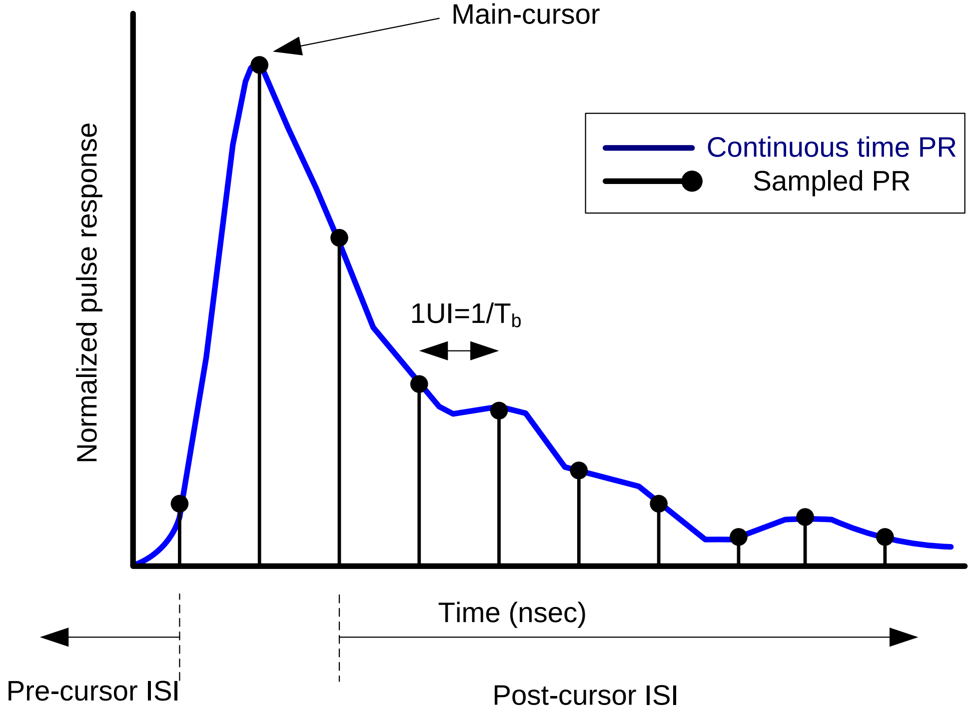
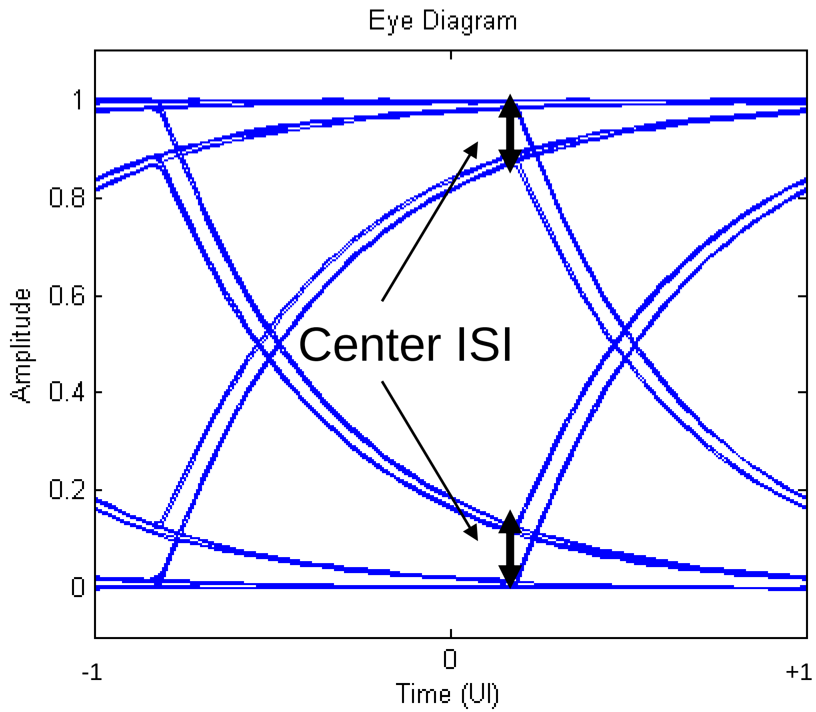
Introduction to Serial/Optical Communication

Lecture 2

Center Inter Symbol Interference (ISI)

