

ECE 546

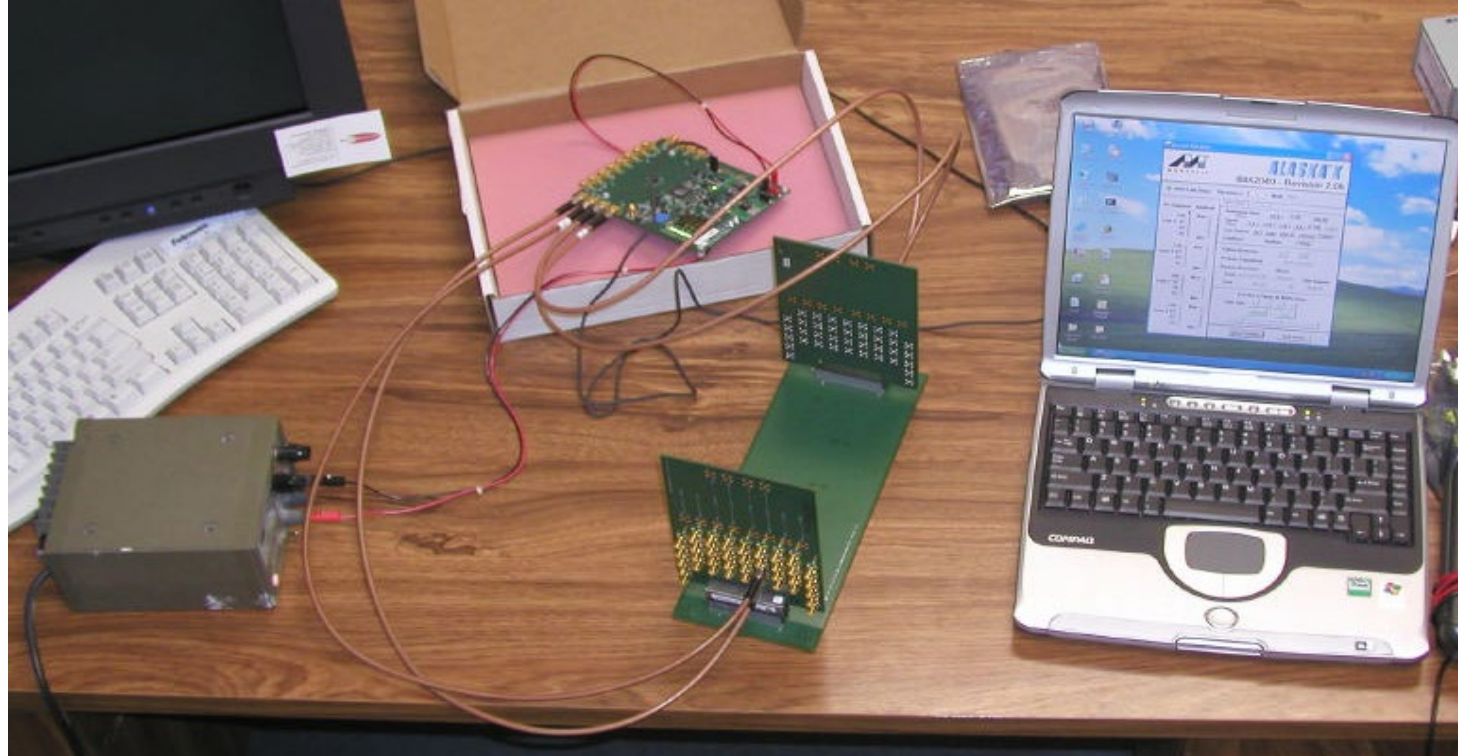
Lecture - 22

Eye Diagrams

Spring 2026

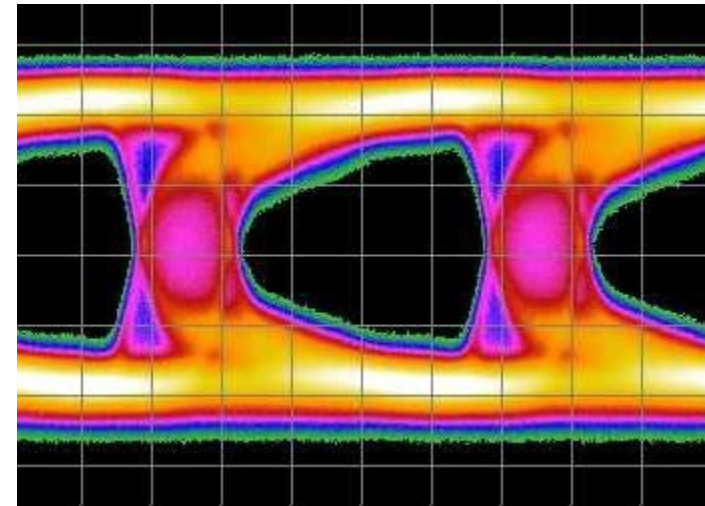
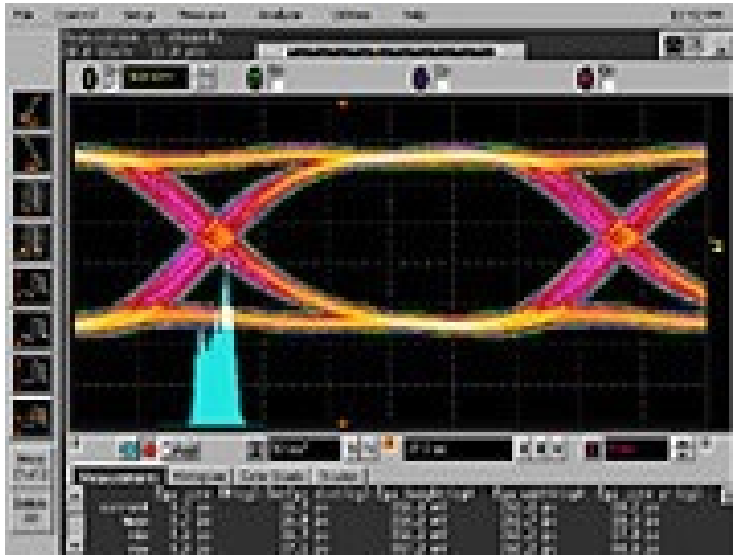
Jose E. Schutt-Aine
Electrical & Computer Engineering
University of Illinois
jesa@illinois.edu

