ECE 451
Advanced Microwave Measurements

Eye Diagrams

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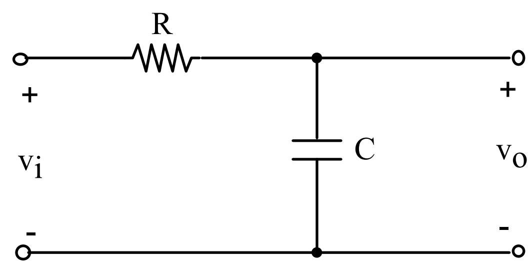
RC Network



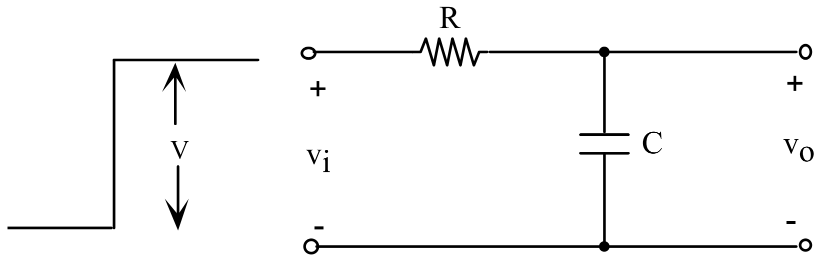
A is the steady-state gain of the network;

$$A = \frac{v_o(f)}{v_i(f)}$$

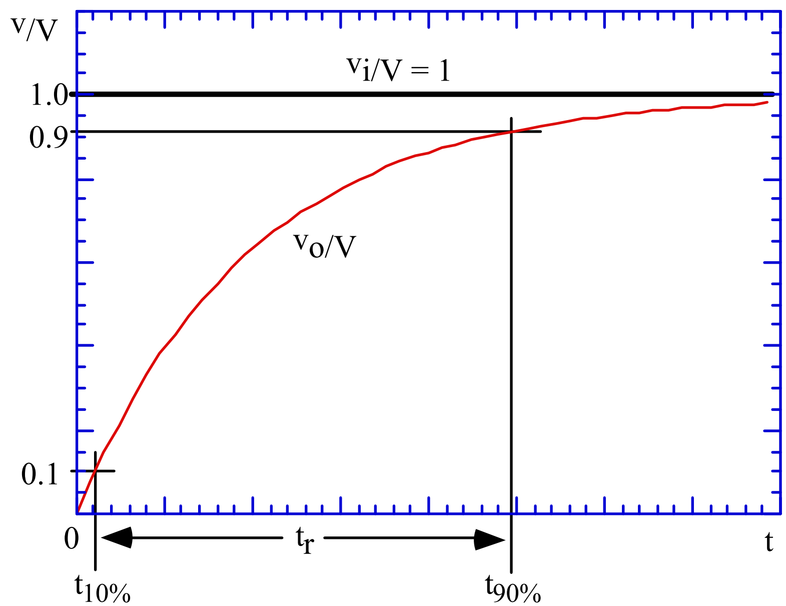
$$|A| = \frac{1}{\sqrt{1+(f/f_2)^2}} \qquad f_2 = \frac{1}{2\pi RC}$$

The gain falls to 0.707 of its low-frequency value at the frequency f_2. f_2 is the *upper 3-dB frequency* or the 3-dB bandwidth of the RC network.

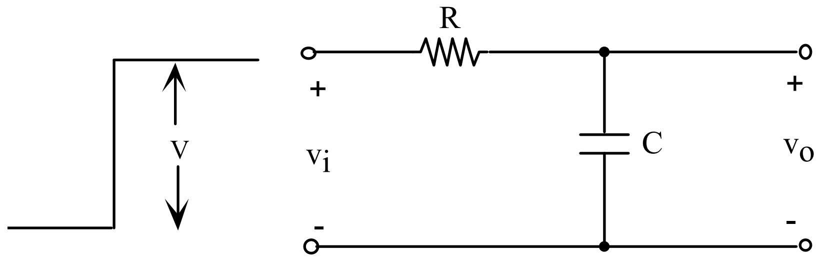
RC Network



$$v_o = V\left(1 - e^{-t/RC}\right)$$



RC Network



Rise time : $t_r = t_{90\%} - t_{10\%}$

$$t_r = 2.2RC = \frac{2.2}{2\pi f_2} = \frac{0.35}{f_2}$$

<u>Rule of thumb</u>: A 1-ns pulse requires a circuit with a 3-dB bandwidth of the order of 2 GHz.

Frequency Dependence of Lumped Circuit Models

– At higher frequencies, a lumped circuit model is no longer accurate for interconnects and one must use a distributed model

– Transition frequency depends on the dimensions and relative magnitude of the interconnect parameters.

$$f \approx \frac{0.3 \times 10^9}{10d\sqrt{\varepsilon_r}} \qquad t_r \approx \frac{0.35}{f}$$

Lumped Circuit or Transmission Line?