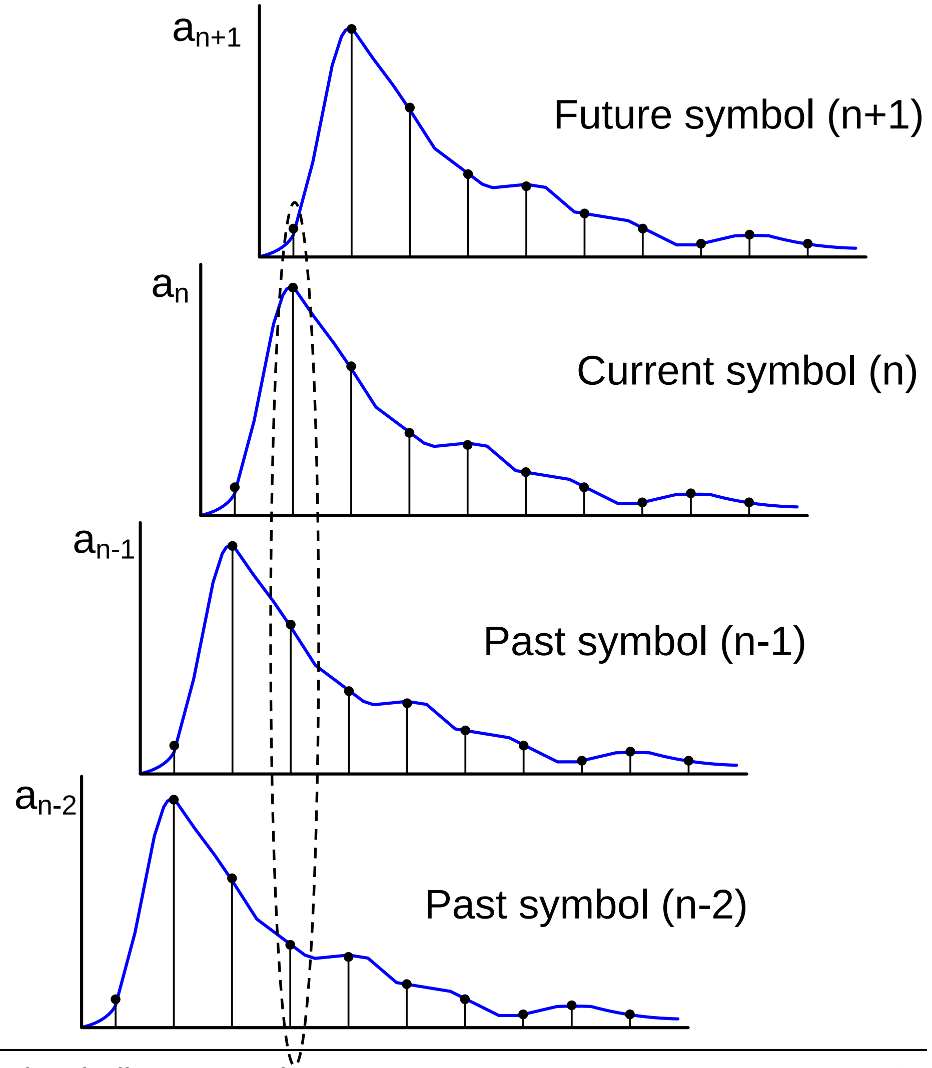




- The continuous time pulse response gives full information about the shape of the eye diagram
- To quantify the vertical eye at the sampling point (center of the eye) it is enough to look at the ISI contributions nx1 UI away from the main cursor where n is any integer
- The ISI following the main cursor is post cursor ISI
- The ISI before the main cursor is pre-cursor ISI

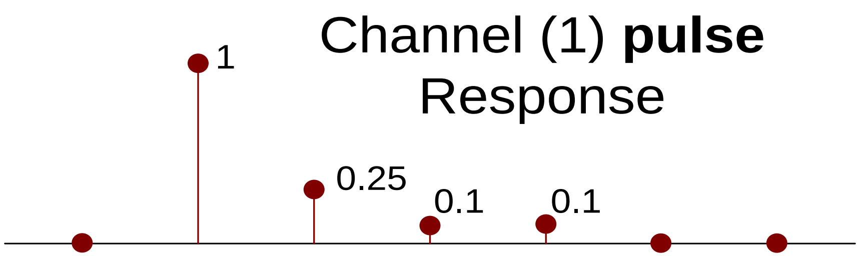
Center Inter Symbol Interference (Cont'd)

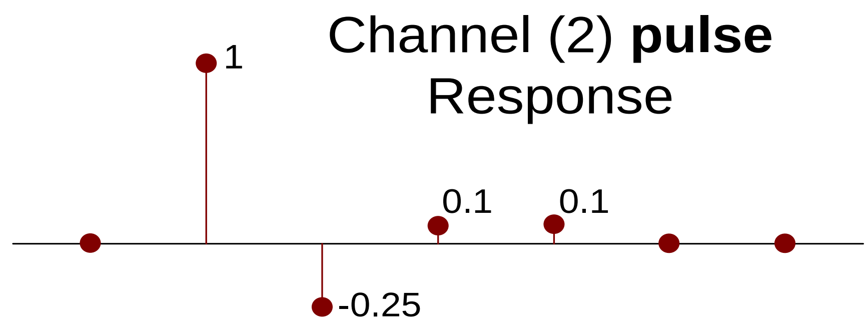
- The transmitted symbols 0s and 1s are represented by $a_n = \pm 1$
- Past symbols add post-cursor ISI to the main-cursor
- Future symbols add pre-cursor ISI to the main-cursor
- The eye closure can be directly calculated if the post and pre-cursor ISI terms are known
- If a_n and a_{n-1} (or a_{n+1}) have opposite polarity (i.e. a transition bit) the ISI terms subtract from the main cursor



Center Inter Symbol Interference (Cont’d)

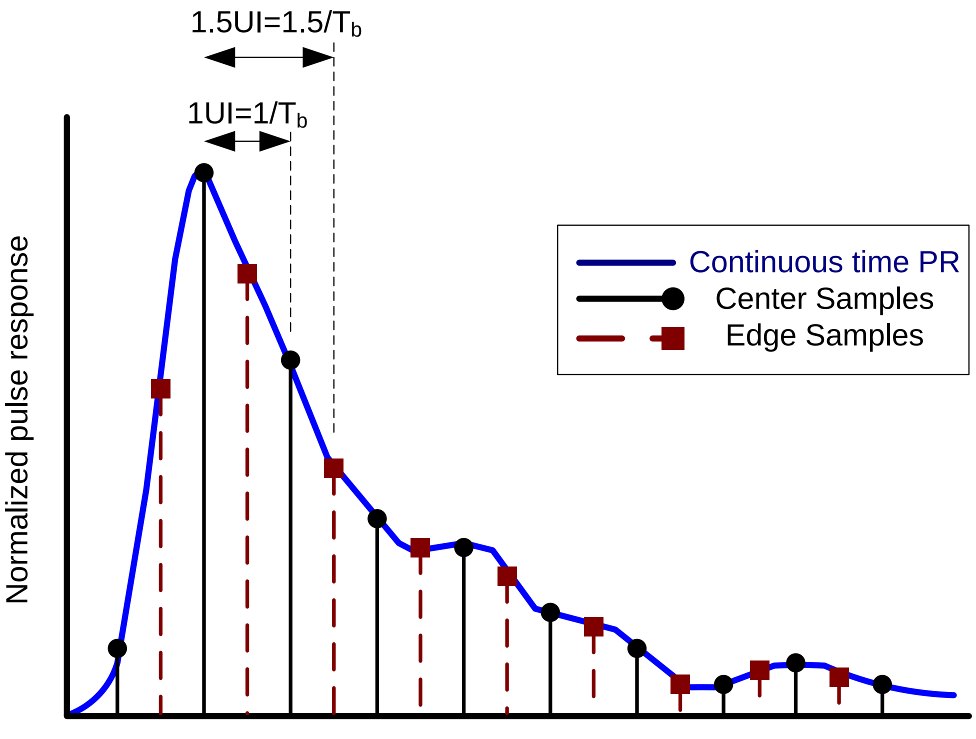
- Problem: Calculate the worst-case vertical eye opening given the following channel pulse responses, and indicate what is the data pattern that results in this worst case eye closure.

