Chapter 8

Digital Links

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- Point-to-point Links
  - Link Power Budget
  - Rise-time Budget
- Power Penalties
  - Dispersions
  - Noise

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)

Selecting the Fiber

Bit rate and distance are the major factors

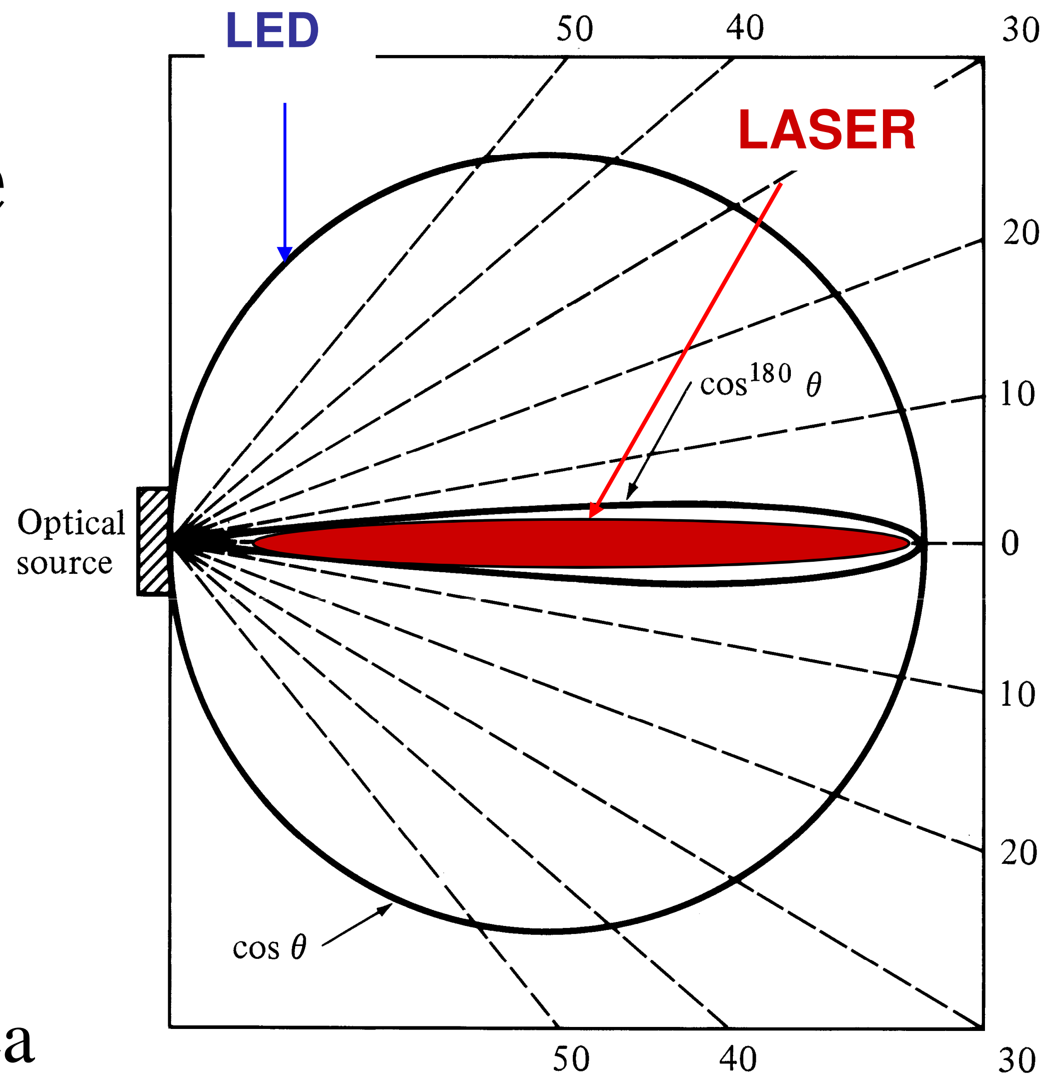
Other factors to consider: attenuation (depends on?) and distance-bandwidth product (depends on?) cost of the connectors, splicing etc.

