mo</td>
</tr>
</tbody>
</table>