- **Determine frequency or bandwidth of signal**
  - RF/Microwave: f= operating frequency
  - Digital: $f=0.35/t_r$

- **Determine the propagation velocity and wavelength**
  - Material medium $v=c/(\varepsilon_r)^{1/2}$
  - Obtain wavelength $\lambda=v/f$

- **Compare wavelenth with feature size**
  - If $\lambda >> d$, use lumped circuit: $L_{tot}= L^*$ length, $C_{tot}= C^*$ length
  - If $\lambda \approx 10d$ or $\lambda<10d$, use transmission-line model

Frequency Dependence of Lumped Circuit Models

Level	Dimension	Frequency	Edge rate
PCB line	10 in	> 55 MHz	< 7ns
Package	1 in	> 400 MHz	< 0.9 ns
VLSI int*	100 um	> 8 GHz	< 50 ps

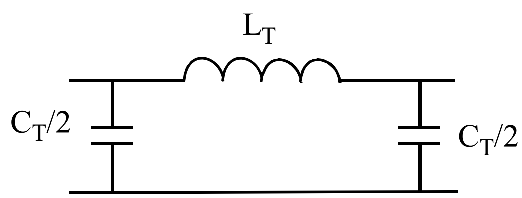
* Using RC criterion for distributed effect

Modeling Interconnections

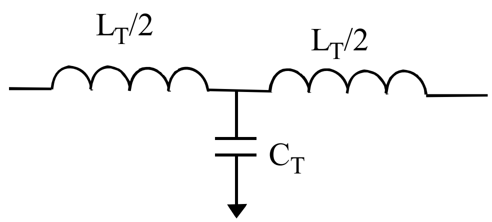
Low Frequency

Short

Mid-range Frequency

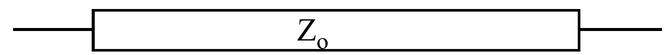


or



Lumped Reactive CKT

High Frequency

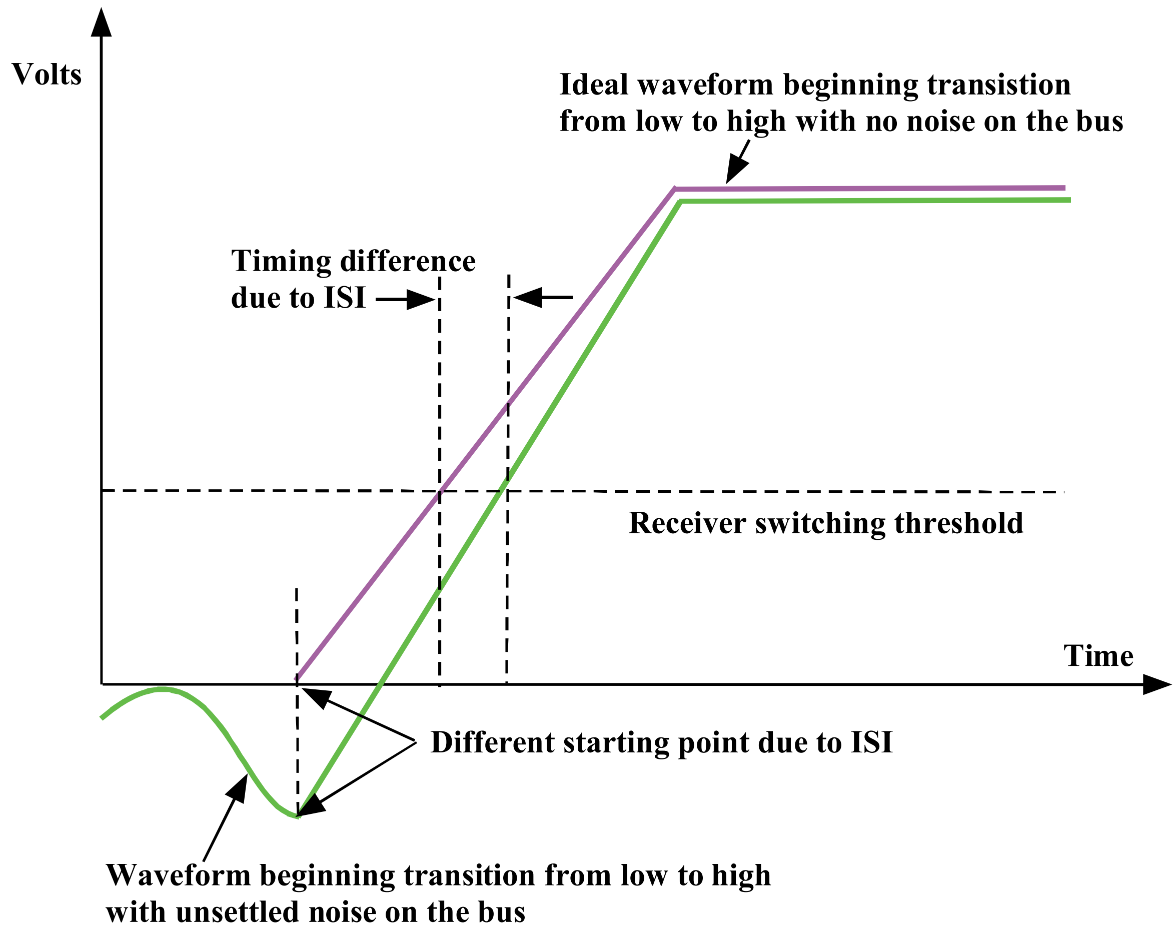


Transmission Line

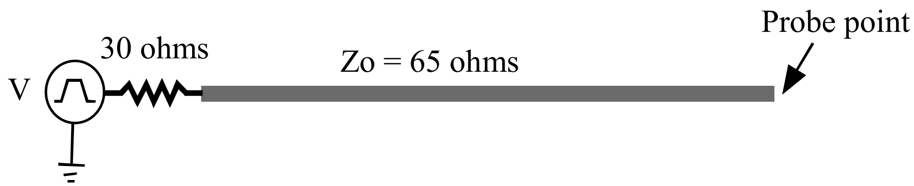
Intersymbol Interference (ISI)