Then decide

- Multimode or single mode
- Step or graded index fiber

Selecting the Optical Source

- Emission wavelength
- Spectral line width (FWHM) and number of modes
- Output power
- Stability
- Emission pattern
- Effective radiating area



Selecting the detector

- Type of detector
  - **APD**: High sensitivity but complex, high bias voltage (40V or more) and expensive
  - **PIN:** Simpler, thermally stable, low bias voltage (5V or less) and less expensive
- Responsivity (that depends on the avalanche gain & quantum efficiency)
- Operating wavelength and spectral selectivity
- Speed (capacitance) and photosensitive area
- Sensitivity (depends on noise and gain)

Typical bit rates at different wavelengths

Wavelength	**LED** Systems	**LASER** Systems.
800-900 nm (Typically Multimode Fiber)	150 Mb/s.km	2500 Mb/s.km
1300 nm (Lowest dispersion)	1500 Mb/s.km	25 Gb/s.km (InGaAsP Laser)
1550 nm (Lowest Attenuation)	1200 Mb/s.km	Up to 500 Gb/s.km (Best demo)

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.

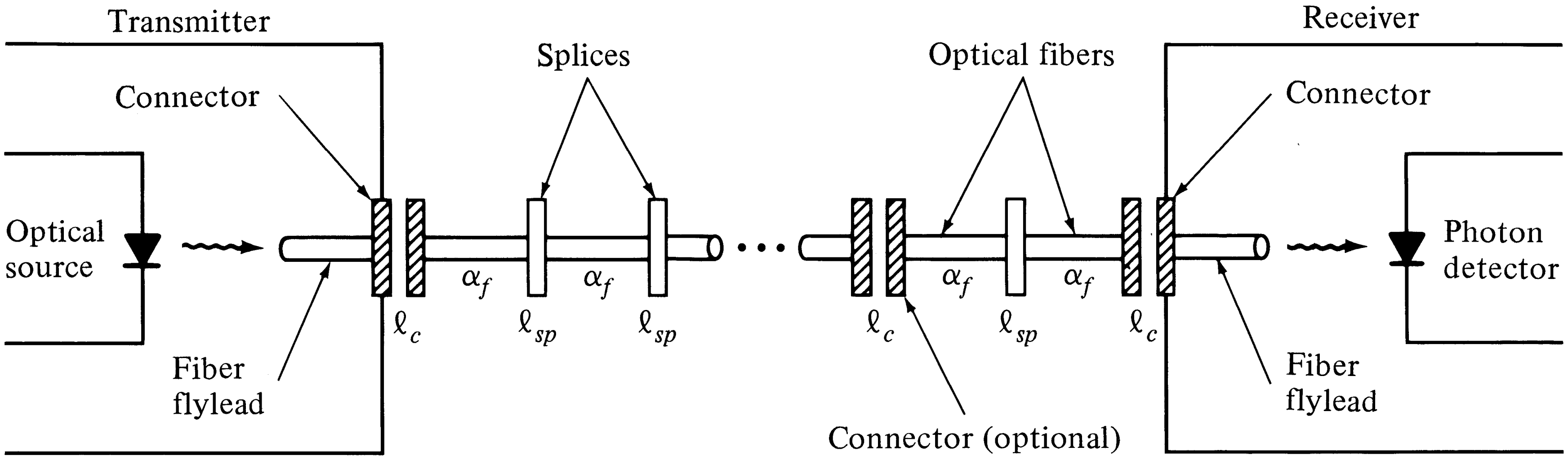
2- Multi-mode fibers are normally used with LEDs. NA and Δ should be optimized for any particular application.

