University of Waterloo

Optical Communication

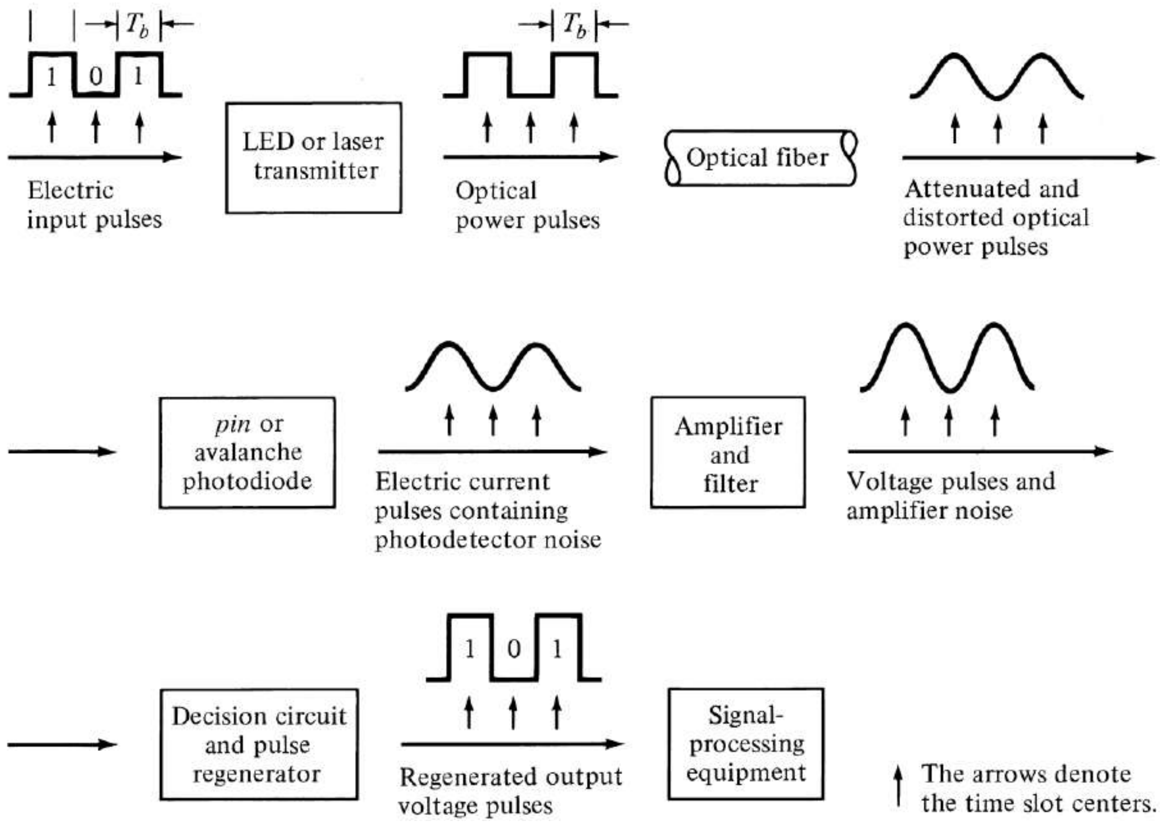
Photonic Transmission Systems (Digital & Analog)

Content

- Digital Photonic transmission System
- Digital Photonic Receiver (BER, Quantum Limit)
- Analog Photonic Transmission System
- Photonic Digital Link Analysis & Design

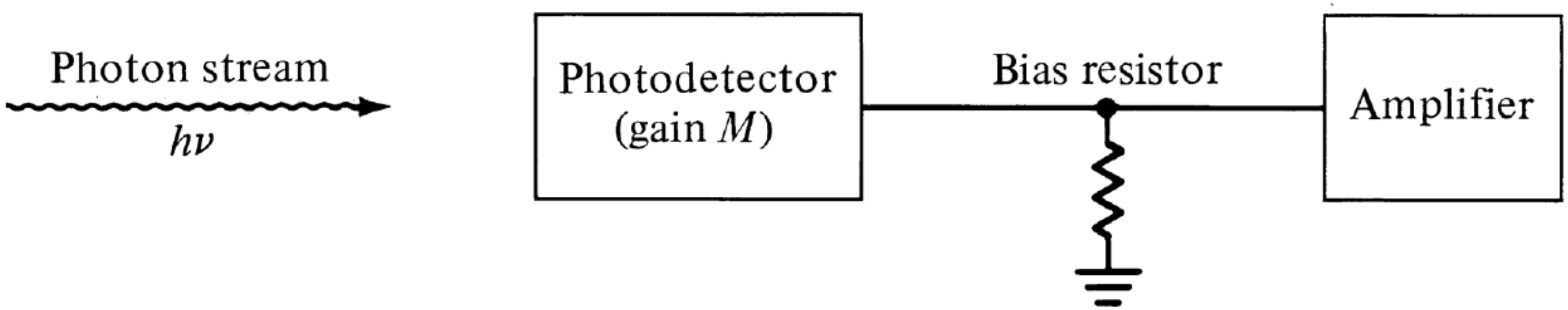
  - Link Loss budget, Link Power budget, Rise Time budget
- System Rise Time and Information Rate

Digital Transmission System (DTS)



- The design of optical receiver is much more complicated than that of optical transmitter because the receiver must first detect weak, distorted signals and the n make decisions on what type of data was sent.

Error Sources in DTS



- Photon detection quantum noise (Poisson fluctuation)

- Bulk dark current
- Surface leakage current
- Statistical gain fluctuation (for avalanche photodiodes)