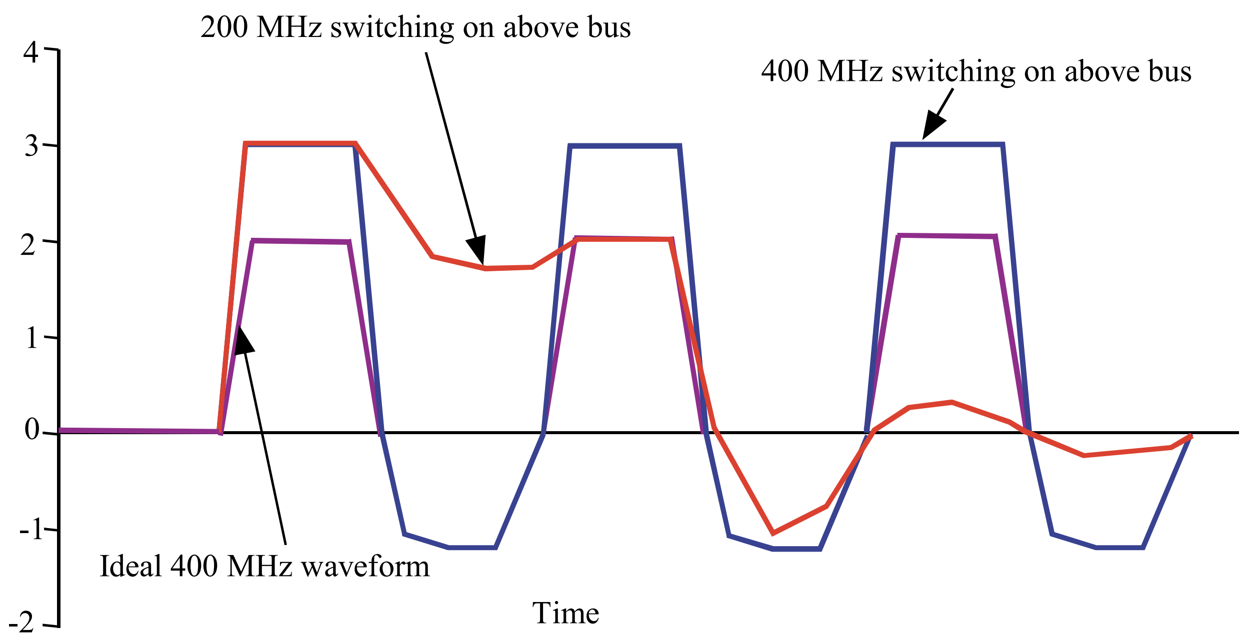
- Signal launched on a transmission line can be affected by previous signals as result of reflections
- ISI can be a major concern especially if the signal delay is smaller than twice the time of flight
- ISI can have devastating effects
- Noise must be allowed to settled before next signal is sent

Intersymbol Interference



Intersymbol Interference and Signal Integrity





Minimizing ISI

- Minimize reflections on the bus by avoiding impedance discontinuities
- Minimize stub lengths and large parasitics from package sockets or connectors
- Keep interconnects as short as possible (minimize delay)
- Minimize crosstalk effects

Jitter Definition

Jitter is difference *in time* between when an event was ideally to occur and when it actually did occur.

- **Timing uncertainties in digital transmission systems**
- **Utmost importance because timing uncertainties cause bit errors**
- **There are different types of jitter**

Jitter Characteristics

- Jitter is a signal timing deviation referenced to a recovered clock from the recovered bit stream
- Measured in Unit Intervals and captured visually with eye diagrams
- Two types of jitter
  - Deterministic (non Gaussian)
  - Random
- The total jitter (TJ) is the sum of the random (RJ) and deterministic jitter(DJ)

Types of Jitter

- Deterministic Jitter (DDJ)
  - Data-Dependent Jitter (DDJ)
  - Periodic Jitter (PJ)
  - Bounded Uncorrelated Jitter (BUJ)