Design Considerations

- Link Power Budget
  - There is enough power margin in the system to meet the given BER
- Rise Time Budget
  - Each element of the link is fast enough to meet the given bit rate

These two budgets give necessary conditions for satisfactory operation

Optical power-loss model



$$P_T = P_S - P_R = ml_c + nl_{sp} + \alpha L + \text{system margin}$$

P_T : Total optical power loss [dB], P_S : Output power of the transmitter [dBm], P_R : Receiver sensitivity [dBm], l_c : connector loss [dB], l_{sp} : splice loss [dB], α : Cable loss [dB/km], L : Cable length [km], m, n : # of connectors, splices

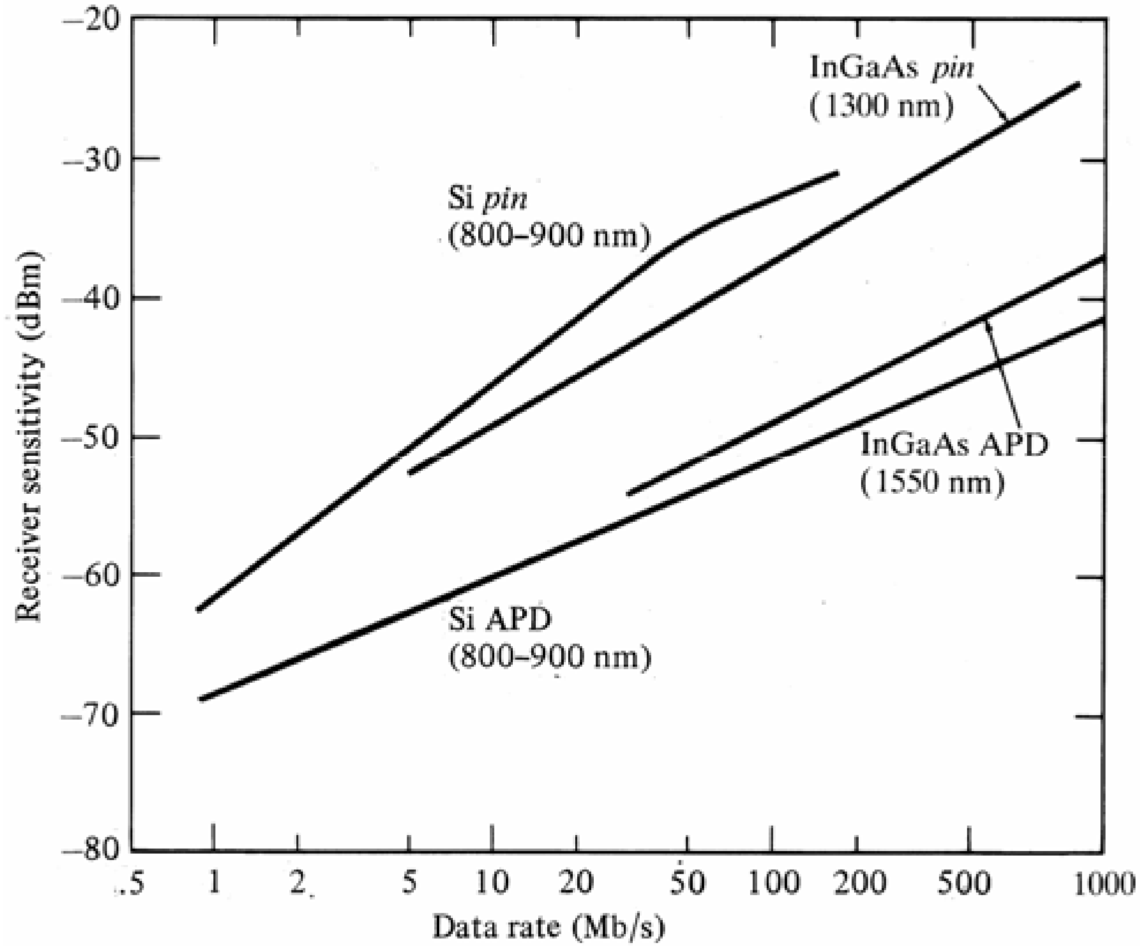
If splice loss is included in cable loss, and no connector in between ,