- Thermal noise

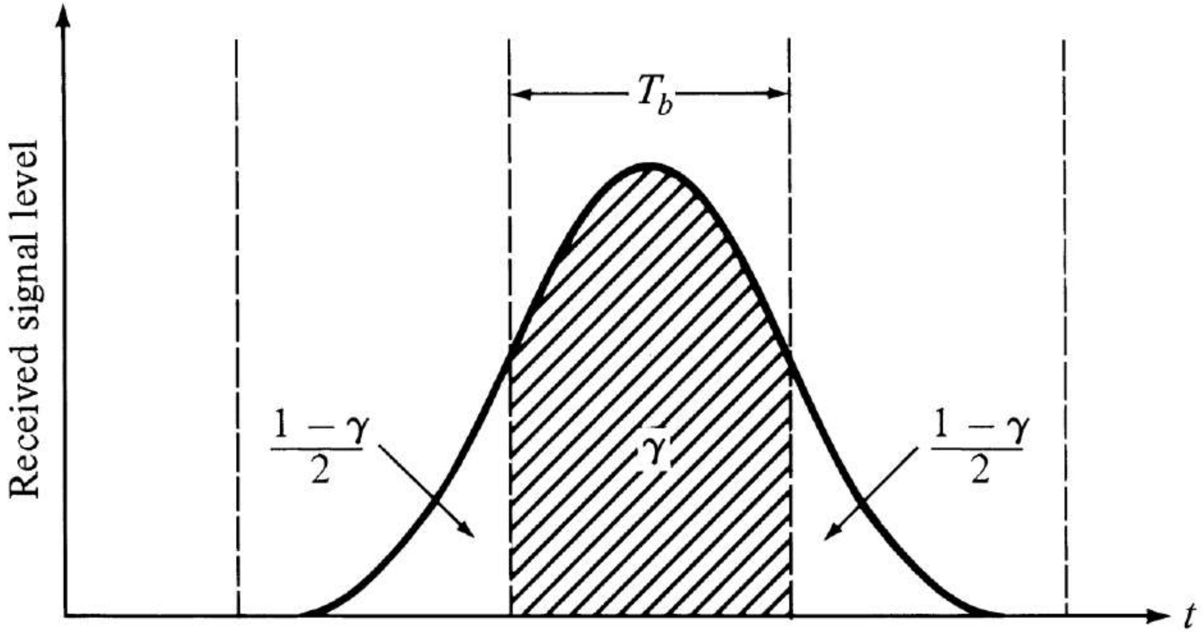
- Amplifier noise

$$\bar{N} = \frac{\eta}{h\nu}\int_0^{\tau} P(t)dt = \frac{\eta}{h\nu}E \quad [7\text{-}1]$$

$$P_r(n) = \bar{N}^n \frac{e^{-\bar{N}}}{n!} \quad [7\text{-}2]$$

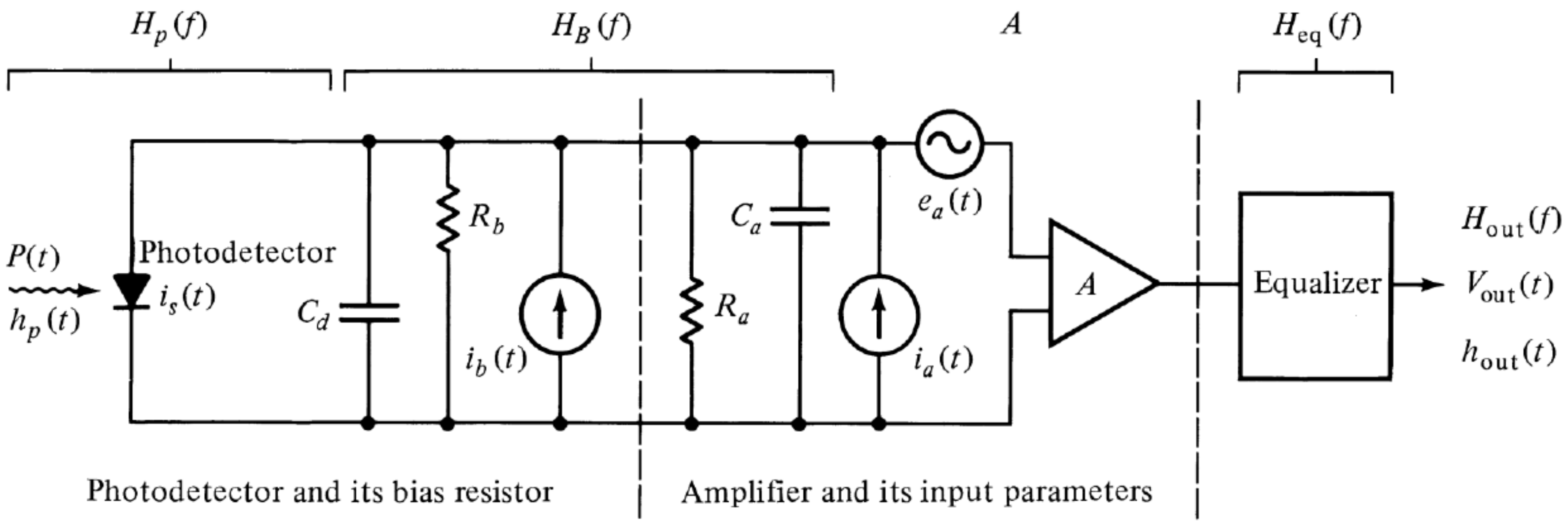
$\bar{N}$ is the average number of electron-hole pairs in photodetector, η is the detector quantum efficiency and E is energy received in a time interval τ and $h\nu$ is photon energy, where $P_r(n)$ is the probability that n electrons are emitted in an interval τ.

InterSymbol Interference (ISI)



Pulse spreading in an optical signal, after traversing along optical fiber, leads to ISI. Some fraction of energy remaining in appropriate time slot is designated by γ, so the rest is the fraction of energy that has spread Into adjacent time slots.

Receiver Configuration



The binary digital pulse train incident on the photodetector can be written in the following form:

$$P(t) = \sum_{n=-\infty}^{+\infty} b_n h_p(t - nT_b) \qquad [7\text{-}3]$$

where T_b is bit period, b_n is an amplitude parameter of the nth message digit and $h_p(t)$ is the received pulse shape which is positive for all t.

- In writing down eq. [7-3], we assume the digital pulses with amplitude *V* represents bit 1 and 0 represents bit 0. Thus b_n can take two values corresponding to each binary data. By normalizing the input pulse $h_p(t)$ to the photodiode to have unit area

$$\int_{-\infty}^{+\infty} h_p(t)\,dt = 1$$

b_n represents the energy in the *n*th pulse.

the mean output current from the photodiode at time *t* resulting from pulse train given in eq. [7-3] is (neglecting the DC components arising from dark current noise):

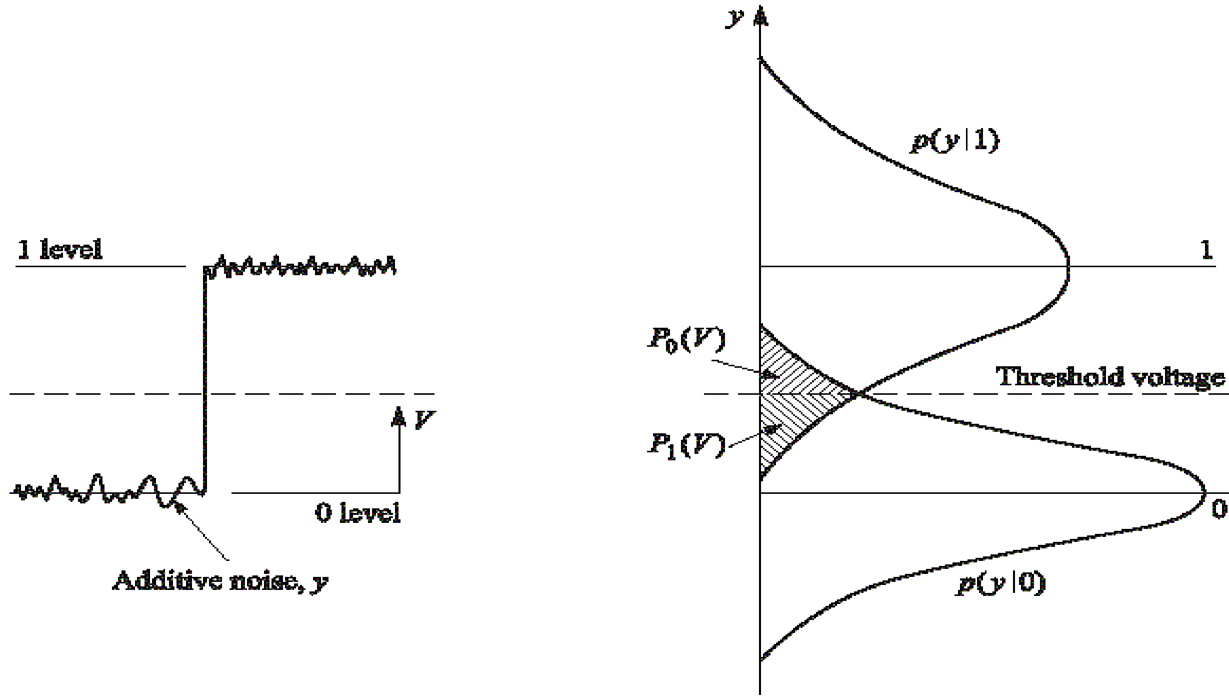
$$\langle i(t) \rangle = \frac{\eta q}{h\nu} M P(t) = \Re_o M \sum_{n=-\infty}^{+\infty} b_n h_p(t - nT_b) \qquad [7\text{-}4]$$