- Random Jitter (RJ)
  - Gaussian Jitter
  - $f^{-\alpha}$ Higher-Order Jitter

Jitter Effects

Bandwidth Limitations

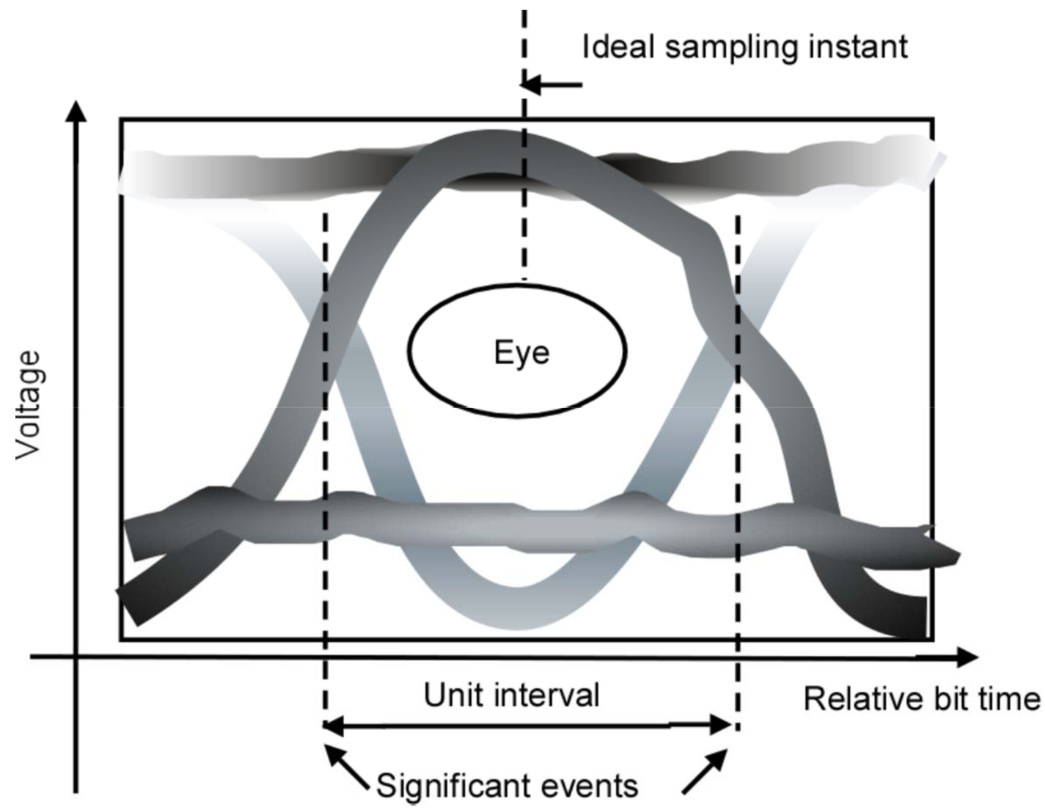
- Cause intersymbol interference (ISI)
- ISI occurs if time required by signal to completely charge is longer than bit interval
- Amount of ISI is function of channel and data content of signal

Oscillator Phase Noise

- Present in reference clocks or high-speed clocks
- In PLL based clocks, phase noise can be amplified