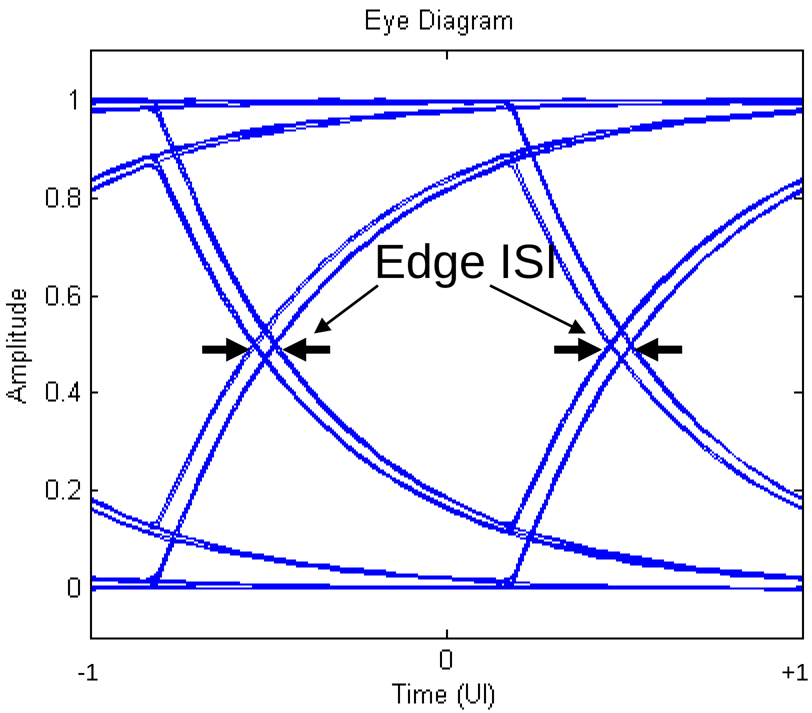




- Solution:
  - Channel (1) worst case eye opening=1-0.25-0.1-0.1=0.55V
  - Channel (1) worst case pattern =“0001X”
  - Channel (2) worst case eye opening=1-0.25-0.1-0.1=0.55V
  - Channel (2) worst case pattern =“0011X”

Edge Inter Symbol Interference (ISI)





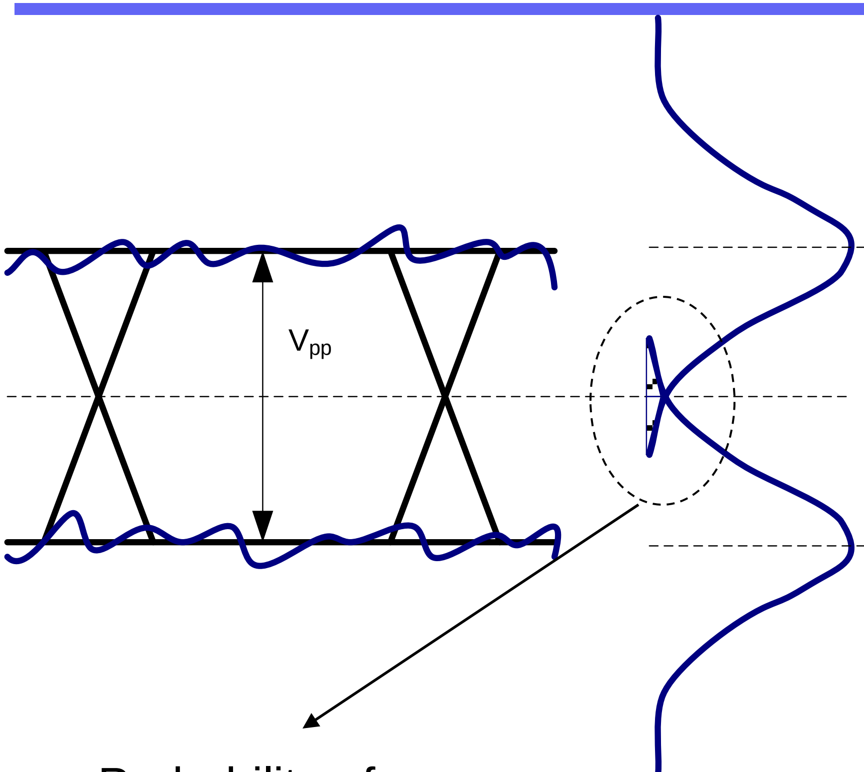
- Edge ISI terms are (n+0.5) UI away from the main cursor, where n is any integer (except for n=-1 and 0)
- Edge ISI results in closure of the horizontal eye opening (data dependent jitter DDJ)

Random Noise

- Random noise can be due to the thermal noise of the Tx driver and/or the Rx receiver circuitry
- It can also arise from the Tx high speed clock which is usually generated from an on-chip PLL
- Random noise added to the transmitted NRZ signal will result in adding uncertainty to and reducing both the vertical and horizontal eye openings
- The effect of noise on the vertical eye can be better treated as voltage noise and can be directly related to the BER
- Assuming a Gaussian distribution for the additive noise with an rms value of σ_n one can show that the BER can be related to the inner noiseless eye opening (V_{pp}) as follows:

$$BER = \int_{\frac{V_{pp}}{2\sigma_n}}^{\infty} \frac{1}{\sqrt{2\pi}} \exp\left(\frac{-u^2}{2}\right) du = \frac{1}{2} erfc\left(\frac{V_{pp}}{2\sqrt{2}\sigma_n}\right)$$

Random Noise (Cont'd)

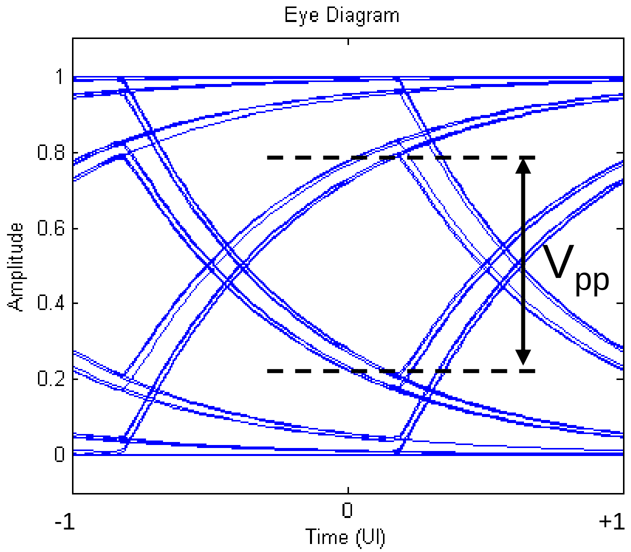


Probability of error

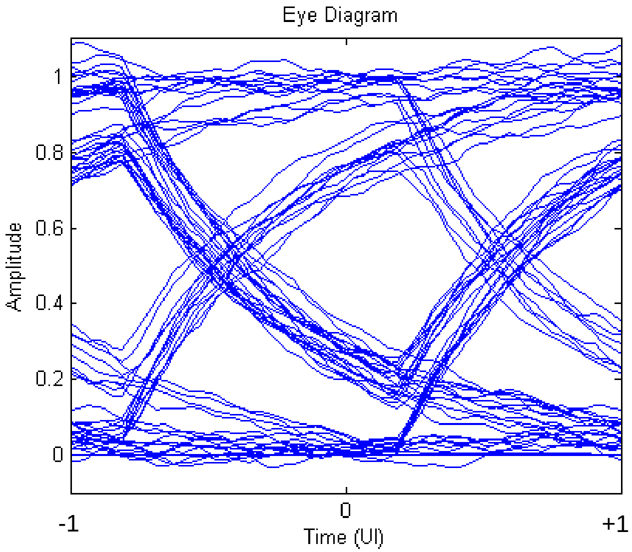
$$BER = \int_{\frac{V_{pp}}{2\sigma_n}}^{\infty} \frac{1}{\sqrt{2\pi}} \exp\left(\frac{-u^2}{2}\right) du$$