Measuring Jitter

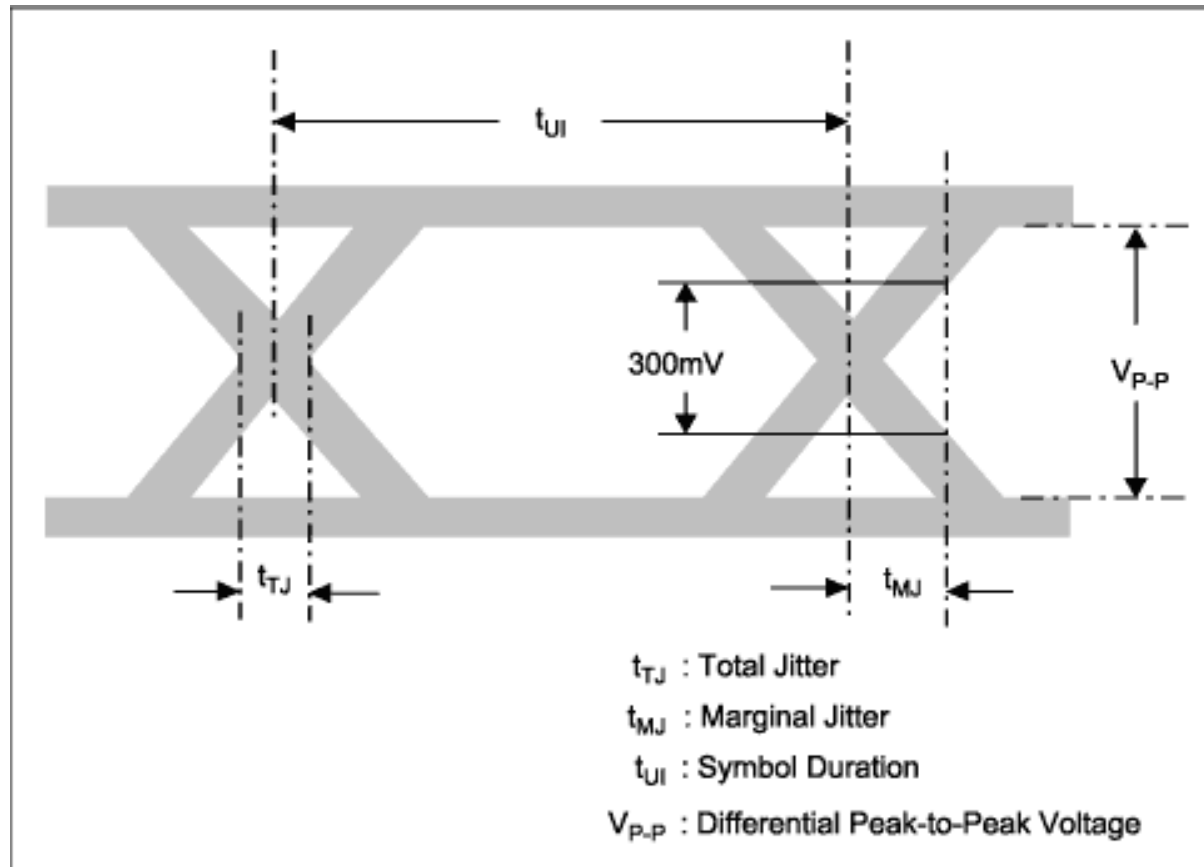


Eye Diagrams

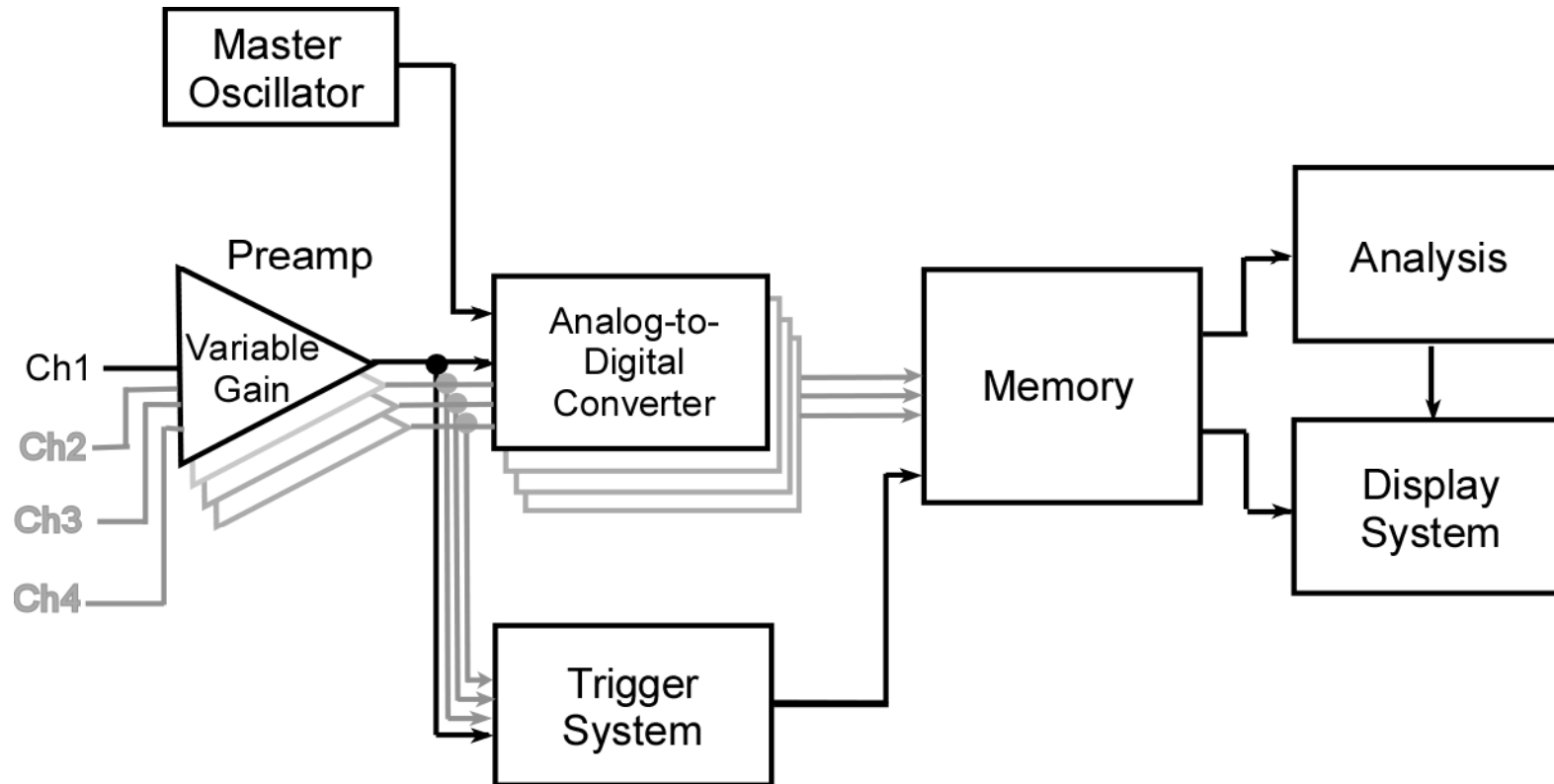
- Eye diagrams are a time domain display of digital data triggered on a particular cycle of the clock. Each period is repeated and superimposed. Each possible bit sequence should be generated so that a complete eye diagram can be made