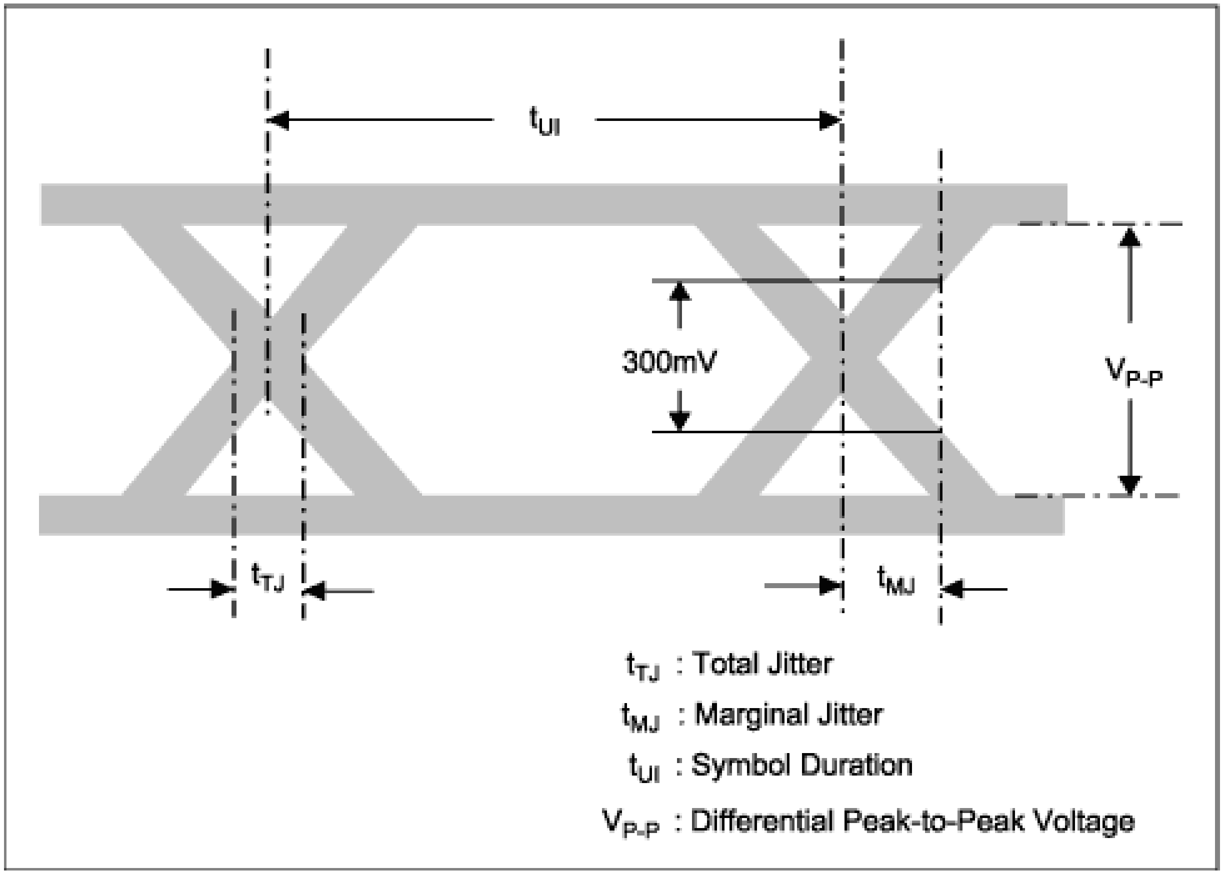
Eye Diagram

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



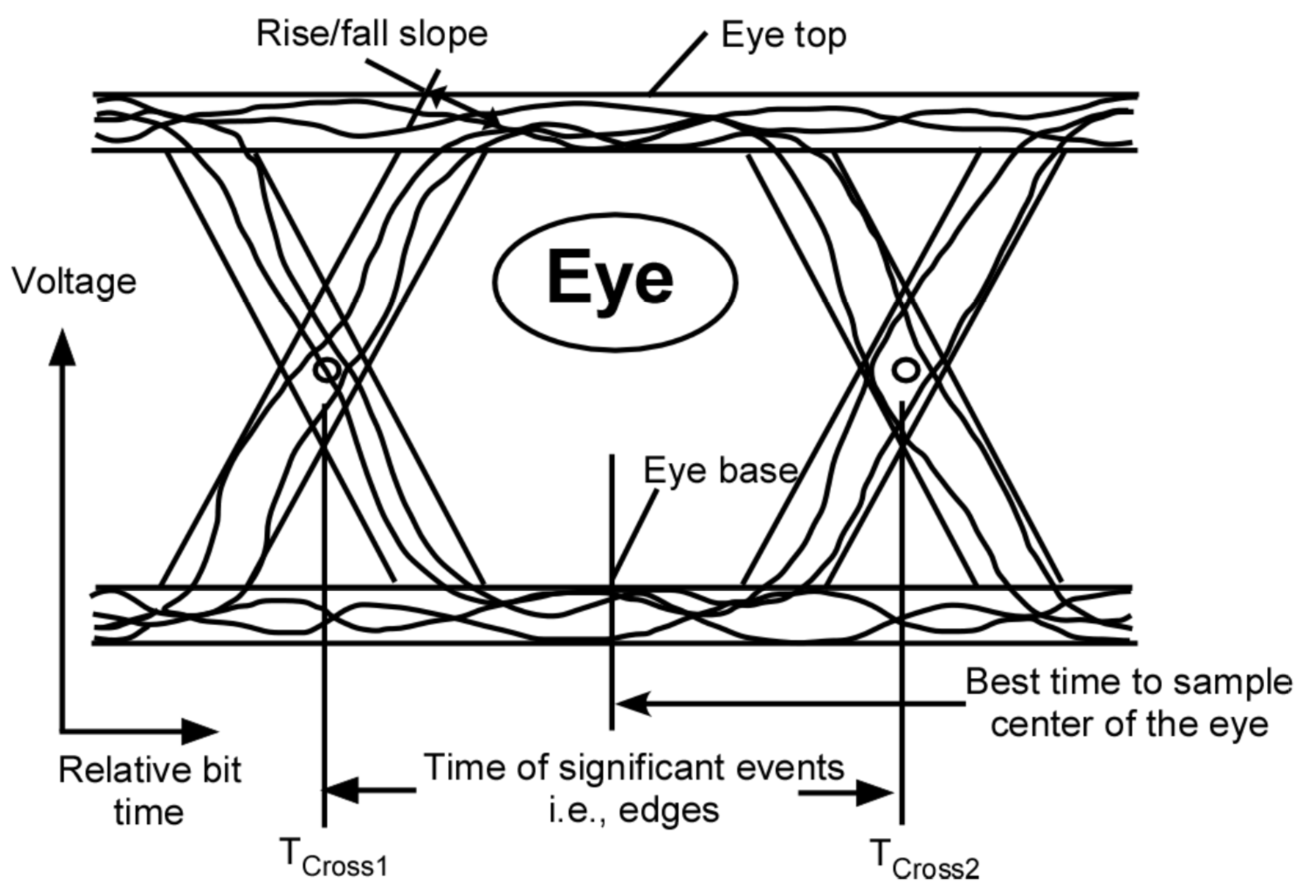
Eye is horizontally centered on the ideal sampling instant