BER	V_p/σ_n
10^{-6}	4.7
10^{-7}	5.2
10^{-8}	5.6
10^{-9}	6
10^{-10}	6.4
10^{-11}	6.7
10^{-12}	**7**
10^{-13}	7.3
10^{-14}	7.6
10^{-15}	**7.9**

Random Noise (Cont'd)



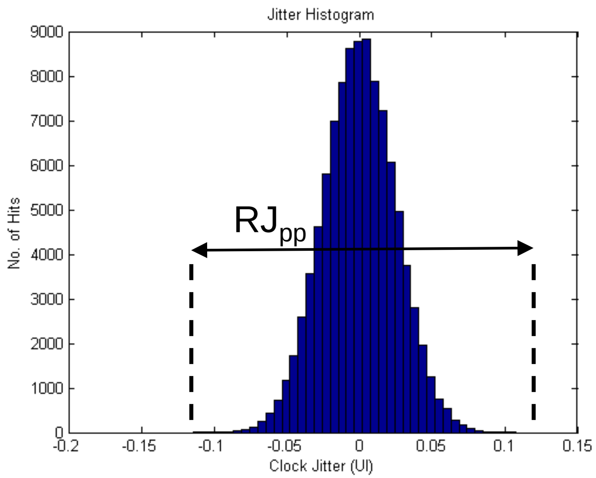
Noise less eye diagram



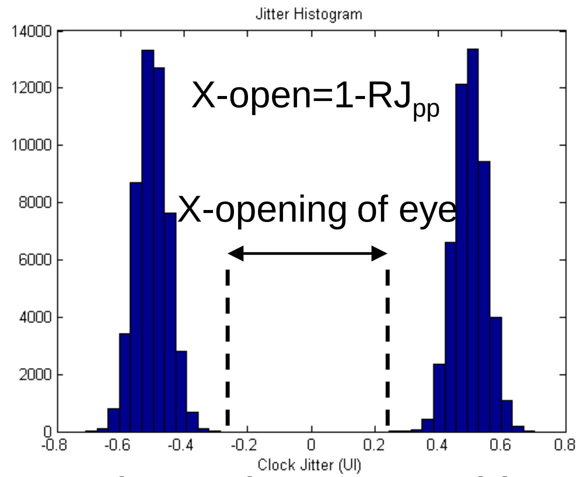
eye diagram with Gaussian random noise

- The noise effect on the horizontal eye opening can be better quantified as jitter, i.e. uncertainty in the timing of the eye zero crossing
- Most serial standards put stringent requirements on jitter produced by Tx drivers, and the jitter that should be tolerated by the receiver (jitter tolerance)
- By observing the signal zero crossing a jitter histogram can be constructed and it can be de-composed into different components of jitter i.e. ISI (which is data dependent), and random jitter, …

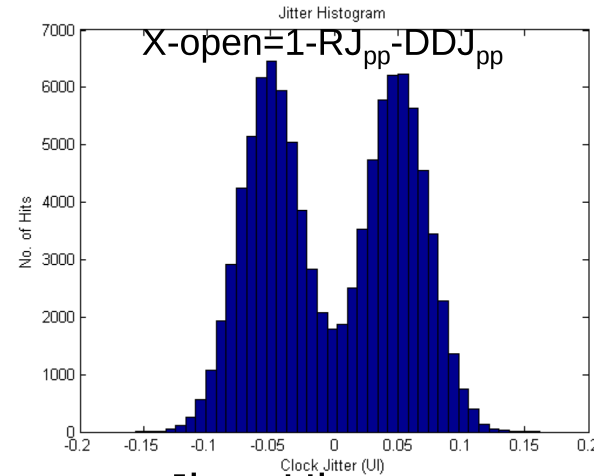
Jitter Histogram



Jitter Histogram due to Gaussian RJ



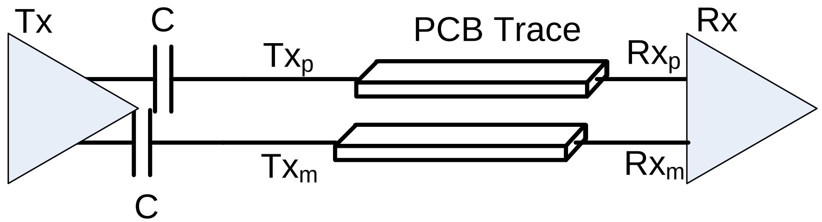
Jitter Histogram with RJ of both eye edges

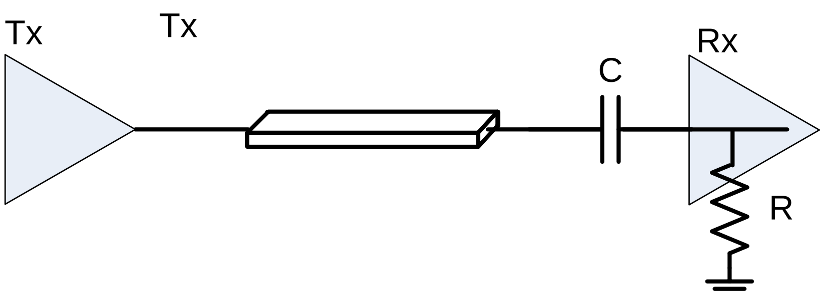


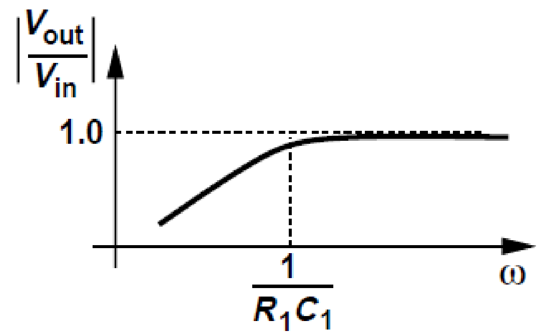
Jitter Histogram including RJ and DDJ

- The value of the peak-to-peak value of a Gaussian distributed random variable (RJ_{PP}) will increase as the observation period increases
- RMS value of a Gaussian random variable is not a function of the observation period →RJ is characterized by its rms value
- Length of observation period is linked to the desired BER, for example for a BER of 1e-12 one has to observe less than 1 error in 1e12 bits, i.e. the observation period should be at least 1e12 bits. To increase the confidence level usually 10x of the number of UIs should be observed
- The effect of data dependent jitter (DDJ) shows as multiple peaks in the histogram