Eye Diagram

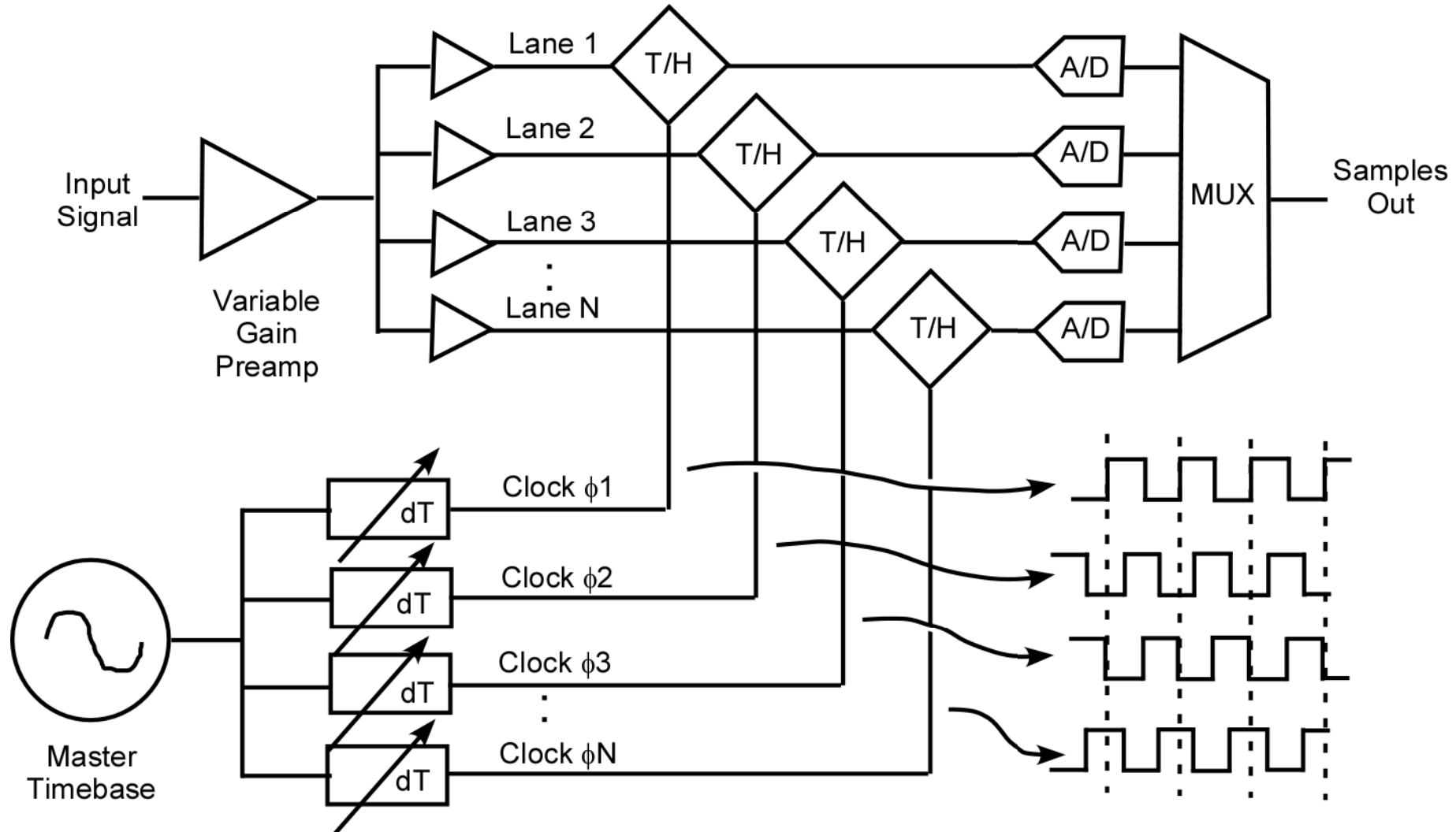


High-Speed Real-Time Oscilloscope



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

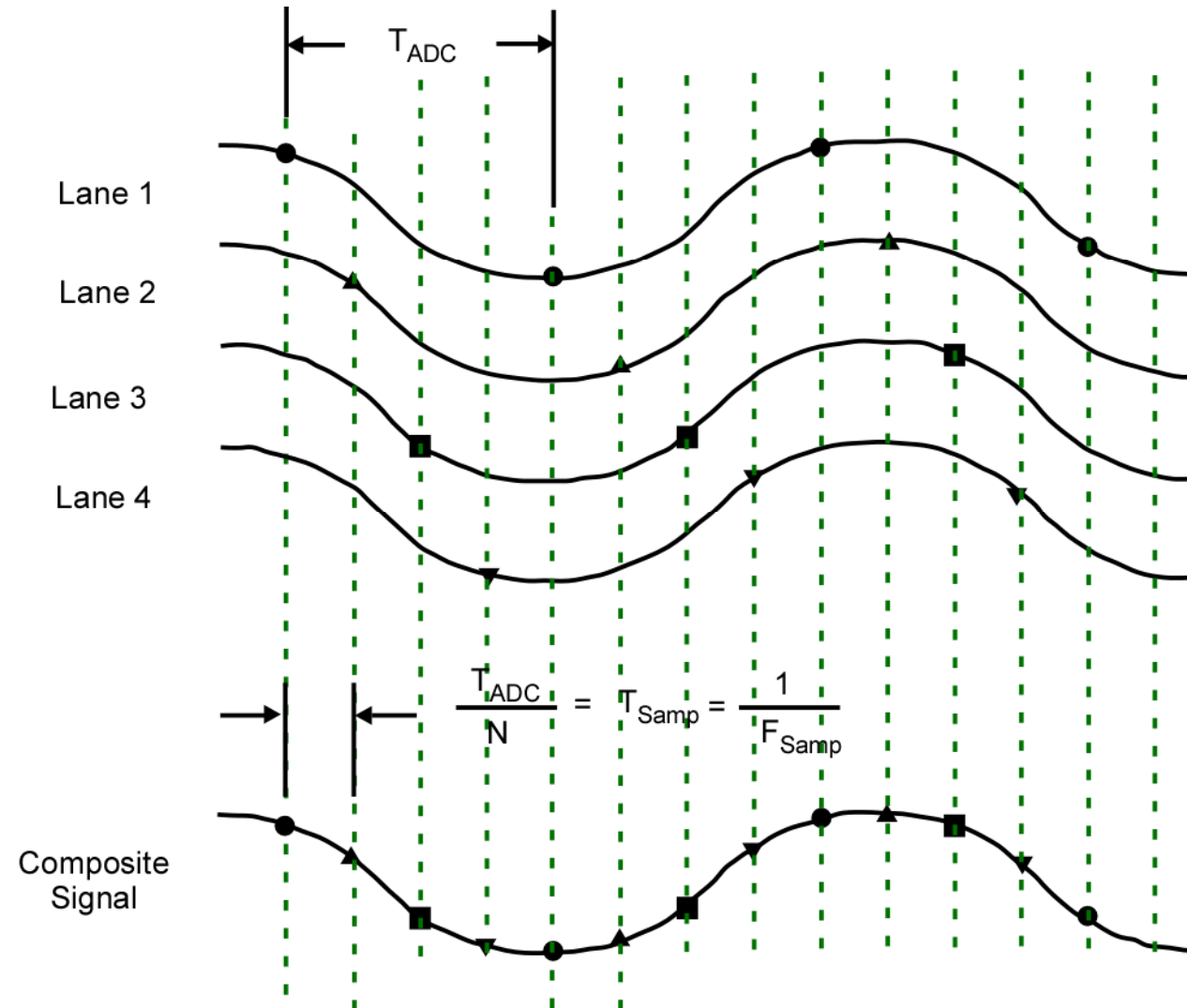
Interleaving Architecture



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



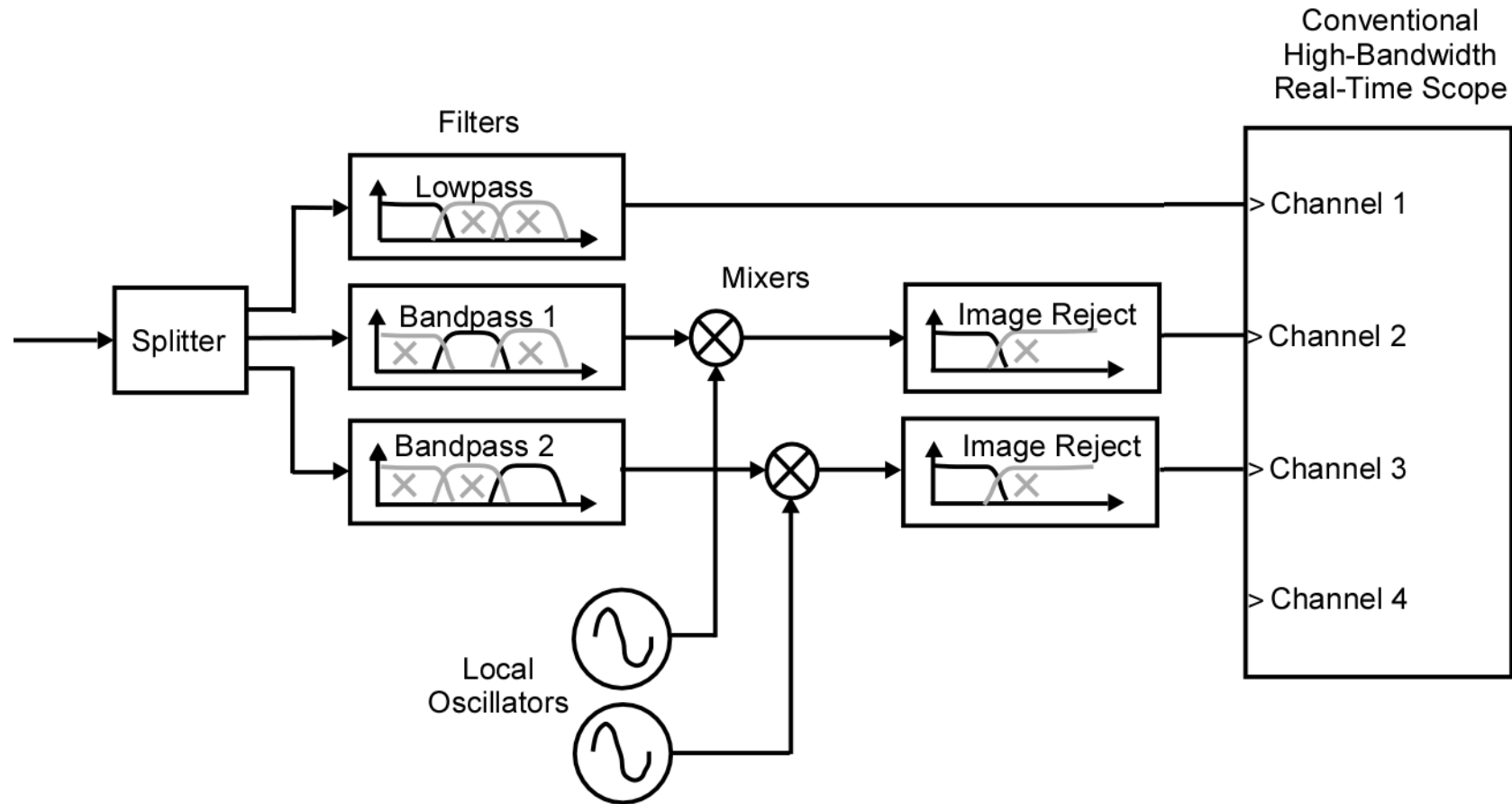
Sampling Procedure

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



Nyquist Criterion

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

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

F_N : Nyquist rate

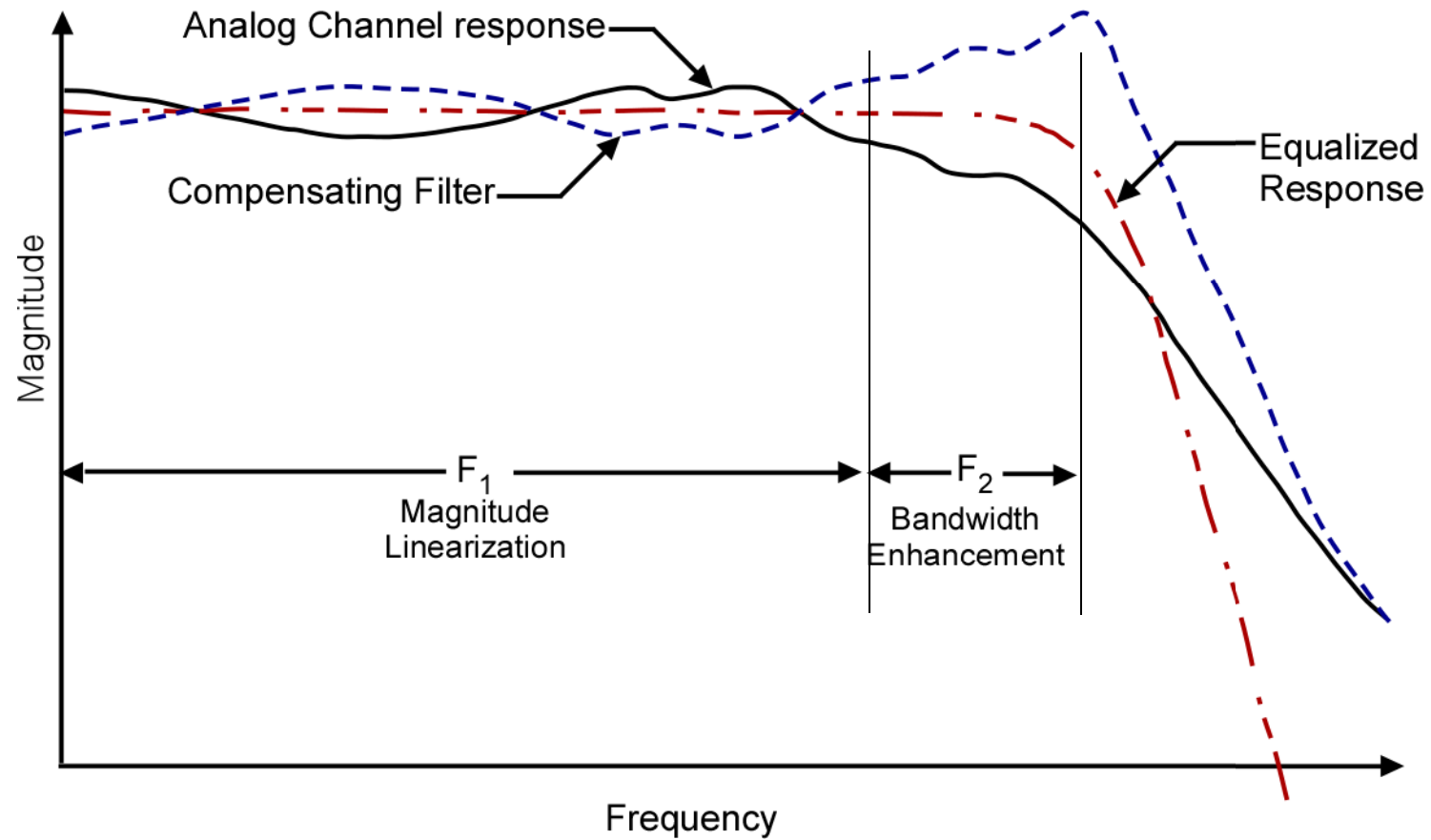
T : sampling interval

B : bandwidth

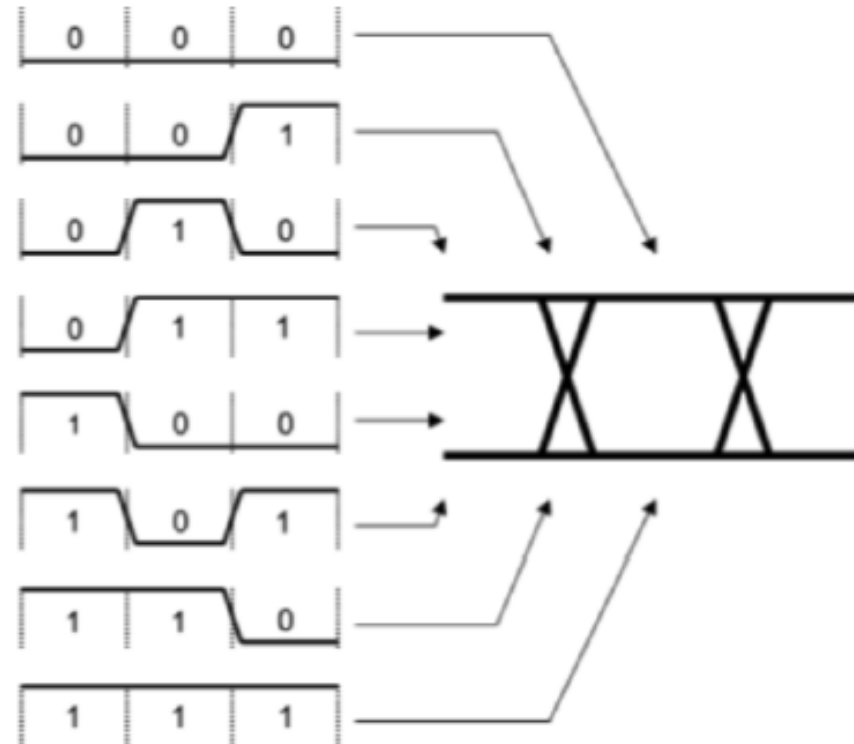
High-Speed Oscilloscopes

- Oscilloscopes use DSP techniques to:
 - Extend their analog bandwidth
 - Flatten their amplitude
- Practice has benefits
- However, limitations should be understood