Eye Diagram



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

Eye Diagram Measurements

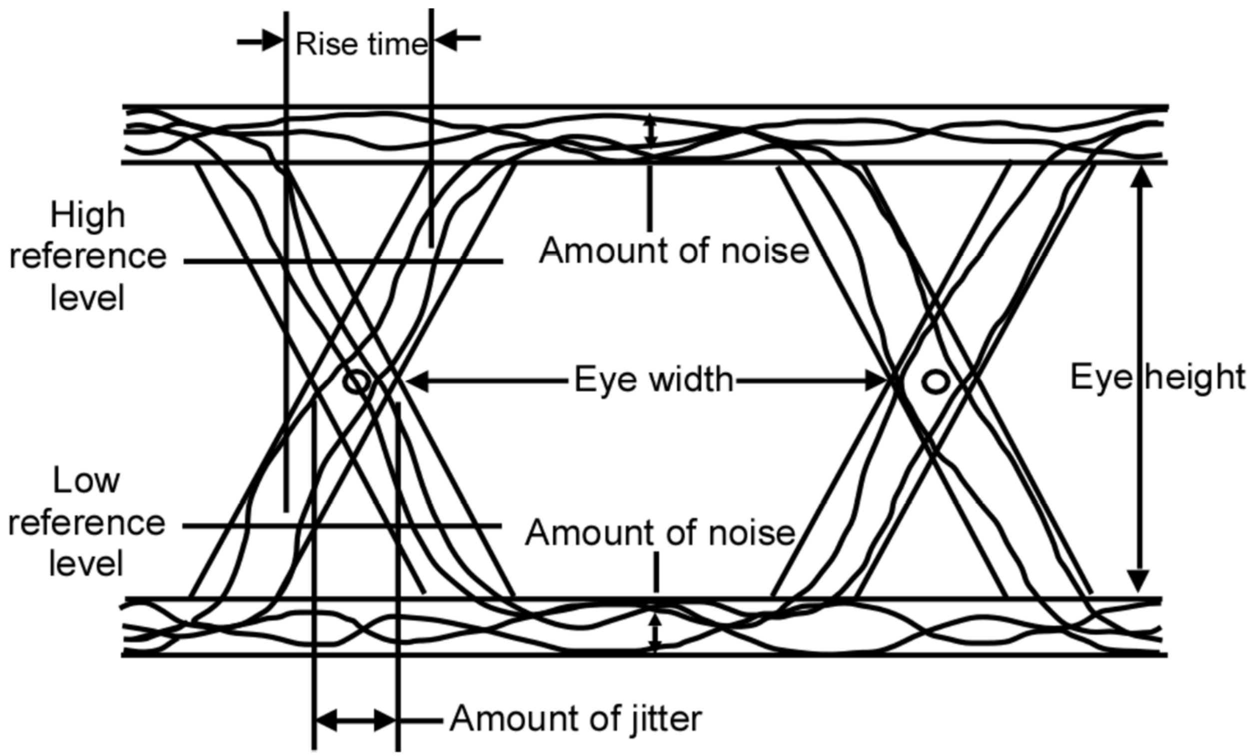


Eye Diagram

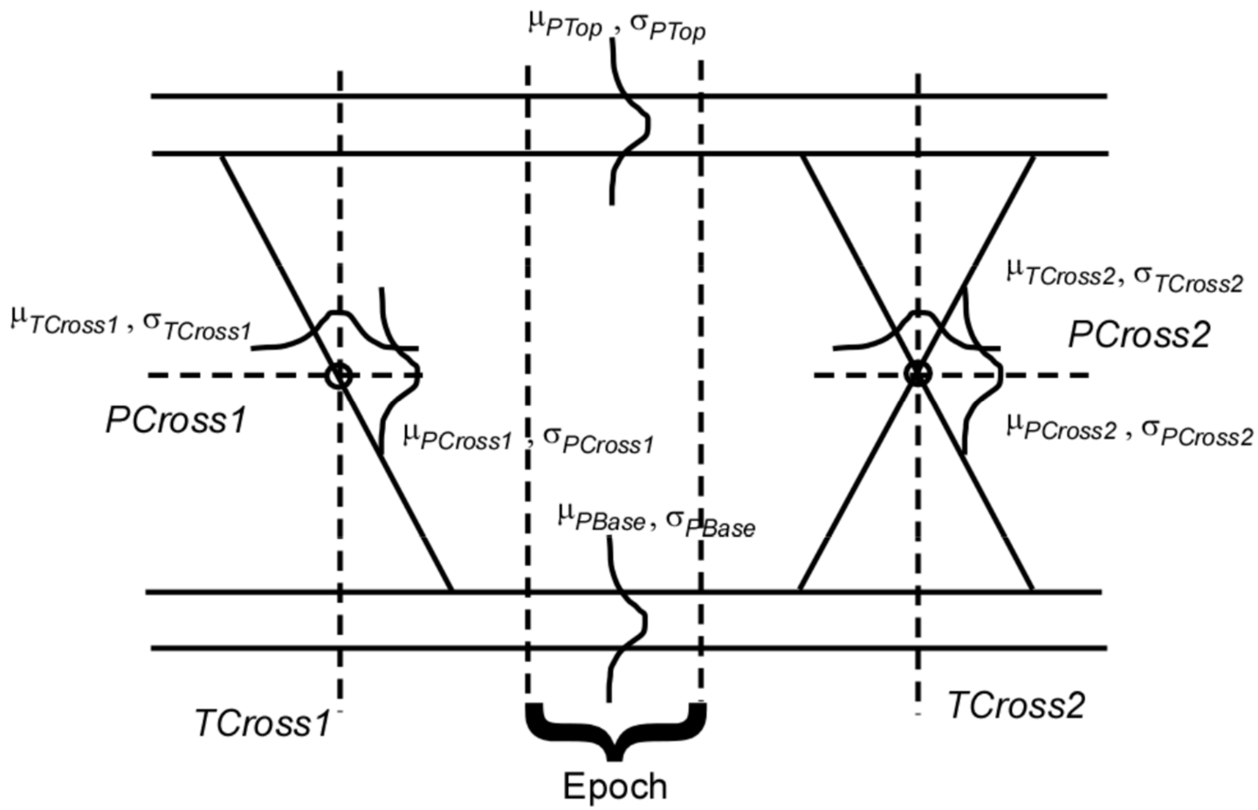
- Unit interval (UI) of a bit sequence is typically independent of the waveform sampling interval of the measurement instrument.
  - Waveform sampling interval must be no more than one half the unit interval to avoid aliasing
  - Rule of thumb for eye diagrams is to sample 5 to 10 times the bit rate
  - 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 Measurements



Reference Levels



Eye Height

Eye Height is the measuremnt of the eye height in volts

$$Eye\ Height = \left(\mu_{PTop} - 3\sigma_{PTop}\right) - \left(\mu_{PBase} + 3\sigma_{PBase}\right)$$