Bit Error Rate (BER)

$$\text{BER} = \text{Probability of Error} = \frac{\text{\# of error over a certain time interval } t}{\text{total \# of pulses transmitted during } t} = \frac{N_e}{N_t} = \frac{N_e}{Bt} \qquad B = 1/T_b$$ [7-5]

- **Probability of Error**= probability that the output voltage is less than the threshold when a 1 is sent + probability that the output voltage is more than the threshold when a 0 has been sent.

V_{th}



Probability distributions for received logical 0 and 1 signal pulses.
the different widths of the two distributions are caused by various signal distortion effects.

$$P_1(v) = \int_{-\infty}^{v} p(y \mid 1)dy \quad \text{probablity that the equalizer output voltage is less than } v, \text{if 1 transmitted}$$

[7-6]

$$P_0(v) = \int_{v}^{\infty} p(y \mid 0)dy \quad \text{probablity that the equalizer output voltage exceeds } v, \text{if 0 transmitted}$$

$$P_e = q_1 P_1(v_{th}) + q_0 P_0(v_{th})$$
$$= q_1 \int_{-\infty}^{v_{th}} p(y\,|\,1)dy + q_0 \int_{v_{th}}^{\infty} p(y\,|\,1)dy \qquad [7\text{-}7]$$

- Where q_1 and q_0 are the probabilities that the transmitter sends 0 and 1 respectively. $q_0 = 1 - q_1$

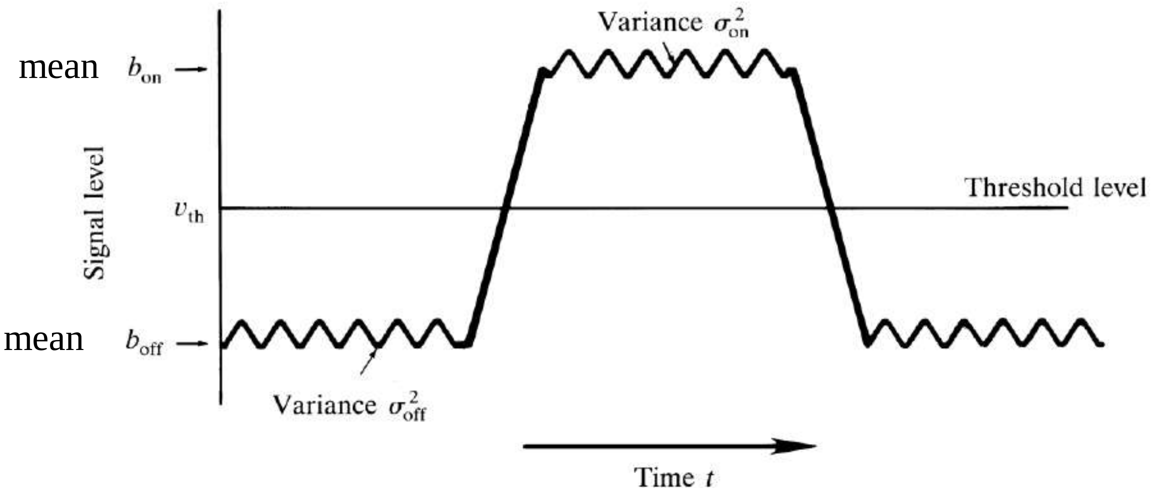
- For an unbiased transmitter $q_0 = q_1 = 0.5$

Gaussian Distribution

$$P_1(v_{th}) = \int_{-\infty}^{v_{th}} p(y\,|\,1)dy = \frac{1}{\sqrt{2\pi}\sigma_{\text{on}}} = \int_{-\infty}^{v_{th}} \exp\left[-\frac{(v-b_{on})^2}{2\sigma_{\text{on}}^2}\right]dv$$

$$P_0(v_{th}) = \int_{v_{th}}^{\infty} p(y\,|\,0)dy = \frac{1}{\sqrt{2\pi}\sigma_{\text{off}}} = \int_{v_{th}}^{\infty} \exp\left[-\frac{(v-b_{\text{off}})^2}{2\sigma_{\text{off}}^2}\right]dv$$

[7-8]



- If we assume that the probabilities of 0 and 1 pulses are equally likely, then using eq [7-7] and [7-8] , BER becomes:

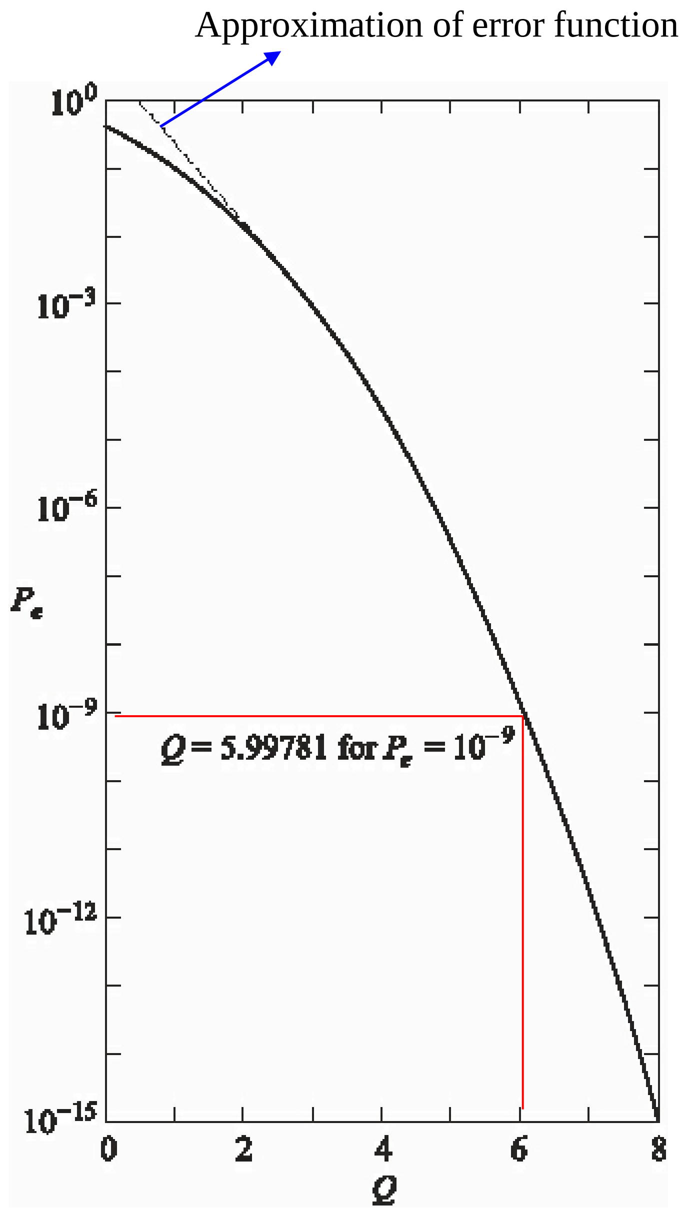
$$\mathrm{BER} = P_e(Q) = \frac{1}{\sqrt{\pi}} \int_{Q/\sqrt{2}}^{\infty} \exp(-x^2)dx = \frac{1}{2}\left[1 - \mathrm{erf}\,(\frac{Q}{\sqrt{2}})\right]$$