AC Coupling Capacitors

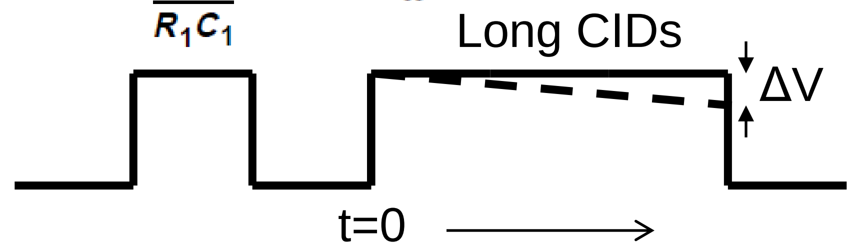






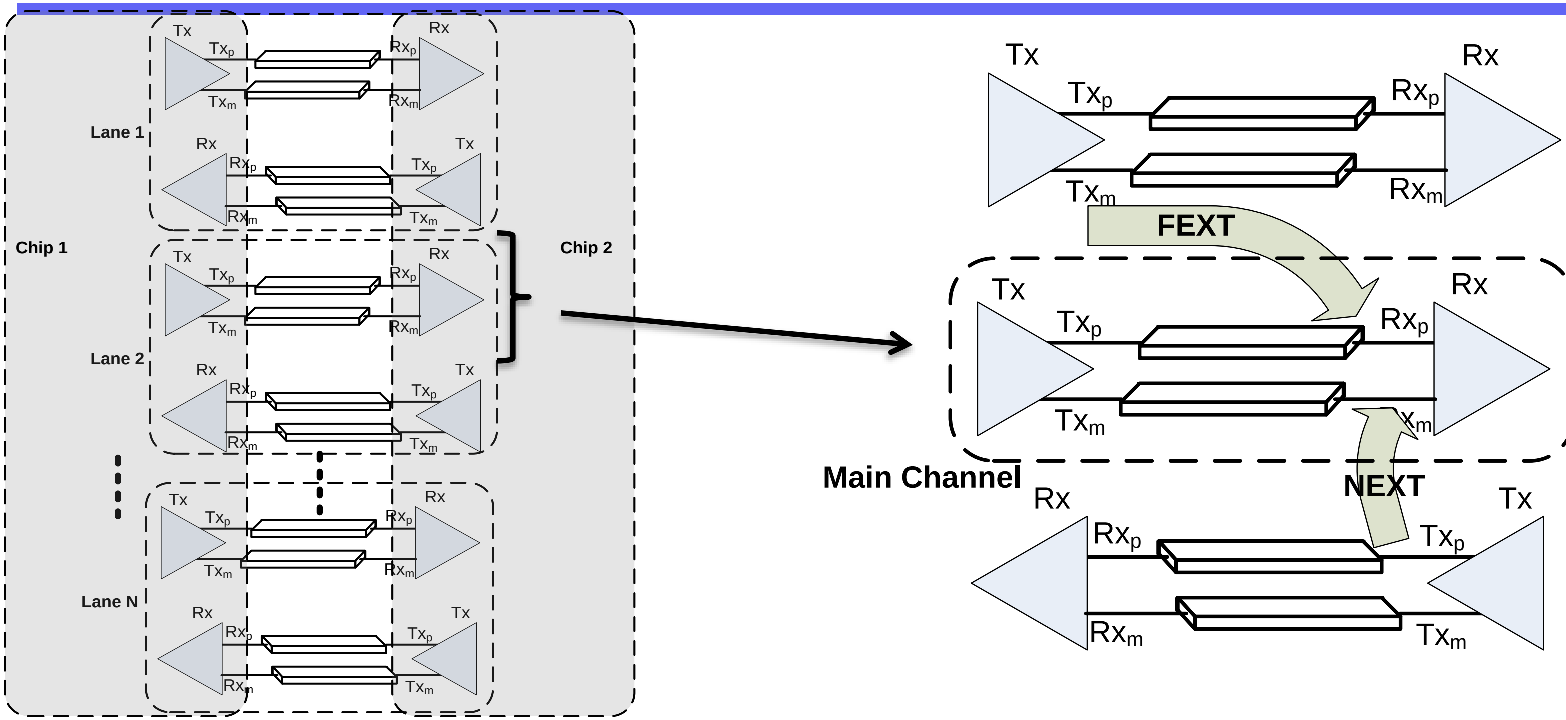
$$\tau = RC$$

$$v_o = V_p \times e^{-t/\tau}$$



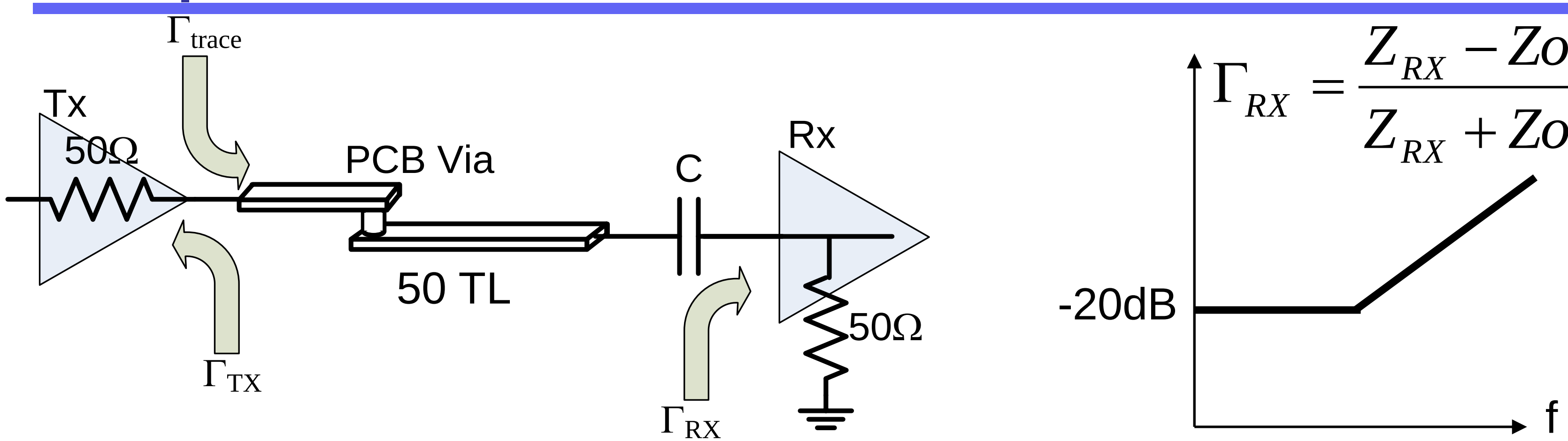
- Many serial standards specify the use of AC coupling capacitors to allow different common mode voltages for the Tx driver and Rx receiver
- The AC coupling capacitors together with the receiver 50Ohm termination form a high pass filter, which attenuates the DC component of the signal
- As long as the cut-off frequency of the HP filter is low enough it will not have a significant impact on the received signal
- Scrambling &/or block coding techniques such 8b/10b, 64b/66b, 128b/130b encoding ensures that the maximum no. of CIDs is < a specific number at the expense of reduced through-put