$$P_T = 2l_c + \alpha L + \text{system margin}$$

Example 8.1

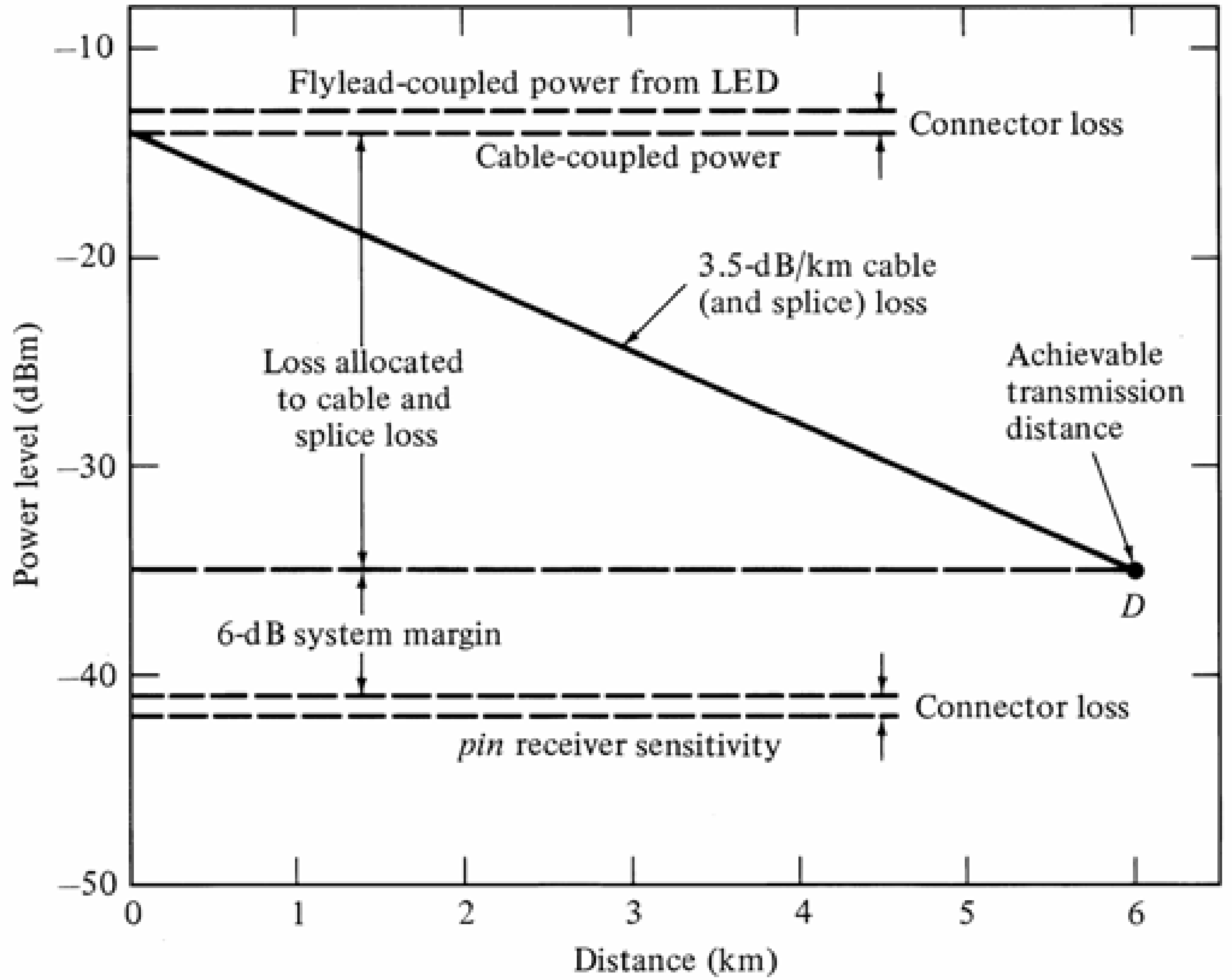
Specifications: Data Rate 20 Mb/s, BER 10^{-9},
Receiver : *pin* photodiode @ 850 nm -> Required input signal = -42 dBm
Optical source : GaAlAs LED with average optical power 50 μW = -13 dBm
Connector loss : 1 dB at both transmitter and receiver
System margin : 6 dB
Thus,
$P_T = P_S - P_R = 29$ dB = 2(1 dB) + αL + 6 dB -> $\alpha L = 21$ dB
If $\alpha = 3.5$ dB/km, then a 6-km transmission path is possible.