$$\approx \frac{1}{\sqrt{2\pi}} \frac{\exp(\text{-}Q^2/2)}{Q} \quad [7\text{-}9]$$

$$Q = \frac{v_{th} - b_{\mathrm{off}}}{\sigma_{\mathrm{off}}} = \frac{b_{\mathrm{on}} - v_{th}}{\sigma_{\mathrm{on}}} \quad [7\text{-}9]$$

$$\mathrm{erf}\,(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-y^2)dy \quad [7\text{-}10]$$

Variation of BER vs Q, according to eq [7-9].



Special Case

In special case when:

$$\sigma_{\text{off}} = \sigma_{\text{on}} = \sigma \;\&\; b_{\text{off}} = 0, b_{\text{on}} = V$$

From eq [7-29], we have: $v_{th} = V/2$

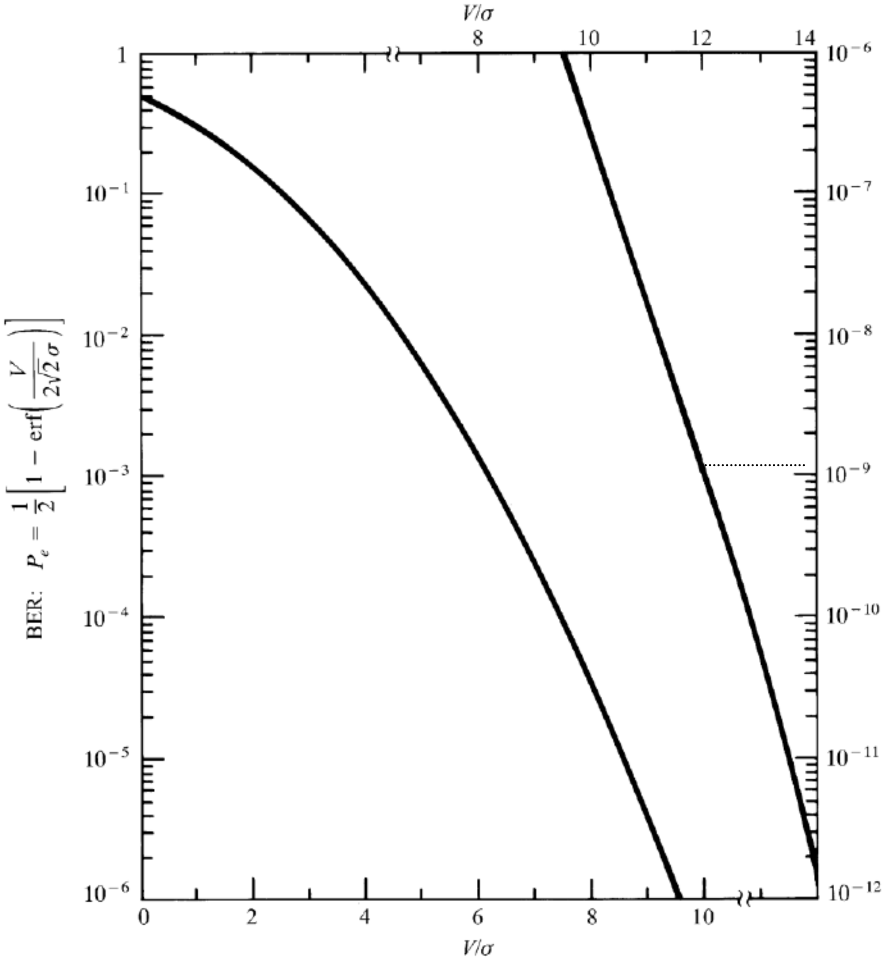
Eq [7-8] becomes:

$$P_e(\sigma) = \frac{1}{2}\left[1 - \text{erf}\left(\frac{V}{2\sqrt{2}\sigma}\right)\right]$$

[7-11]

$\frac{V}{\sigma}$ is peak signal - to - rms - noise ratio.

Study example 7-1 pp. 286 of the textbook.



Quantum Limit

- Minimum received power required for a specific BER assuming that the photodetector has a 100% quantum efficiency and zero dark current. For such ideal photo-receiver,

$$P_e = P_1(0) = \exp(-\bar{N}) \quad [7\text{-}12]$$

- Where $\bar{N}$ is the average number of electron-hole pairs, when the incident optical pulse energy is E and given by eq [7-1] with 100% quantum efficiency $(\eta = 1)$.
- Eq [7-12] can be derived from eq [7-2] where $n=0$.

- Note that, in practice the sensitivity of receivers is around 20 dB higher than quantum limit because of various nonlinear distortions and noise effects in the transmission link.

Analog Transmission System

- In photonic analog transmission system the performance of the system is mainly determined by signal-to-noise ratio at the output of the receiver.
- In case of amplitude modulation the transmitted optical power *P(t)* is in the form of:

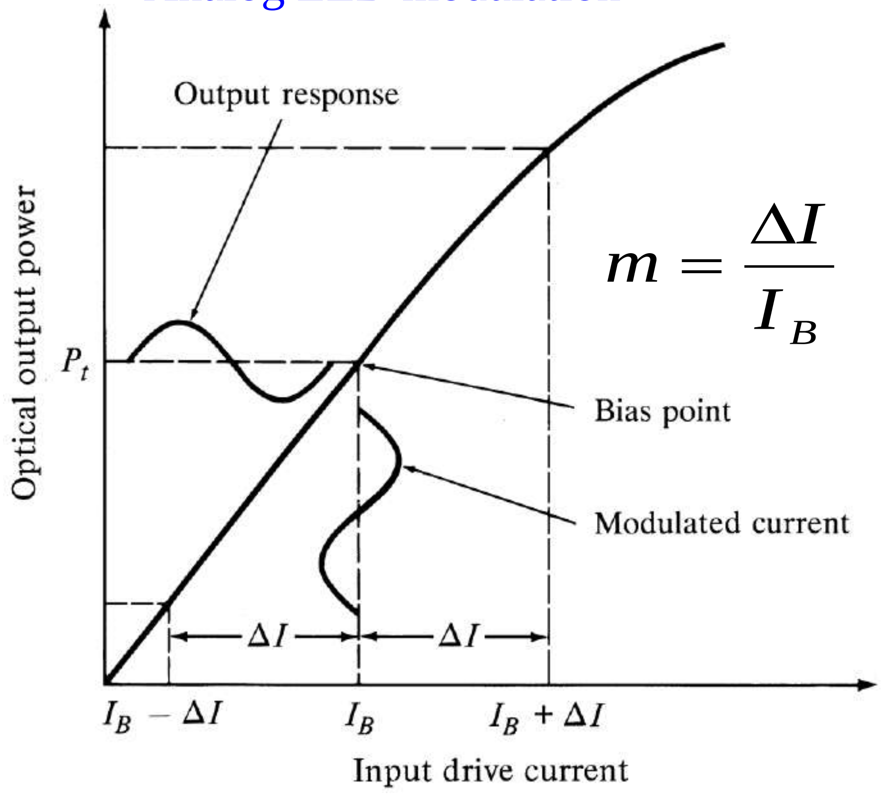
$$P(t) = P_t[1 + ms(t)]$$

where *m* is modulation index, and *s(t)* is analog modulation signal.

- The photocurrent at receiver can be expressed as:

$$i_s(t) = \Re_0 M P_r [1 + ms(t)]$$ [7-13]

Analog LED modulation



$$m = \frac{\Delta I}{I_B}$$

- By calculating mean square of the signal and mean square of the total noise, which consists of quantum, dark and surface leakage noise currents plus resistance thermal noise, the S/N can be written as:

$$\frac{S}{N}=\frac{\langle i_s^2\rangle}{\langle i_N^2\rangle}=\frac{(1/2)(\Re_0 MmP_r)^2}{2q(\Re_0 P_r+I_D)M^2F(M)B+(4k_BTB/R_{eq})F_t}$$
$$=\frac{(1/2)(MmI_P)^2}{2q(I_P+I_D)M^2F(M)B+(4k_BTB/R_{eq})F_t} \qquad [7\text{-}14]$$

I_P : primary photocurrent $=\Re_0 P_r$; I_D : primary bulk dark current;

I_L : Surface - leakage current; $F(M)$: excess photodiode noise factor $\approx M^x$

B : effective noise bandwidth; R_{eq} : equivalent resistance of photodetector load and amplifier

F_t : noise figure of baseband amplifier; P_r : average received optical power

pin Photodiode *S/N*

- For *pin* photodiode, *M=1:*

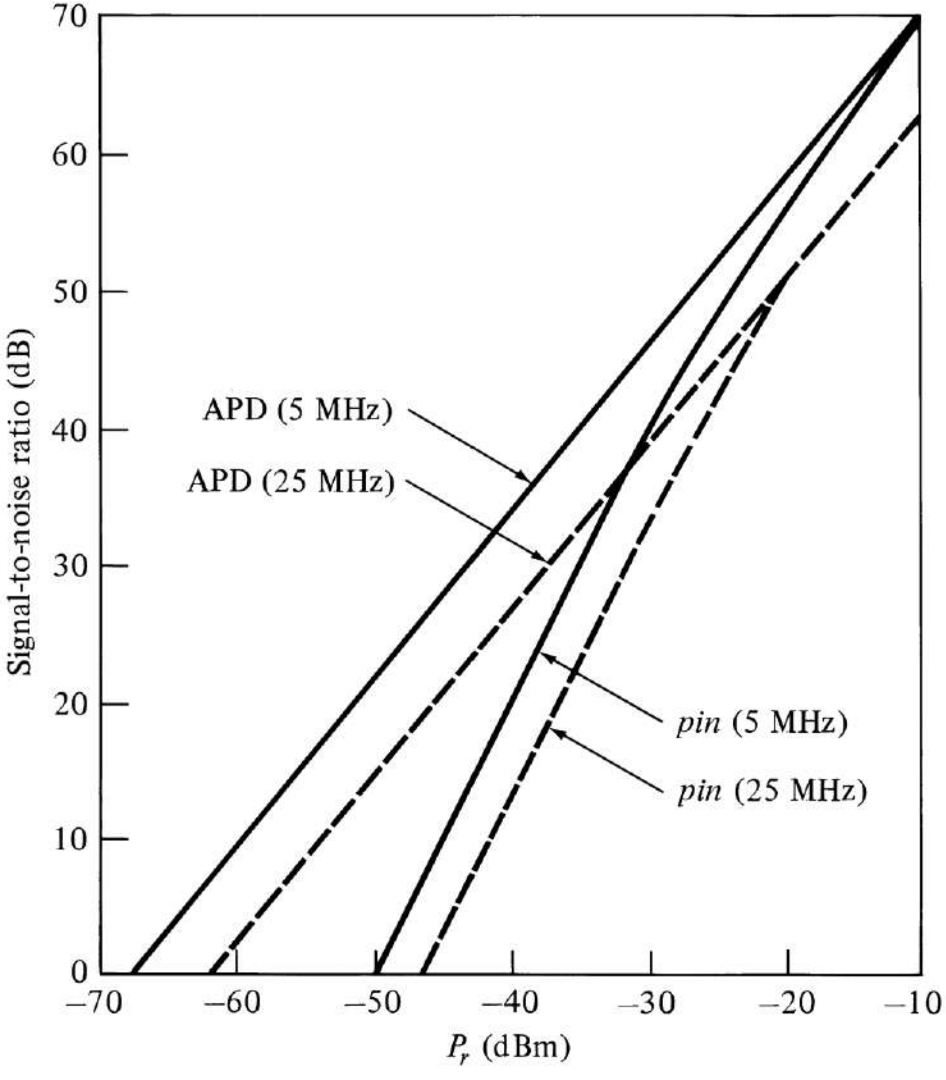
$$\frac{S}{N} \cong \frac{(1/2)(I_P m)^2}{(4k_B TB/R_{eq})F_t} = \frac{(1/2)m^2 \Re_0{}^2 P_r{}^2}{(4k_B TB/R_{eq})F}$$

Low input signal level [7-15]

$$\frac{S}{N} \cong \frac{m^2 \Re_0 P_r}{4qB}$$

Large signal level [7-16]

SNR vs. optical power for photodiodes



Photonic Digital Link Analysis & Design

- Point-to-Point Link Requirement:

  - Data Rate
  - BER
  - Distance
  - Cost & Complexity

- Analysis Methods:

  - Link loss & S/N analysis (link power budget analysis and loss allocation) for a prescribed BER
  - Dispersion (rise-time) analysis (rise-time budget allocation)

System Design Choices: Photodetector, Optical Source, Fiber

- Photodetectors: Compared to APD, PINs are less expensive and more stablewith temperature. However PINs have lower sensitivity.
- Optical Sources:

1- LEDs: 150 (Mb/s).km @ 800-900 nm and larger than 1.5 (Gb/s).km @ 1330 nm

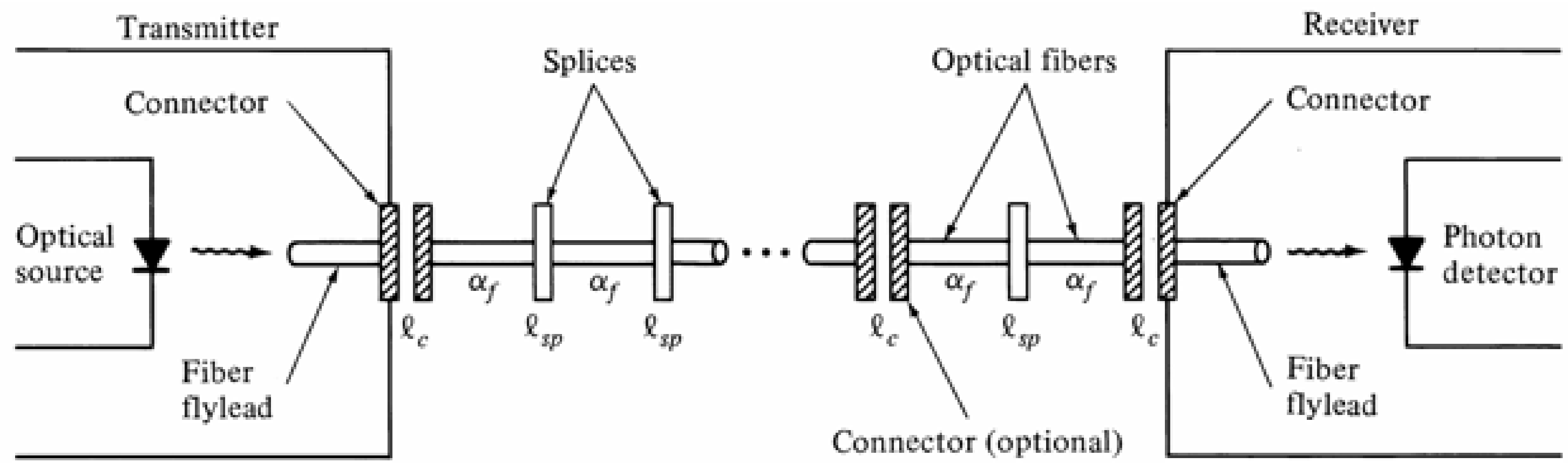
2- InGaAsP lasers: 25 (Gb/s).km @ 1330 nm and ideally around 500 (Gb/s).km @ 1550 nm. 10-15 dB more power. However more costly and more complex circuitry.

- Fiber:

1- Single-mode fibers are often used with lasers or edge-emitting LEDs.

2- Multi-mode fibers are normally used with LEDs. NA and Δ should be optimized for any particular application.