Channel Cross Talk



- The received signal is corrupted by cross talk from neighboring channels
- NEXT (near end cross talk) represent the cross talk signal injected from the lower Tx, for example through the package
- FEXT (far end cross talk) represents the cross talk signal injected from the top Tx, which has to propagate through the channel
- Cross talk signals see a high-pass type of response since this phenomena can be mostly modeled via capacitive coupling

Impedance Mismatches & Reflections



$$\Gamma_{RX} = \frac{Z_{RX} - Zo}{Z_{RX} + Zo}$$

- PCB vias, connectors, packages, and traces in the high-speed signal path create impedance discontinuities and result in reflections
- On chip Tx and Rx termination resistances vary over process resulting in finite reflection coefficients, which bounces back and forth a portion of the signal power
- Reflected signals interfere with the main signal creating ripples in the **frequency response**
- This shows as ripples in the channel **pulse response** at a location depending on the distance of the discontinuity from the receiver, and the magnitude of the ripple is related to the reflected signal
- Reflections can only be cancelled by a feed forward or decision feedback equalizer **with many taps**

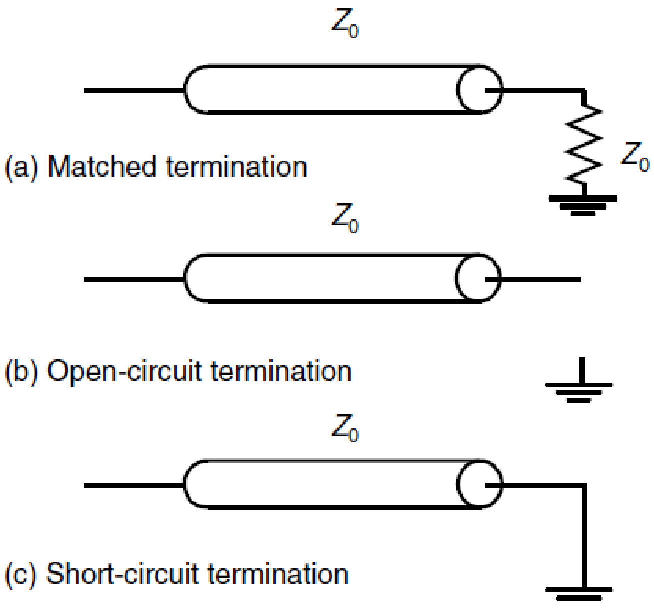
Impedance Mismatches & Reflections

- The termination of a TL determines how much of the wave is reflected upon arrival at the wire end
- The reflection coefficient Γ_{RX} determines the relationship between the voltages of the incident and reflected waveforms:

$$\Gamma_{RX} = \frac{V_{refl}}{V_{inc}} = \frac{Z_{RX} - Z_o}{Z_{RX} + Z_o}$$

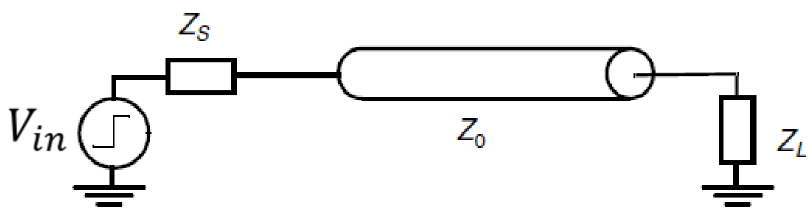
- The total voltage at the termination end is the sum of incident and reflected waves:

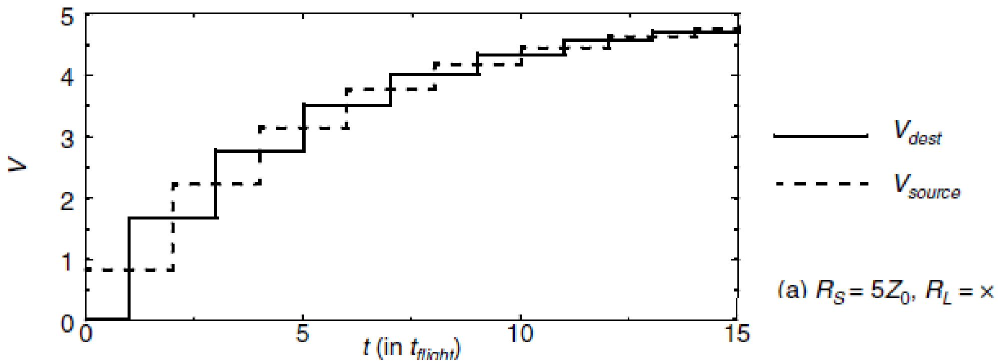
$$V_{des} = V_{inc}(1 + \Gamma_{RX})$$



- If the terminating resistance is equal to Z_o, no waveform is reflected $\Gamma_{RX} = 0$
- For an open circuit ($Z_{RX} = \infty$), $\Gamma_{RX} = 1$. The total voltage waveform is twice the incident
- For a short circuit ($Z_{RX} = 0$), $\Gamma_{RX} = -1$. The total voltage waveform is 0

Impedance Mismatches & Reflections





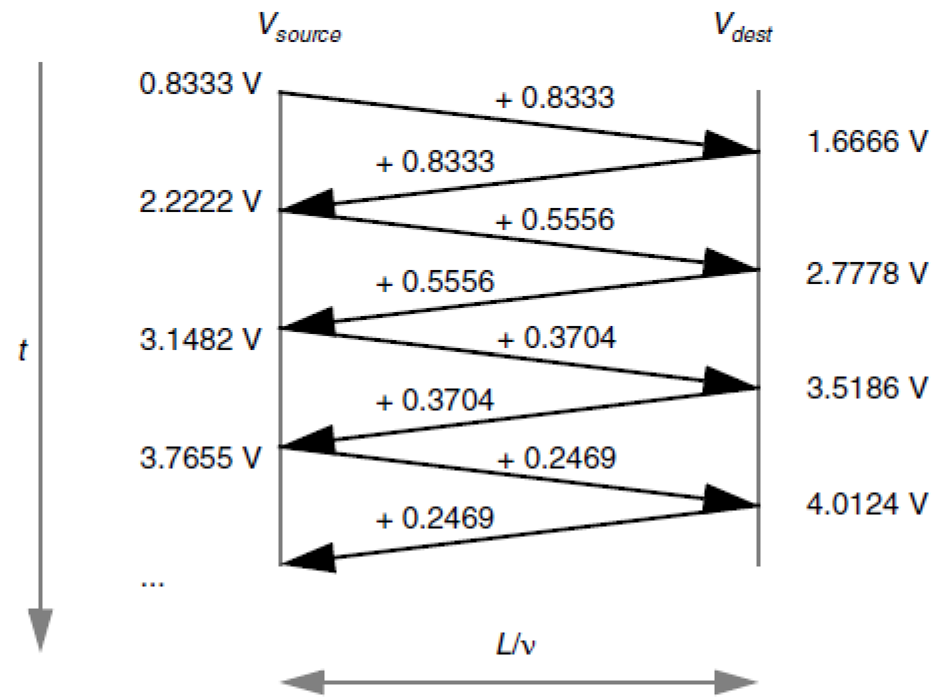
- The transient behavior of a complete transmission line is influenced by the characteristic impedance Z_o, the source impedance Z_S, and the loading impedance Z_L
- For example, for $Z_S = 5Z_o$ a small fraction of the incoming signal V_{in} (0→5V step) is injected into the transmission line.
- The amount injected is determined by the resistive divider formed by the Z_s and Z_o