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 0.3 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)

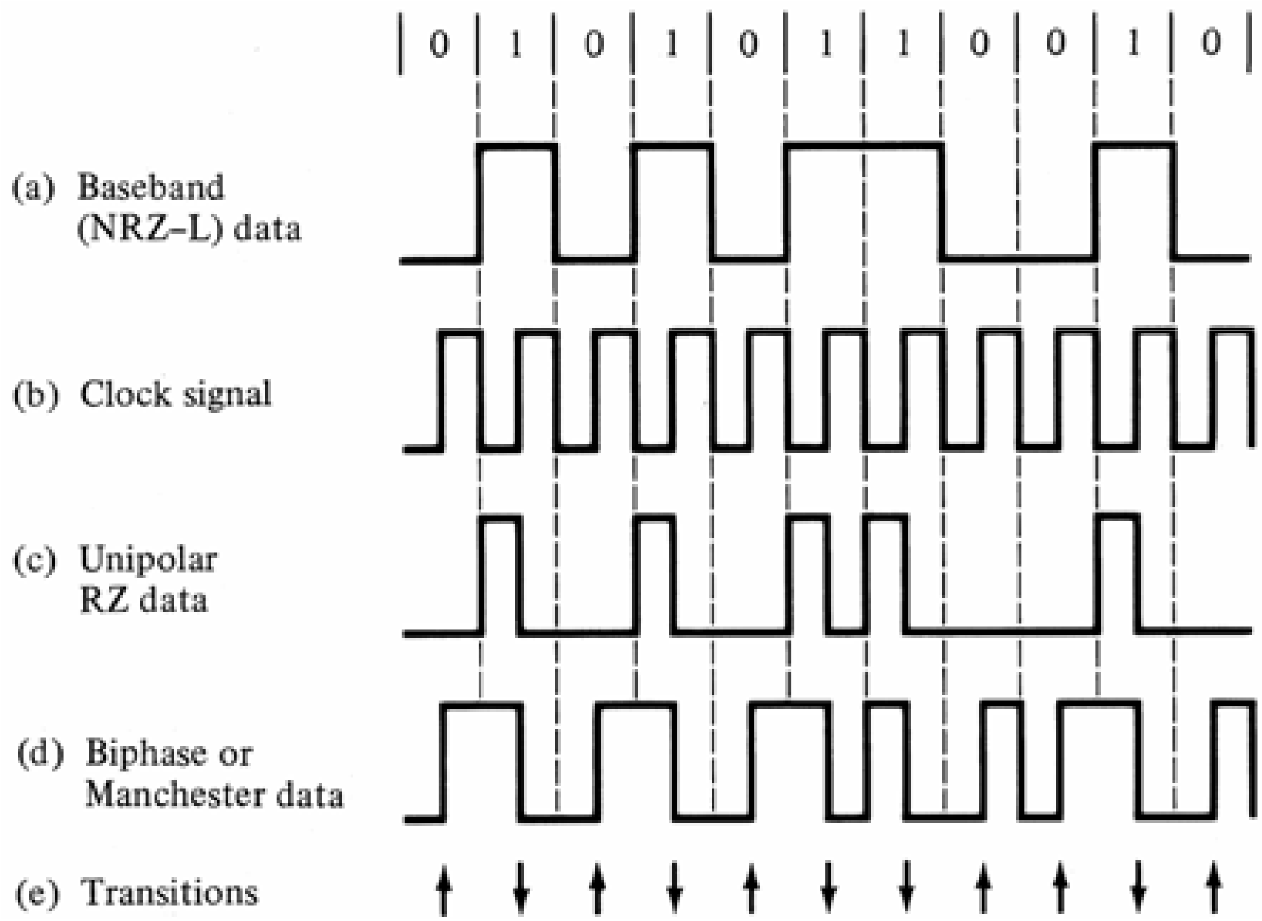
Rise Time Budget

- Total rise time depends on:
  - Transmitter rise time (t_{tx})
  - Group Velocity Dispersion (t_{GVD})
  - Modal dispersion rise time (t_{mod})
  - Receiver rise time (t_{rx})

$$t_{sys} = \left(\sum_{i=1}^{N} t_i^2 \right)^{1/2}$$

Total rise time of a digital link should not exceed 70% for a NRZ bit period, and 35% of a RZ bit period