Scope Channel Equalization



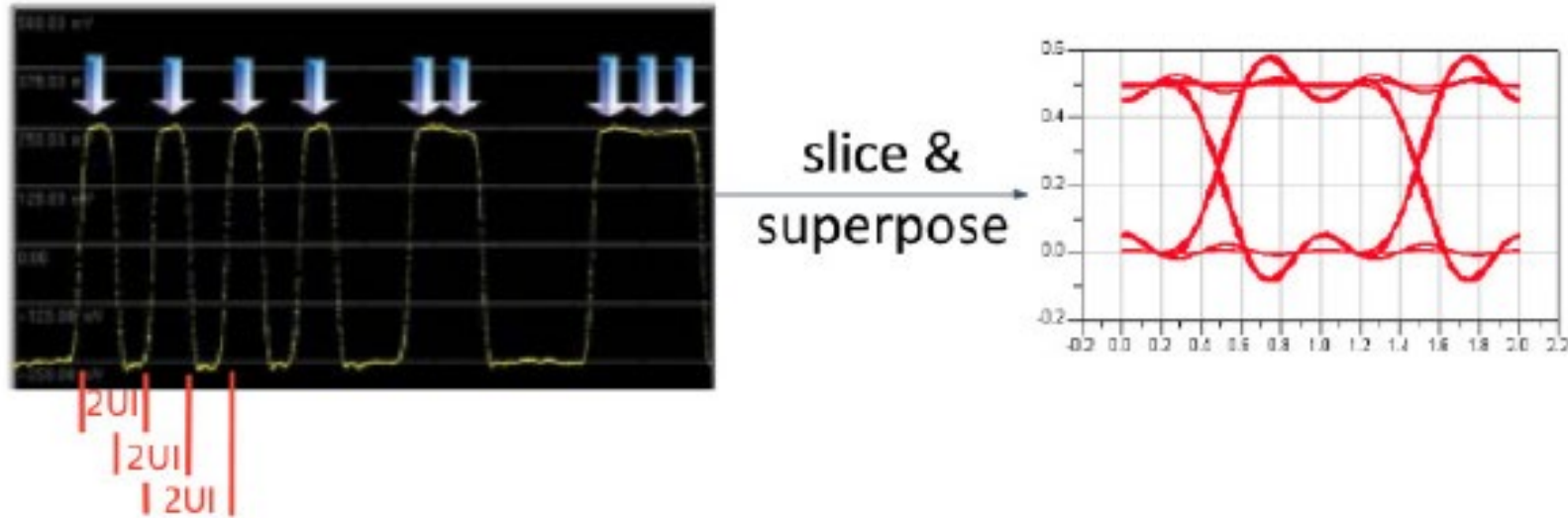
Construction of Eye Diagram



3 transitions are combined to construct the eye diagram

Source: Halim Park, "Comprehensive Algorithm for Eye Diagram Crossing Point Detection and Eye Parameter Extraction in Transient Simulation", MS Thesis, UIUC, 2024

Construction of Eye Diagram

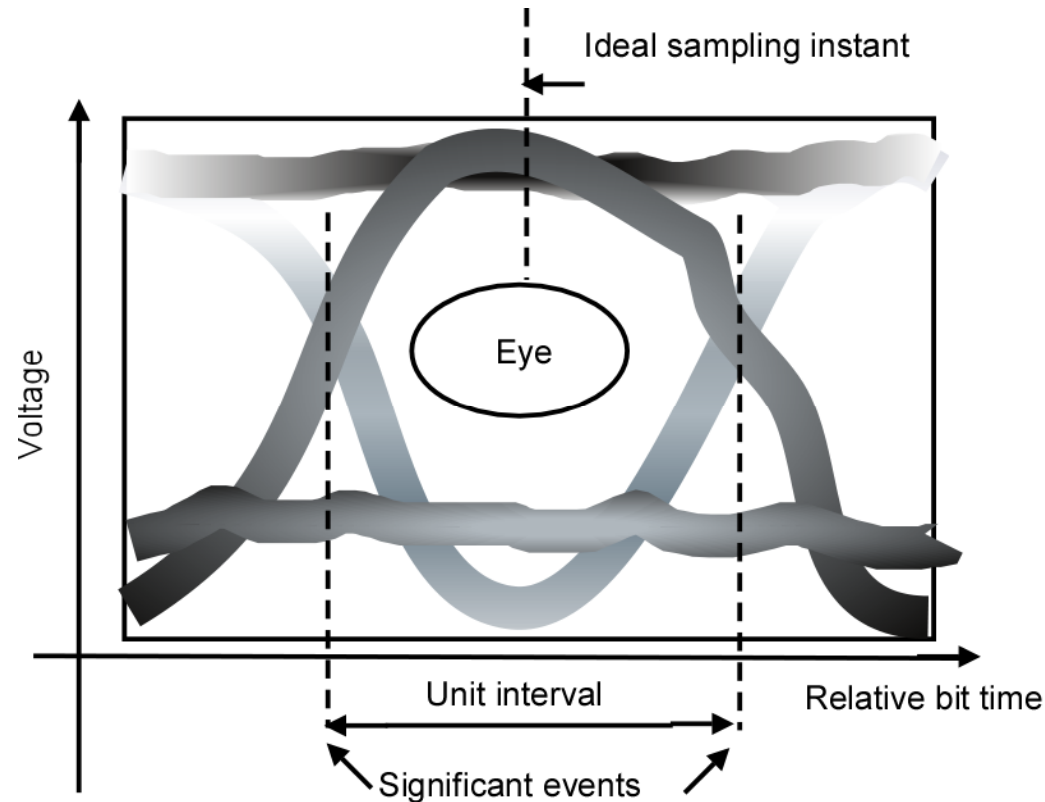


Time-domain signal is sliced to construct the eye diagram

Source: Halim Park, "Comprehensive Algorithm for Eye Diagram Crossing Point Detection and Eye Parameter Extraction in Transient Simulation", MS Thesis, UIUC, 2024

Eye Diagram

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



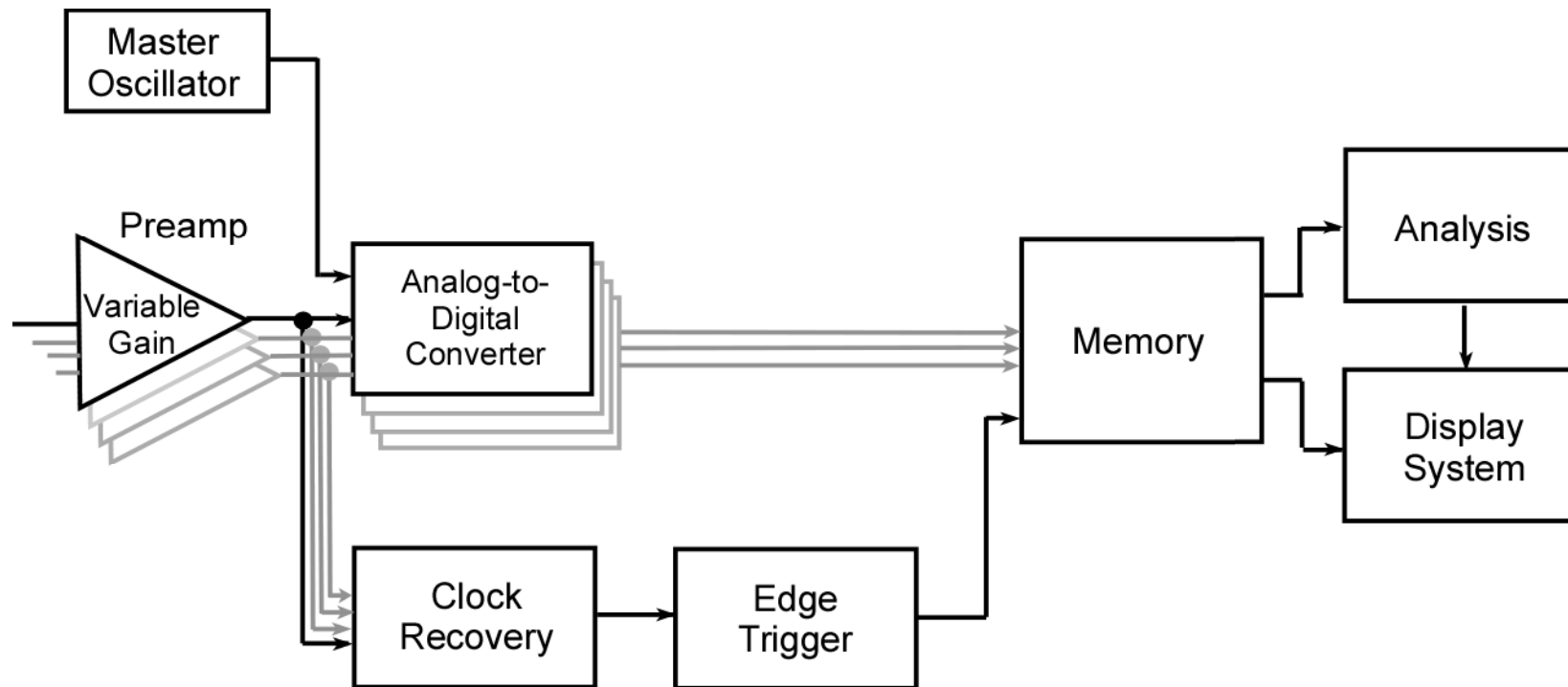
Eye is horizontally centered on the ideal sampling instant