$$V_{source} = V_{in}\frac{Z_o}{Z_s+Z_o}=0.83\text{V}$$

- This signal reaches the end of the line after L/ν sec, where L stands for the length of the wire and is fully reflected
- When the reflected wave reaches the source node again it is reflected with an amplitude determined by the source reflection coefficient, $\Gamma_s = \frac{5Z_o - Z_o}{5Z_s+Z_o} = 2/3$
- This results in a source voltage of 0.83+0.83*(1+2/3)=2.22V

Lattice Diagram

- The voltage amplitude at source and destination nodes gradually reaches its final value of V_{in}.
- The overall rise time is, however, many times L/ν
- *lattice diagram* contains the values of the voltages at the source and destination ends, as well as the values of the incident and reflected wave forms.
- The line voltage at a termination point equals the sum of the previous voltage, the incident, and reflected waves



[ref] Digital Integrated Circuits, A Design Perspective, by Jan N. Rabaey

Impedance Mismatches & Reflections

- **For $R_S = Z_o/5$**, a large portion of the input is injected in the line. Its value is doubled at the destination end, which causes a severe overshoot.
- At the source end, the phase of the signal is reversed ($\Gamma_S = -2/3$).
- The signal bounces back and forth and exhibits severe ringing. It takes multiple L/v before it settles.
- **For $R_S = Z_o$** half of the input signal is injected at the source.
- The reflection at the destination end doubles the signal, so that the final value is reached immediately.
- It is obvious that this is the most effective case.

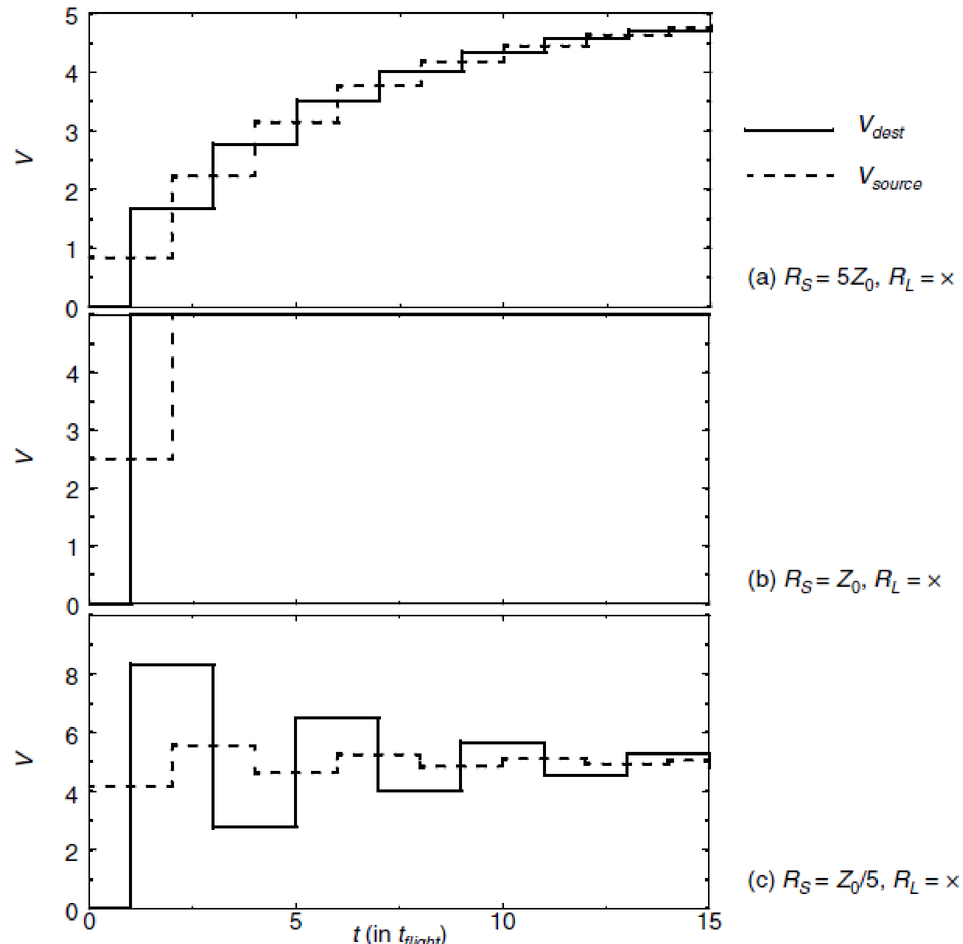
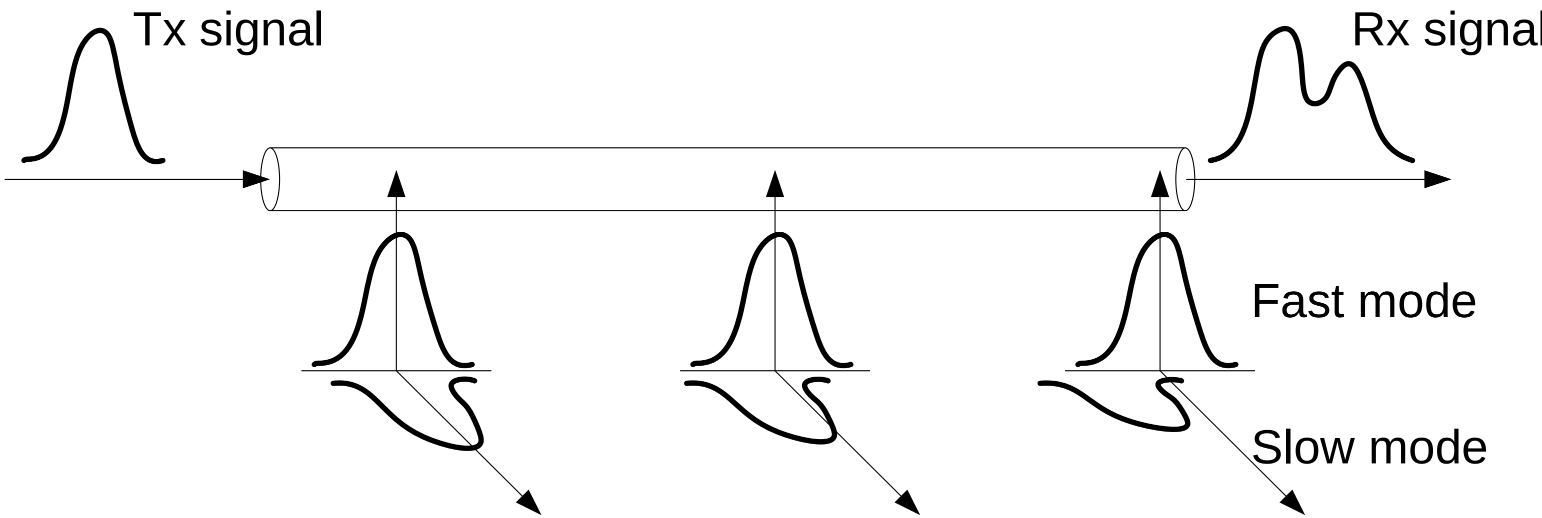