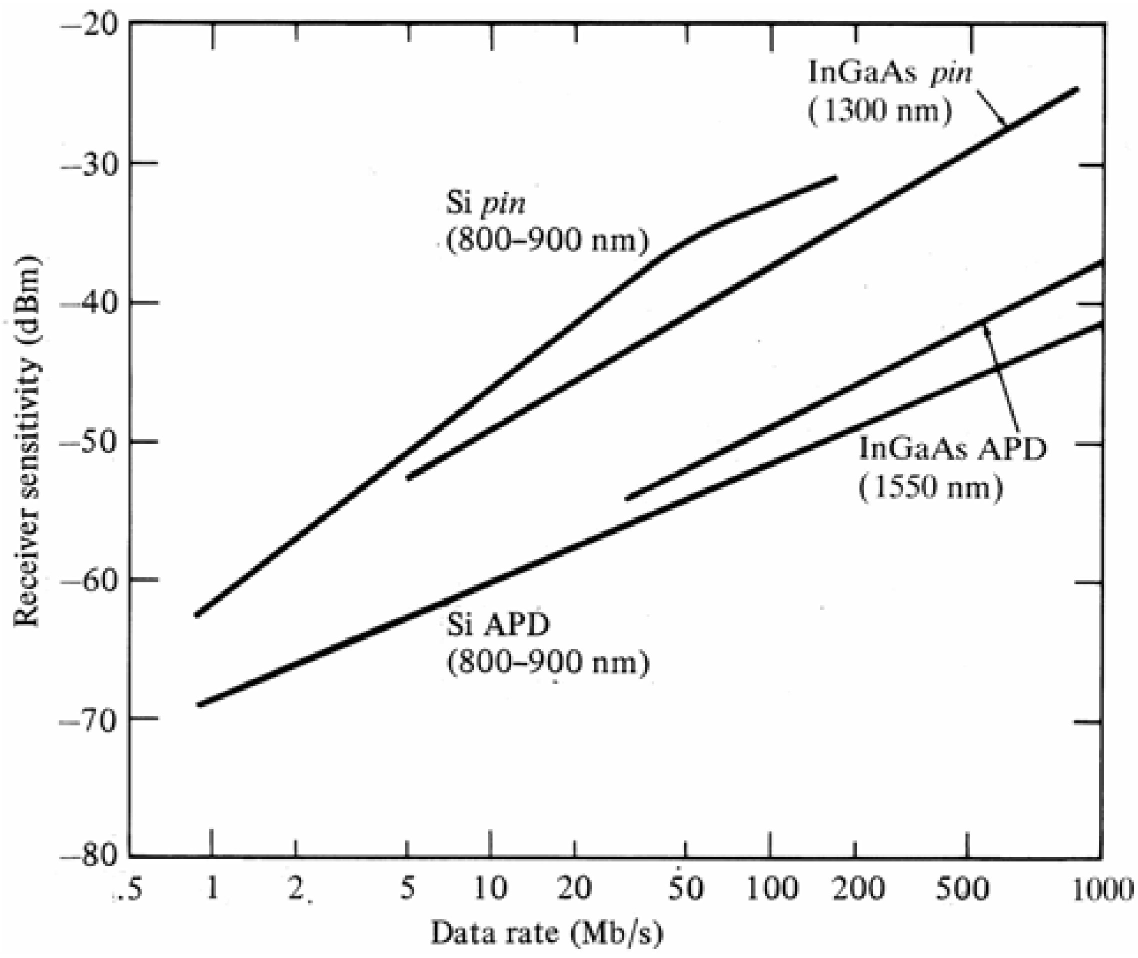
Link Power/Loss Analysis



$$P_T[dB] = P_s[dBm] - P_R[dBm]$$ Total Power Loss

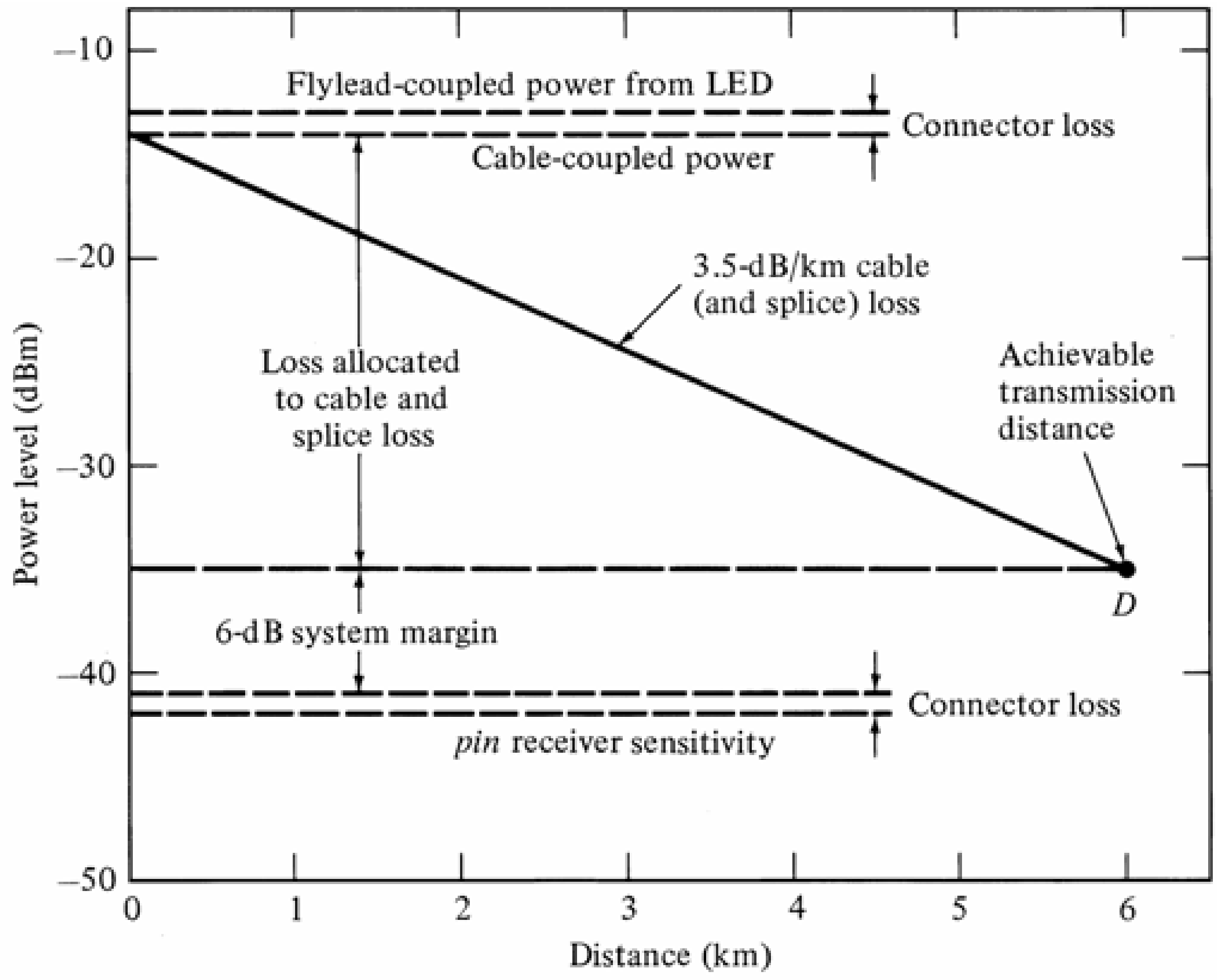
$$P_T = 2l_c[dB] + \alpha_f[dB/km] \times L[km] + \text{System Margin}$$

Receiver Sensitivities vs. Bit Rate



The Si PIN & APD and InGaAsP PIN plots for BER= 10^{-9}. The InGaAs APD plot is for BER=10^{-11}.

Link Loss Budget [Example 8.1]



Link Power Budget Table [Example 8.2]

- Example: [SONET OC-48 (2.5 Gb/s) link]

  Transmitter: 3dBm @ 1550 nm; Receiver: InGaAs APD with -32 dBm sensitivity @ 2.5 Gb/s;

  Fiber: 60 km long with o.3 dB/km attenuation; jumper cable loss 3 dB each, connector loss of 1 dB each.

Component/loss parameter	Output/sensitivity /loss	Power margin (dB)
Laser output	3 dBm	
APD Sensitivity @ 2.5 Gb/s	-32 dBm	
Allowed loss	3-(-32) dBm	35
Source connector loss	1 dB	34
Jumper+Connector loss	3+1 dB	30
Cable attenuation	18 dB	12
Jumper+Connector loss	3+1 dB	8
Receiver Connector loss	1 dB	7(final margin)

Dispersion Analysis (Rise-Time Budget)

$$t_{sys} = [t_{tx}{}^2 + t_{\mathrm{mod}}{}^2 + t_{GVD}{}^2 + t_{rx}{}^2]^{1/2}$$

$$= \left[t_{tx}{}^2 + \left(\frac{440 L^q}{B_0} \right)^2 + D^2 \sigma_\lambda{}^2 L^2 + \left(\frac{350}{B_{rx}} \right)^2 \right]^{1/2}$$

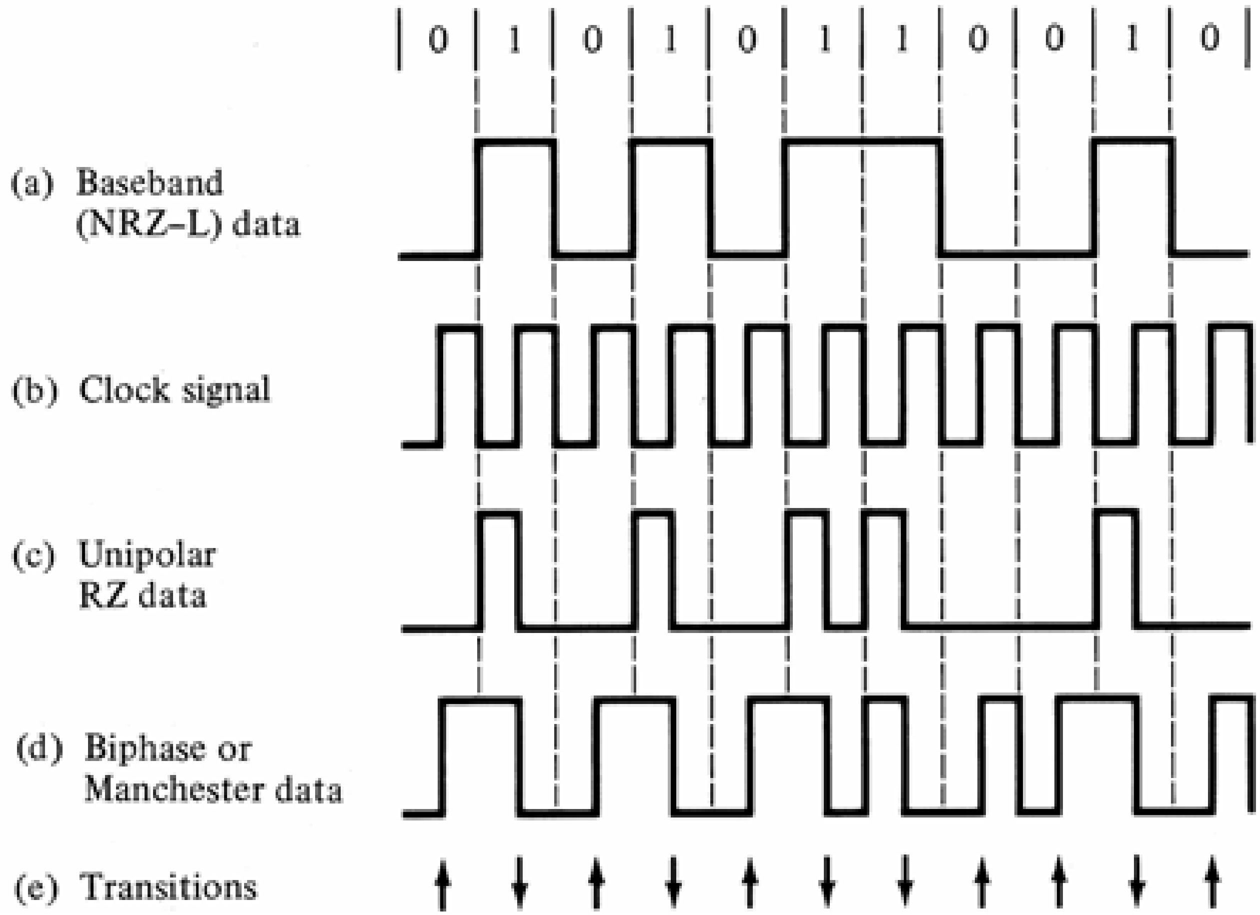
$t_{tx}[ns]$: transmitter rise time $t_{rx}[ns]$: receiver rise time $t_{\mathrm{mod}}[n]$: modal dispersion