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

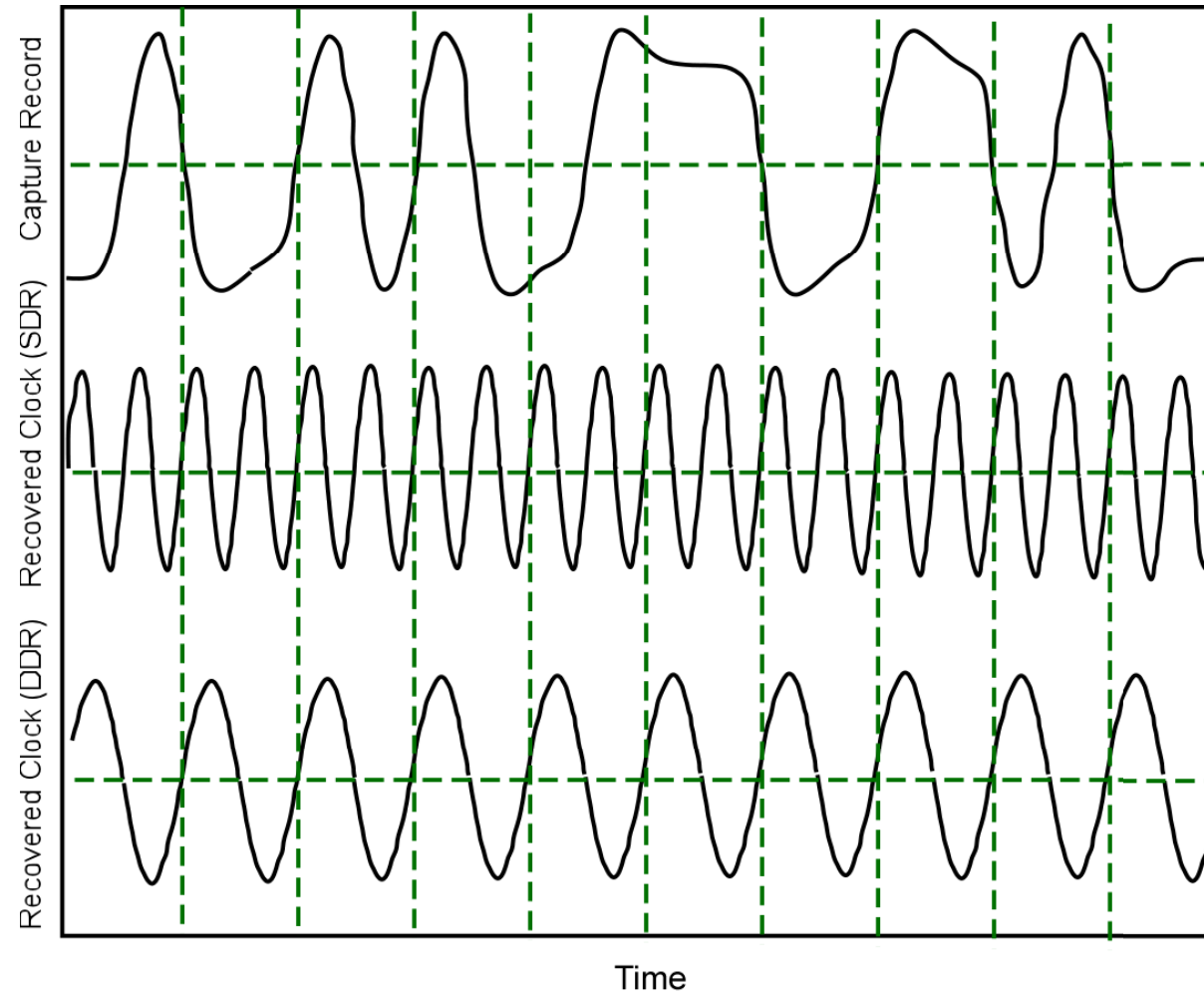
Large eye openings ensure that the receiving device can reliably decide between high and low logic states even when the decision threshold fluctuates or the decision time instant varies.

Eye Diagram Construction

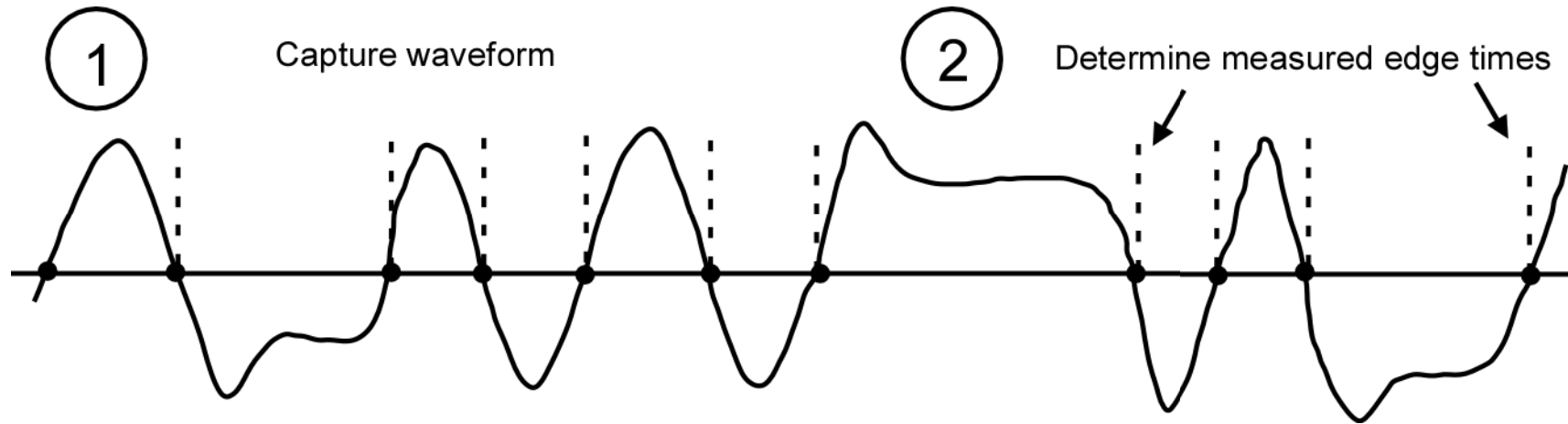


Eye diagram construction in real-time oscilloscope is based on hardware clock recovery and trigger circuitry