μ_{PTop} : mean value of eye top

σ_{PTop} : standard deviation of eye top

μ_{PBase} : mean value of eye base

σ_{PBase} : standard deviation of eye base

Eye Width

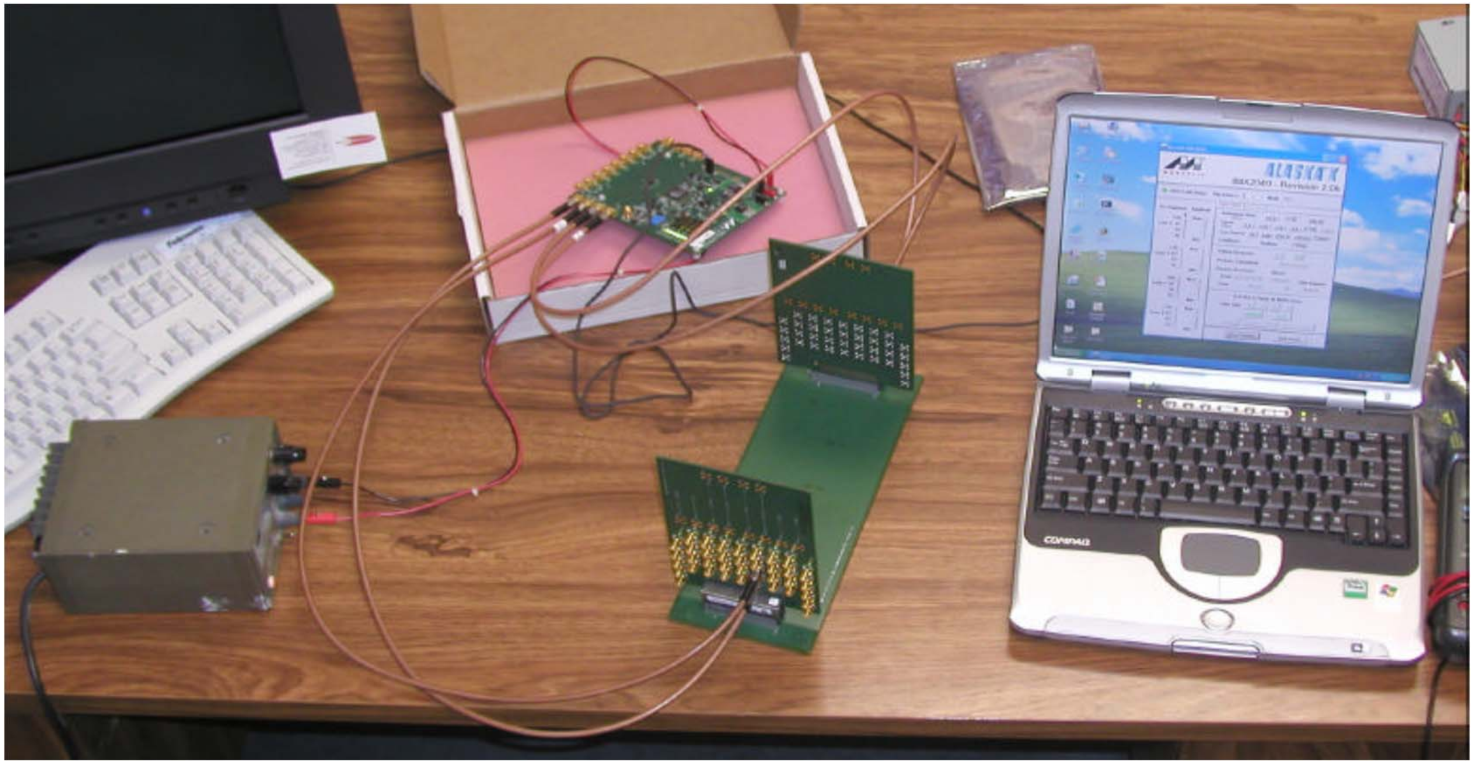
Eye Width **is the measuremnt of the eye width in seconds**

$$Eye\,Width = \left(\mu_{TCross\,2} - 3\sigma_{TCross\,2}\right) - \left(\mu_{TCross\,1} + 3\sigma_{TCross\,1}\right)$$

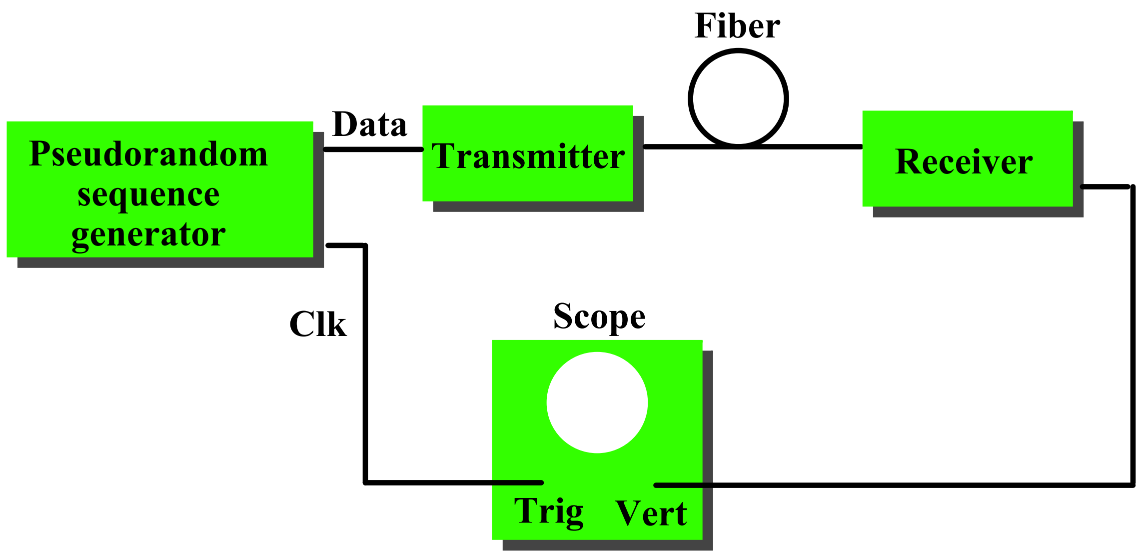
Crossing percent **measurement is the eye crossing point expressed as a percentage of the eye height**