$B_{rx}[MHz]$: 3 dB Electrical BW $L[km]$: Length of the fiber $B_0[MHz]$: BW of the 1 km of the fiber;

$q \approx 0.7$ t_{GVD}[ns]: rise-time due to group velocity dispersion

$D[ns/(km.nm)]$: Dispersion σ_λ [nm]: Spectral width of the source

Two-level Binary Channel Codes



System rise-Time & Information Rate

- In digital transmission system, the system rise-time limits the bit rate of the system according to the following criteria:

$$t_{sys} < 70\% \text{ of NRZ bit period}$$

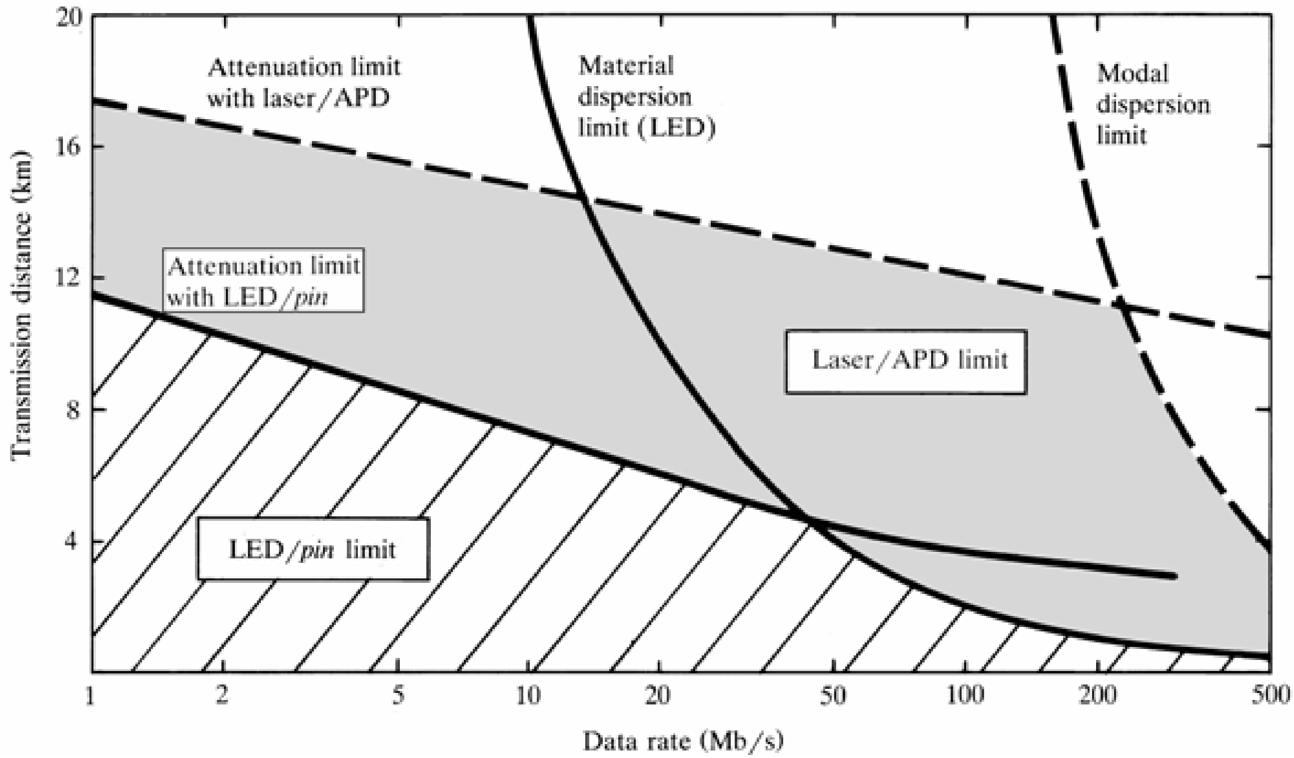
$$t_{sys} < 35\% \text{ of RZ bit period}$$

Example

- Laser Tx has a rise-time of 25 ps at 1550 nm and spectral width of 0.1 nm. Length of fiber is 60 km with dispersion 2 ps/(nm.km). The InGaAs APD has a 2.5 GHz BW. The rise-time budget (required) of the system for NRZ signaling is 0.28 ns whereas the total rise-time due to components is 0.14 ns. (The system is designed for 20 Mb/s).

Example: Transmission Distance for MM-Fiber

- NRZ signaling, source/detector: 800-900 nm LED/pin or AlGaAs laser/APD combinations. $BER = 10^{-9}$; LED output=-13 dBm;fiber loss=3.5 dB/km;fiber bandwidth 800 MHz.km; *q*=0.7; 1-dB connector/coupling loss at each end; 6 dB system margin, material dispersion ins 0.07 ns/(km.nm); spectral width for LED=50 nm. Laser ar 850 nm spectral width=1 nm; laser ouput=0 dBm, Laser system margin=8 dB;



Example:Transmission Distance for a SM Fiber

- Communication at 1550 nm, no modal dispersion, Source:Laser; Receiver:InGaAs-APD (11.5 log *B* -71.0 dBm) and PIN (11.5log *B*-60.5 dBm); Fiber loss =0.3 dB/km; D=2.5 ps/(km.nm): laser spectral width 1 and 3.5 nm; laser output 0 dBm,laser system margin=8 dB;