Eye Diagram Construction



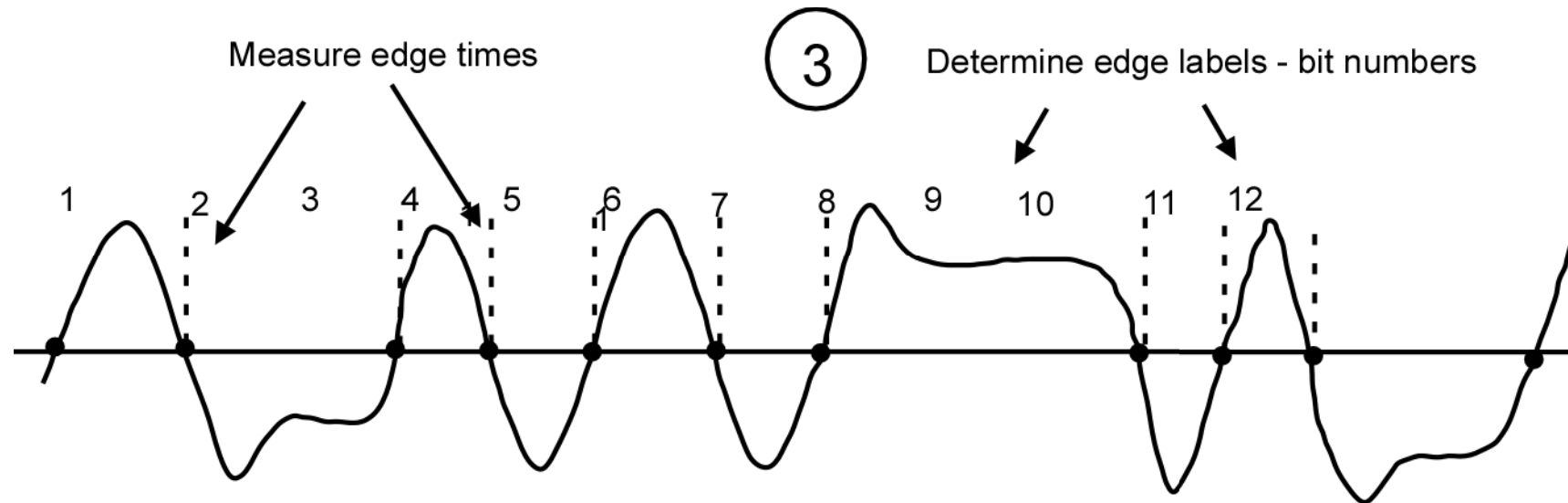
Eye Diagram Construction



1. Capture of the Waveform Record

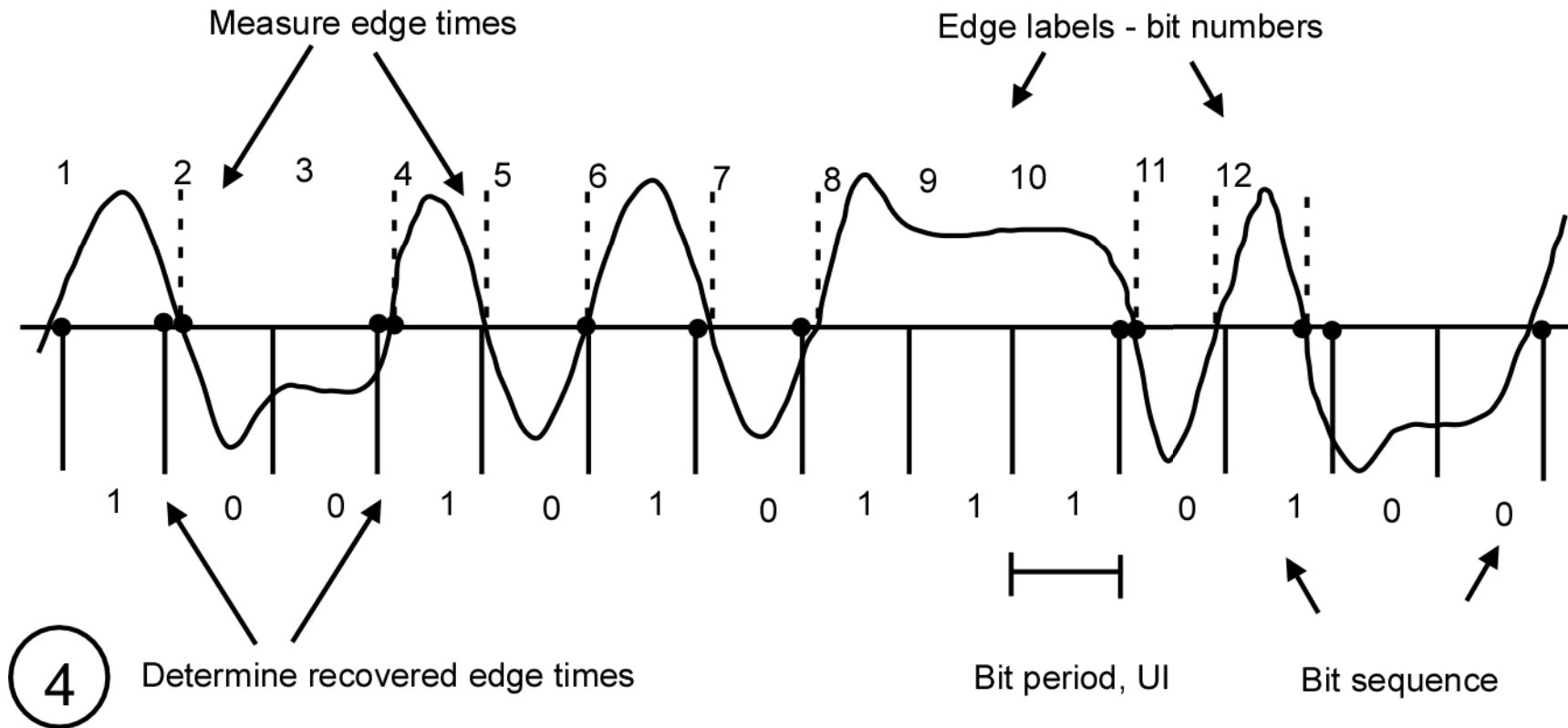
2. Determine the Edge Times

Eye Diagram Construction



3. Determine the Bit Labels

Eye Diagram Construction

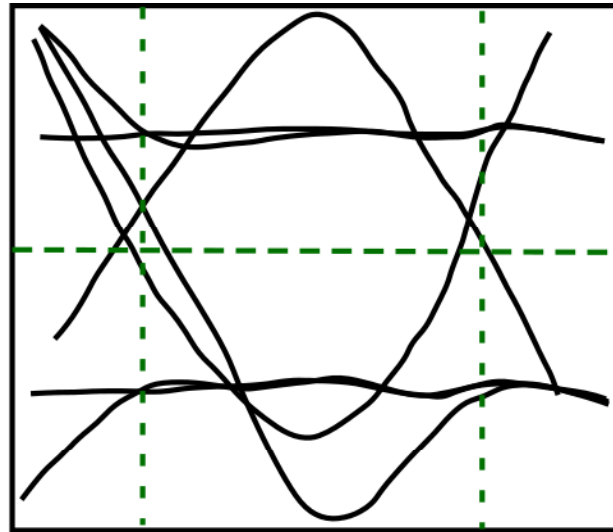


4. Clock Recovery

Eye Diagram Construction

5

Slice waveform
and overlay slices



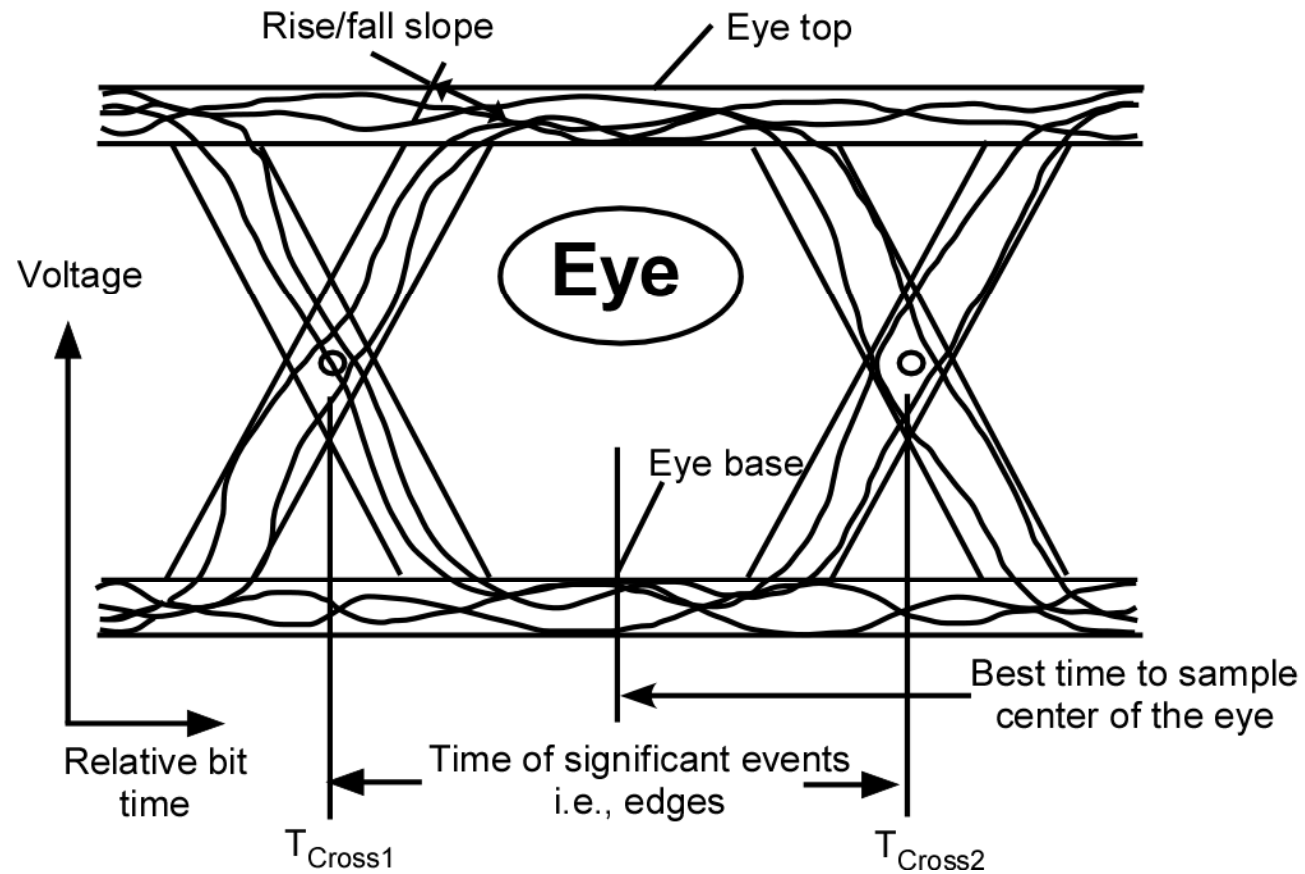
6

Display eye
diagram-folded
view of the
waveform

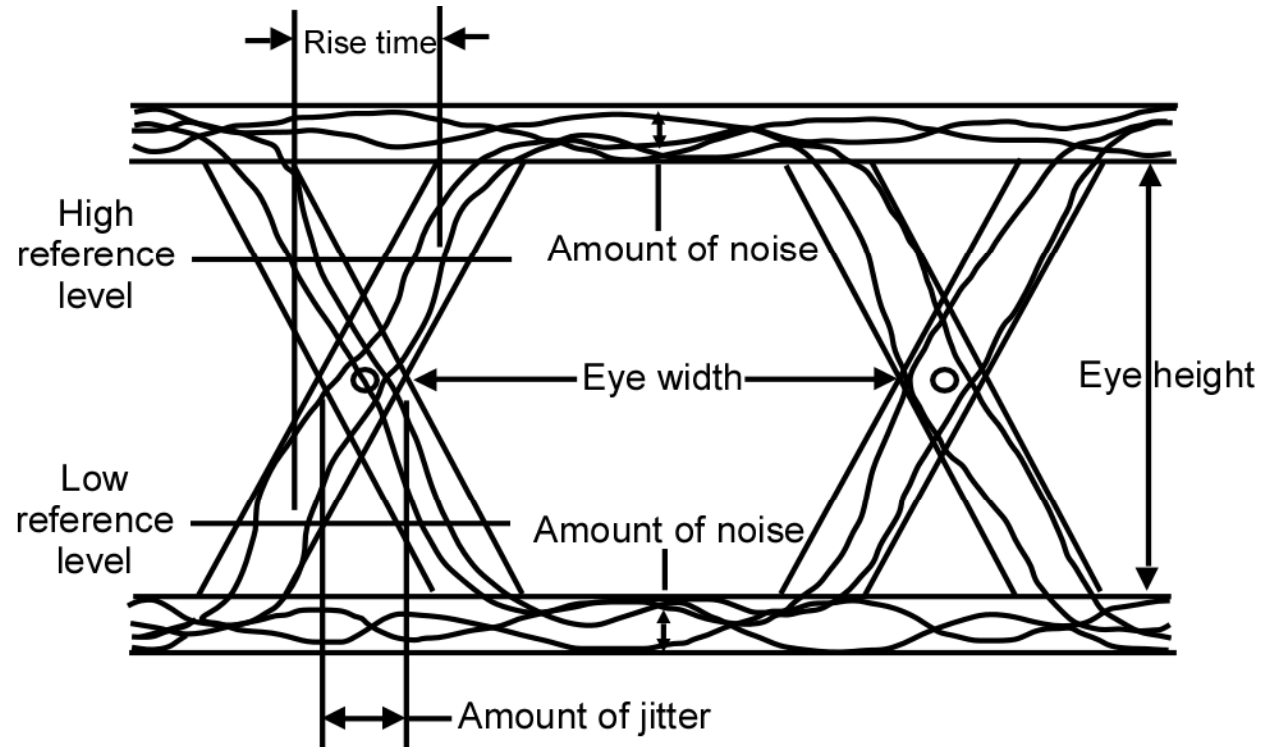
5. Slice Overlay

6. Display

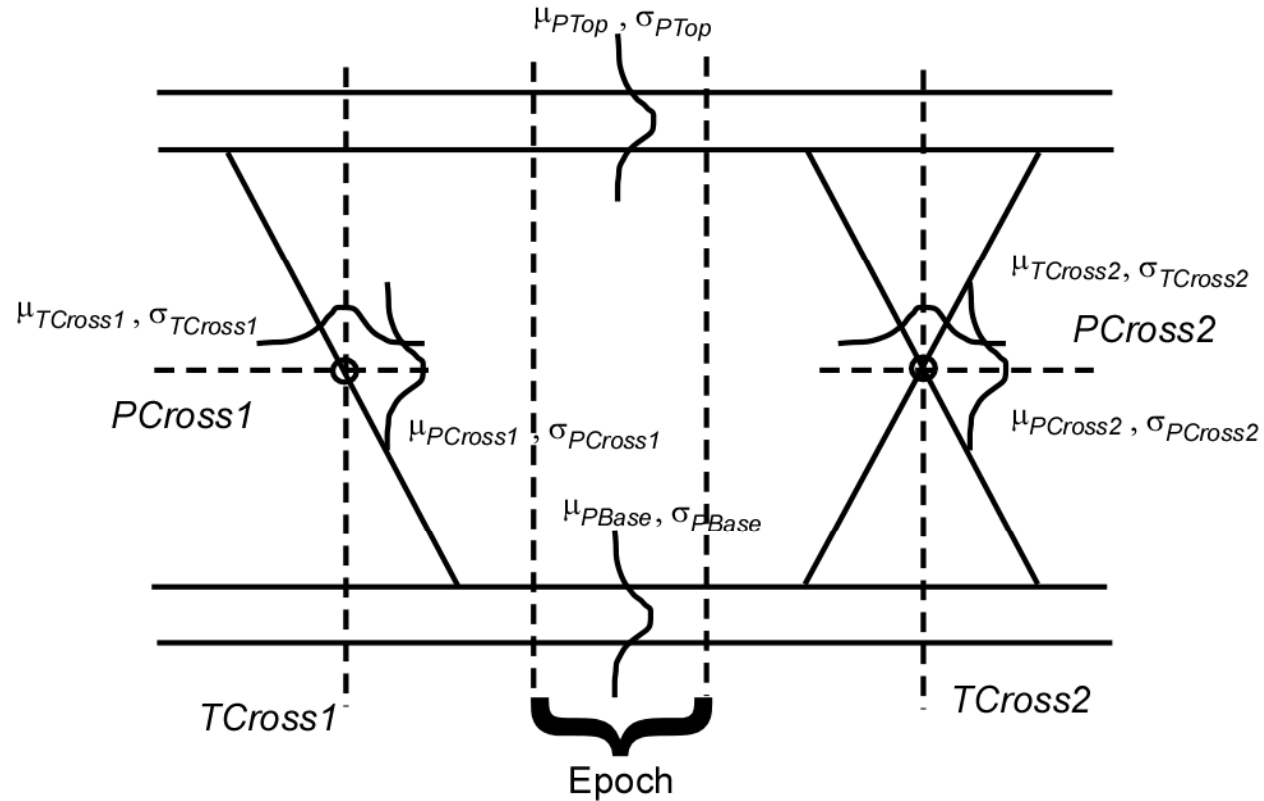
Eye Diagram Measurements



Eye Diagram Measurements



Reference Levels



Eye Height

Eye Height is the measurement of the eye height in volts

$$\text{Eye Height} = \left(\mu_{P\text{Top}} - 3\sigma_{P\text{Top}} \right) - \left(\mu_{P\text{Base}} + 3\sigma_{P\text{Base}} \right)$$

$\mu_{P\text{Top}}$: mean value of eye top

$\sigma_{P\text{Top}}$: standard deviation of eye top

$\mu_{P\text{Base}}$: mean value of eye base

$\sigma_{P\text{Base}}$: standard deviation of eye base

Eye Width

Eye Width is the measurement of the eye width in seconds

$$\text{Eye Width} = (\mu_{TCross2} - 3\sigma_{TCross2}) - (\mu_{TCross1} + 3\sigma_{TCross1})$$

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