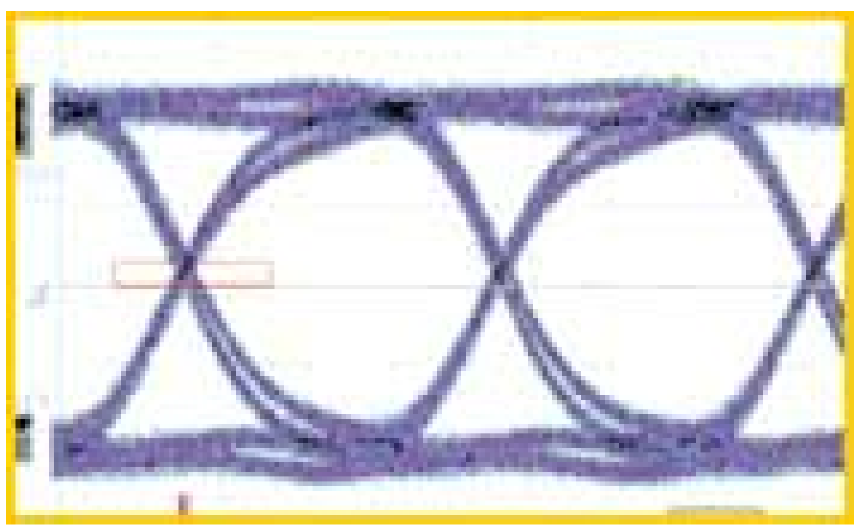
$$\text{Crossing Percent} = \frac{\left(\mu_{PCross1} - \mu_{PBase}\right)}{\left(\mu_{PTop} - \mu_{PBase}\right)} \times 100\%$$

Measuring Jitter



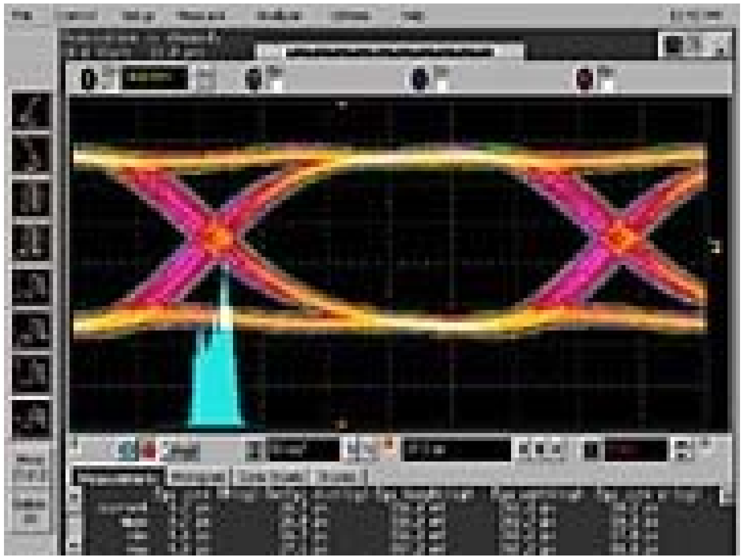
Eye Pattern Analysis

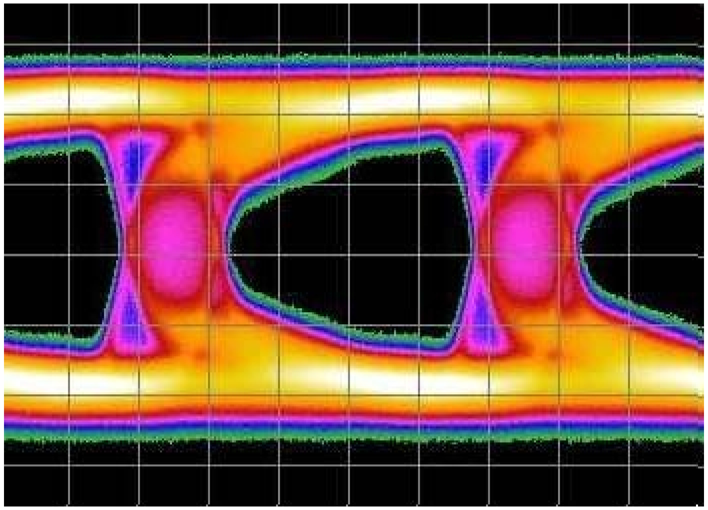




Eye Diagrams

• 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





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

Probe Further

- D. Derickson and M. Muller, “Digital Communications Test and Measurement”, Prentice Hall, 2007.
- Kyung Suk (Dan) Oh and Xingchao (Chuck) Yuan, High-Speed Signaling: Jitter Modeling, Analysis, and Budgeting, Prentice Hall, 2012
- Mike Peng Li, Jitter, Noise and Signal Integrity at High-Speed, Prentice Hall, 2008