Figure 4.21 Transient response of transmission line.

Optical Fiber Systems: PMD



- Polarization mode dispersion (PMD) is one of the main sources of dispersion in SMF fiber
- The difference in the refractive index experienced by the 2 orthogonal modes in fiber leads to a fast and slow wave
- If the difference between the arrival times is comparable to the bit period this results in dispersion (or ISI)
- Optical systems must include some sort of PMD compensation (electronic or optical)

PMD (Cont'd)

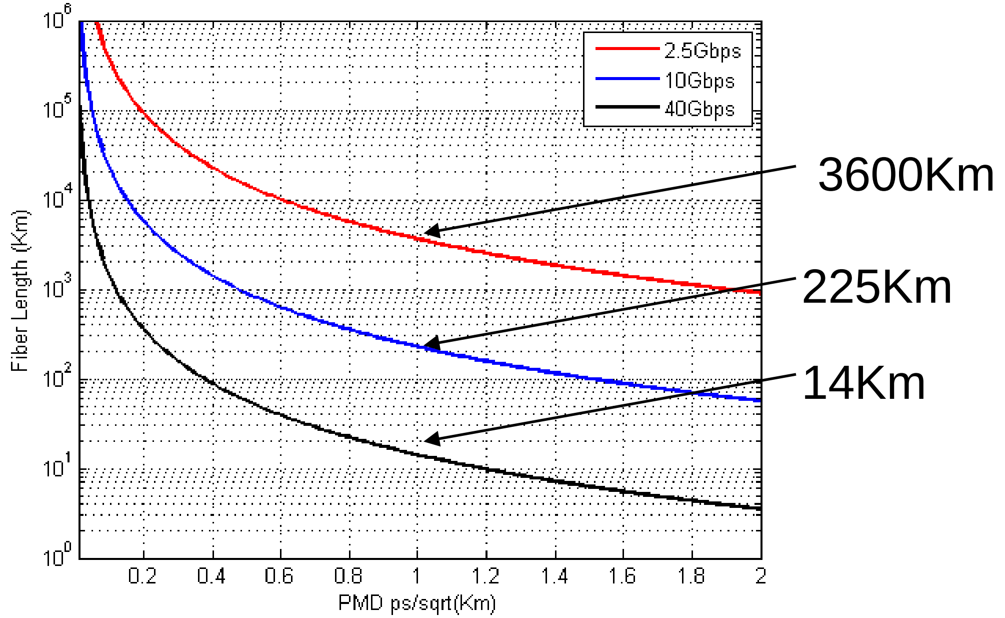
- To a first order the impulse response of optical fiber with PMD can be expressed as:

$$h_{PMD}(t) = \gamma\delta(t) + (1-\gamma)\delta(t-\Delta\tau)$$

- γ is proportional to the optical power in the fast state of polarization
- 1- γ is proportional to the optical power in the slow state of polarization
- $\Delta\tau$ is the differential group delay (DGD) between the fast and slow modes
- The average DGD per unit length of fiber is defined as:

$$\Delta\tau_{avg} = PMD\sqrt{L}$$

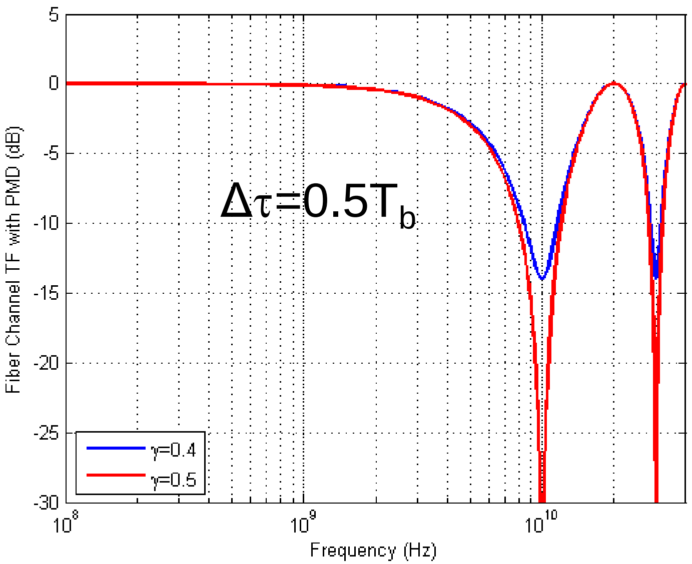
PMD (Cont'd)



- For installed fibers PMD =0.5-2 $ps/\sqrt{km}$
- For new fibers PMD =0.05 $ps/\sqrt{km}$
- In order to avoid system failure due to PMD, the average DGD should be less than $0.15T_b$ (assuming no equalization or repeaters)

$$\Delta\tau_{avg} < 0.15T_b \Rightarrow \quad L = \left(\frac{0.15T_b}{PMD} \right)^2$$

PMD (Cont'd)



- The frequency domain characteristics of a PMD dominated fiber channel can be obtained by taking the Fourier transform of its impulse response:

$$H_{PMD}(f) = \gamma + (1-\gamma)e^{-j\omega\Delta\tau}$$

- The transfer function exhibits minima at $f=(K+0.5)/\Delta\tau$, where K is any integer
- If γ=0.5, these minima becomes nulls in the TF making it difficult to equalize