$$\text{Crossing Percent} = \frac{(\mu_{PCross1} - \mu_{PBase})}{(\mu_{PTop} - \mu_{PBase})} \times 100\%$$

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 6σ 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

$$\text{Noise pp} = \begin{cases} \max(P_{Top}) - \min(P_{Top}), \text{ or} \\ \max(P_{Base}) - \min(P_{Base}) \end{cases}$$

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

$$\text{Noise RMS} = \begin{cases} \sigma_{P_{Top}} \\ \text{or} \\ \sigma_{P_{Base}} \end{cases}$$

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

$$\text{S/N Ratio} = \frac{\left(\mu_{P\text{Top}} - \mu_{P\text{Base}} \right)}{\left(\sigma_{P\text{Top}} - \sigma_{P\text{Base}} \right)}$$

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

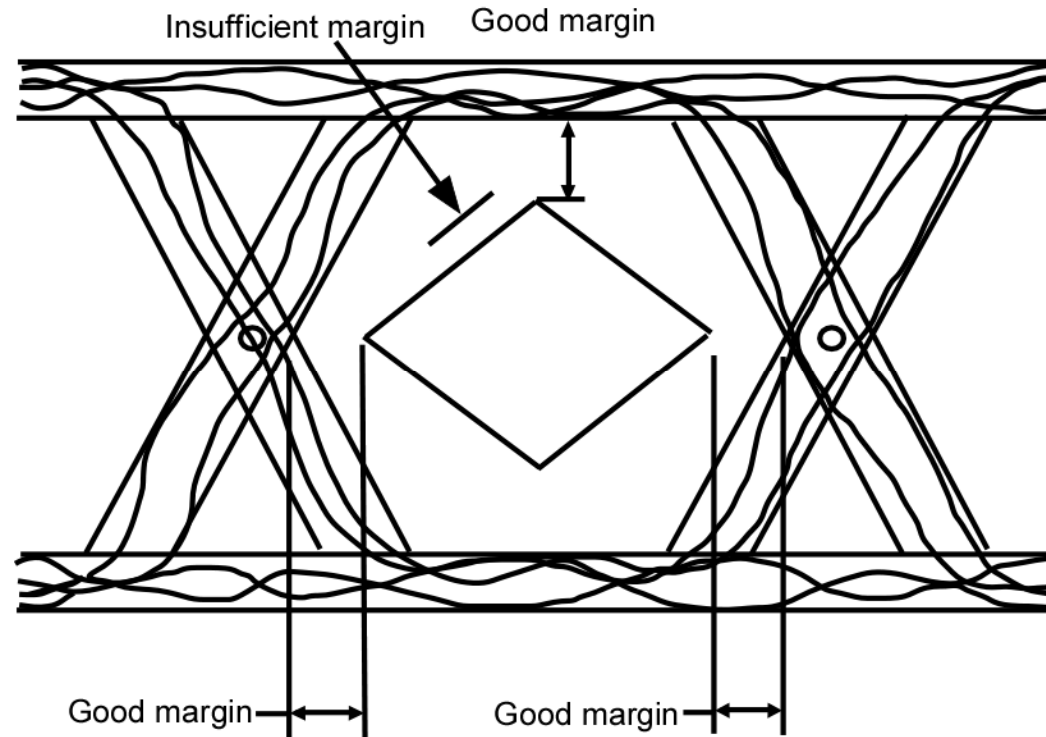
$$\text{DCD} = \frac{\text{TDCD}_{\text{p-p}}}{\left(\mu_{\text{TCross}2} - \mu_{\text{TCross}1} \right)} \times 100\%$$

Eye Quality Factor

Quality factor is the ratio of the eye size to noise

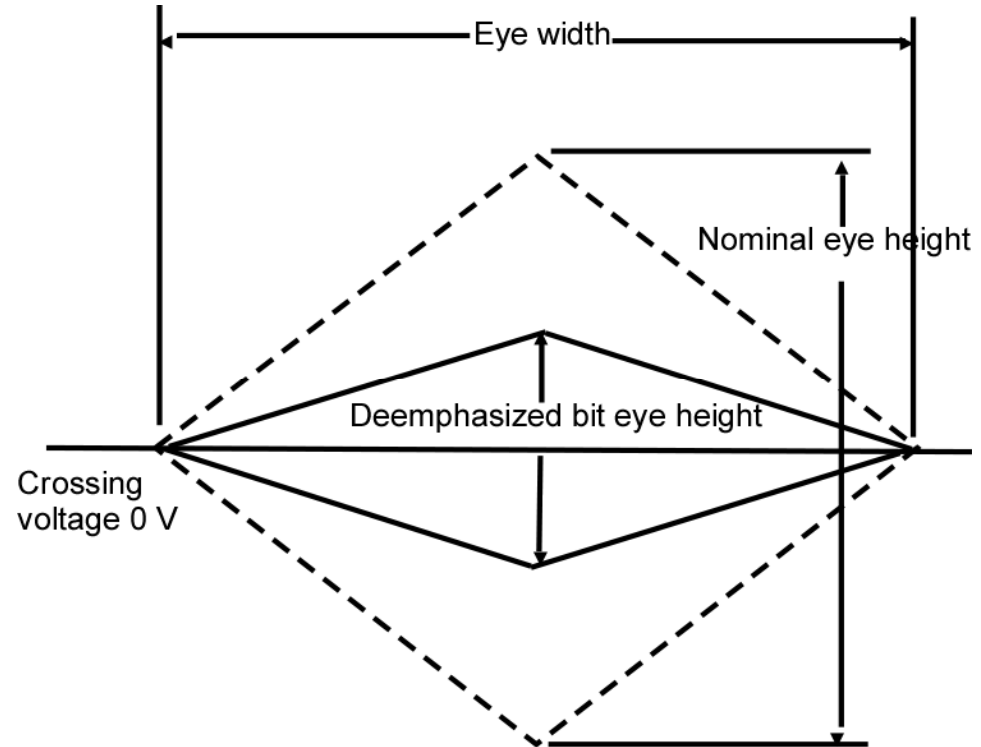
$$\text{Quality Factor} = \frac{\left(\mu_{PTop} - \mu_{PBase} \right)}{\left(\sigma_{PTop} + \sigma_{PBase} \right)}$$

Margin Testing



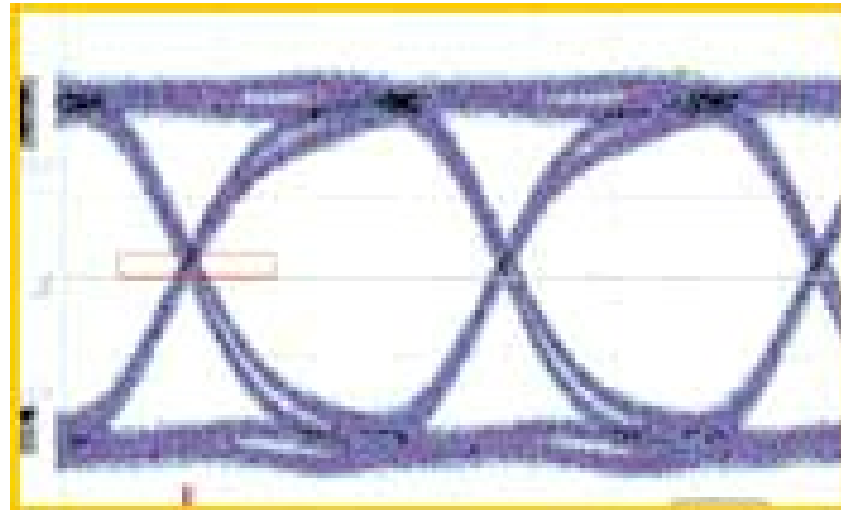
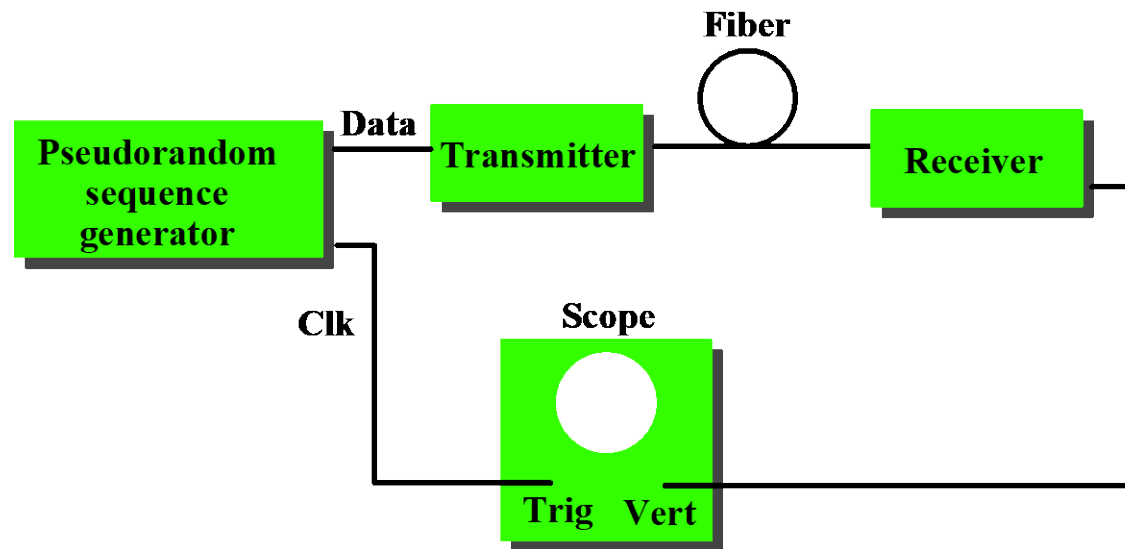
Eye diagram with low margin

Eye Diagram Specifications

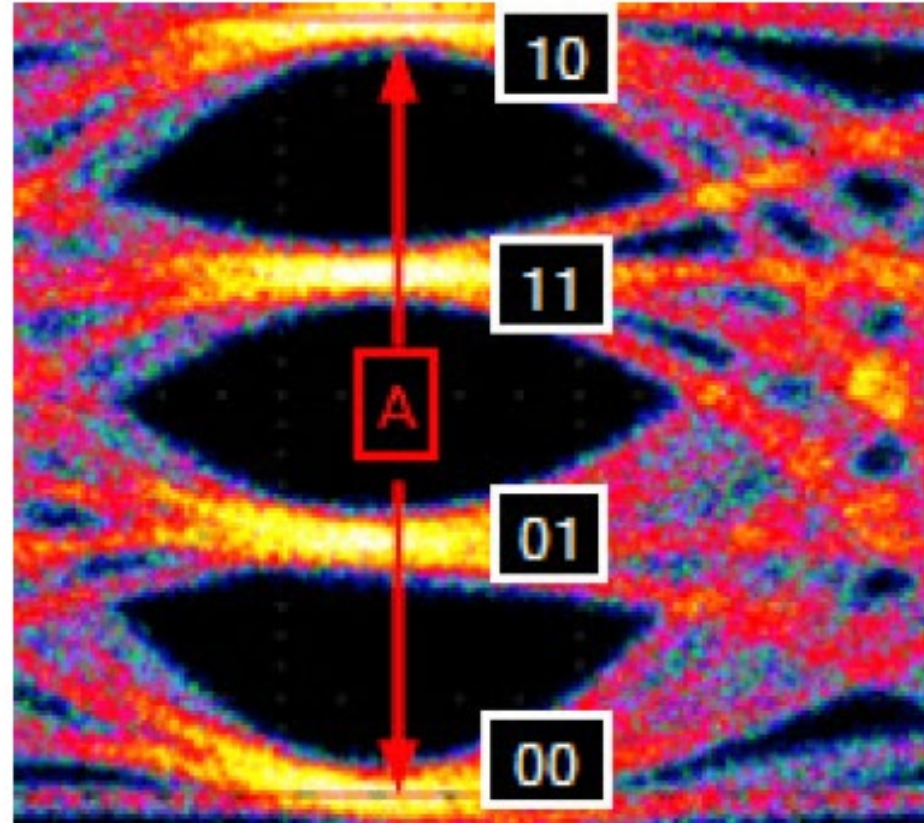


PCI Express 2.0 eye diagram specification for full and deemphasized signals

Eye Pattern Analysis



PAM4 Eye Diagram

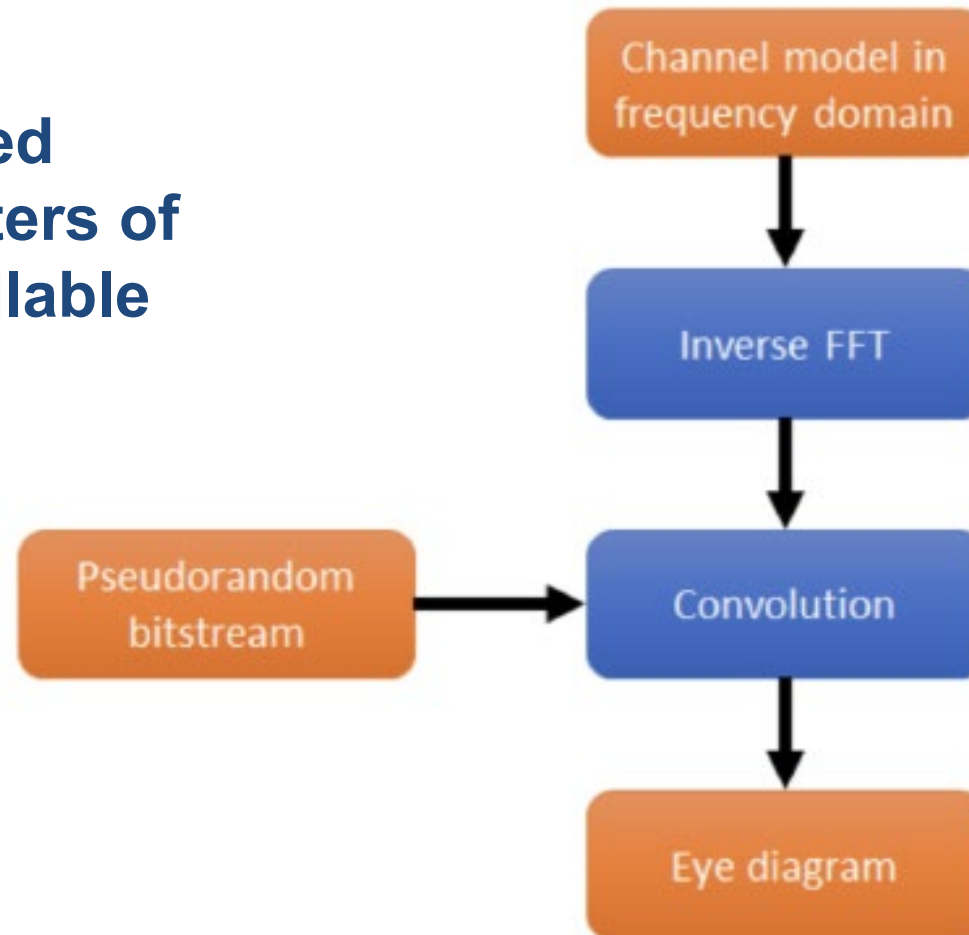


4 distinct voltage levels representing 2-bit combinations – 00, 01, 11, 10

Source: Halim Park, "Comprehensive Algorithm for Eye Diagram Crossing Point Detection and Eye Parameter Extraction in Transient Simulation", MS Thesis, UIUC, 2024

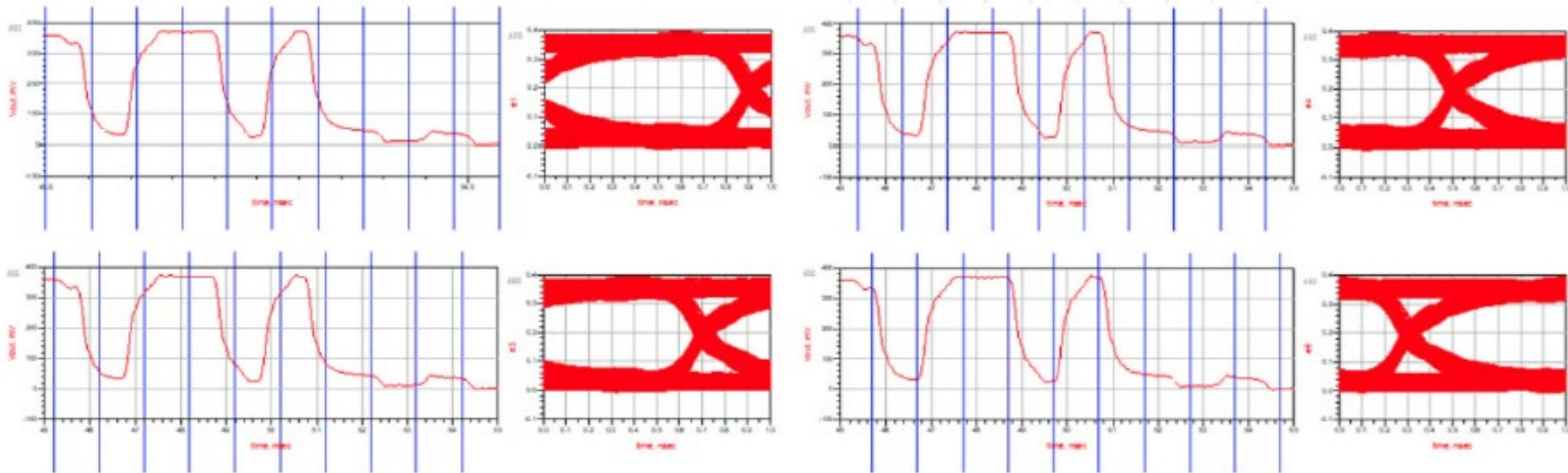
Eye Diagram Simulation

Can be performed
when S-Parameters of
channel are available



Source: Halim Park, "Comprehensive Algorithm for Eye Diagram Crossing Point Detection and Eye Parameter Extraction in Transient Simulation", MS Thesis, UIUC, 2024

Slicing Timings



Different slicing timings will produce different eyes for the same waveform

Source: Halim Park, "Comprehensive Algorithm for Eye Diagram Crossing Point Detection and Eye Parameter Extraction in Transient Simulation", MS Thesis, UIUC, 2024

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

$$BERate \left[\frac{Errors}{s} \right] = BER \left[\frac{Errors}{Bits} \right] \cdot Datarate \left[\frac{Bits}{s} \right]$$

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

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

Source: D. Derickson and M. Muller, "Digital Communications Test and Measurement", Prentice Hall, 2007