Two-level Binary Channel Codes



Rise Time

The response of the receiver front end is modeled by 1st order lowpass filter with a unit step response:

$$g(t) = \left[1 - \exp(-2\pi B_{rx} t)\right] u(t)$$

where B_{rx} denotes the 3-dB electrical bandwidth. The rise time t is defined as the time interval between $g(t) = 0.1$ and $g(t) = 0.9$, *10- to 90-percent rise time*, thus

$$t_{rx} = \frac{350}{B_{rx}}$$

where B_{rx} has unit MHz and t_{rx} has unit ns.

The rise time due to GVD over a length L is approximated by

$$t_{GVD} = |D| \sigma_\lambda L$$

σ_λ : half-power spectral width of the source

Modal Dispersion Rise Time

Assume optical fiber has a Gaussian temporal response and its Fourier transform given below:

$$g(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-t^2/2\sigma^2} \xrightarrow{\mathcal{F}} G(\omega) = \frac{1}{\sqrt{2\pi}} e^{-\omega^2\sigma^2/2}$$

The time $t_{1/2}$ required for the pulse to reach its half-maximum value is:

$$g(t_{1/2}) = 0.5g(0) \rightarrow t_{1/2} = \left(2\ln 2\right)^{1/2}\sigma$$

If t_{FWHM} is defined as the time when the full width of the pulse is at its half-maximum, $t_{FWHM} = 2t_{1/2} = 2\sigma\left(2\ln 2\right)^{1/2}$

The 3-dB optical bandwidth is related to t_{FWHM} by

$$\omega_{3dB} = \frac{\sqrt{2\ln 2}}{\sigma};\, f_{3dB} = B_{3dB} = \frac{\sqrt{2\ln 2}}{2\pi\sigma} = \frac{0.44}{t_{FWHM}}$$

Let t_{FWHM} be the rise time resulting from modal dispersion,

$$t_{\mathrm{mod}} = t_{\mathrm{FWHM}} = \frac{0.44}{B_{\mathrm{M}}}$$

Since the bandwidth B_M can be approximated by the empirical relation:

$$B_M = \frac{B_0}{L^q}$$

where B_0 : bandwidth of a 1-km cable, q : modal equilibrium factor , range [0.5 (steady-state modal equilibrium,1 (little mode mixing)], 0.7 is reasonable.

$$t_{\mathrm{mod}} = \frac{0.44}{B_{\mathrm{M}}} = \frac{0.44L^q}{B_0}$$

If t_{mod} has unit ns, and B_M has unit MHz,

$$t_{\mathrm{mod}} = \frac{440}{B_{\mathrm{M}}} = \frac{440L^q}{B_0}$$

Dispersion Analysis (Rise-Time Budget)

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

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

Example 8.3: Rise-time budget for a multimode link

LED : rise time 15 ns; spectral width 40 nm;

Fiber : material-dispersion related rise time 21 ns over 6 km link; 400 MHz·km bandwidth-distance product, $q = 0.7$ -> t_{mod} =3.9 ns

Receiver : 25 MHz bandwidth -> t_{rx} =14 ns

$$t_{sys} = [t_{tx}^2 + t_{\mathrm{mod}}^2 + t_{GVD}^2 + t_{rx}^2]^{1/2} = \left[15^2 + 3.9^2 + 21^2 + 14^2 \right]^{1/2} = 30 \text{ ns}$$

For 20 Mb/s NRZ system, $T_{b,NRZ}$ = 50 ns. Thus, $t_{sys} < .7T_{b,NRZ}$ and the rise-time requirement is met.

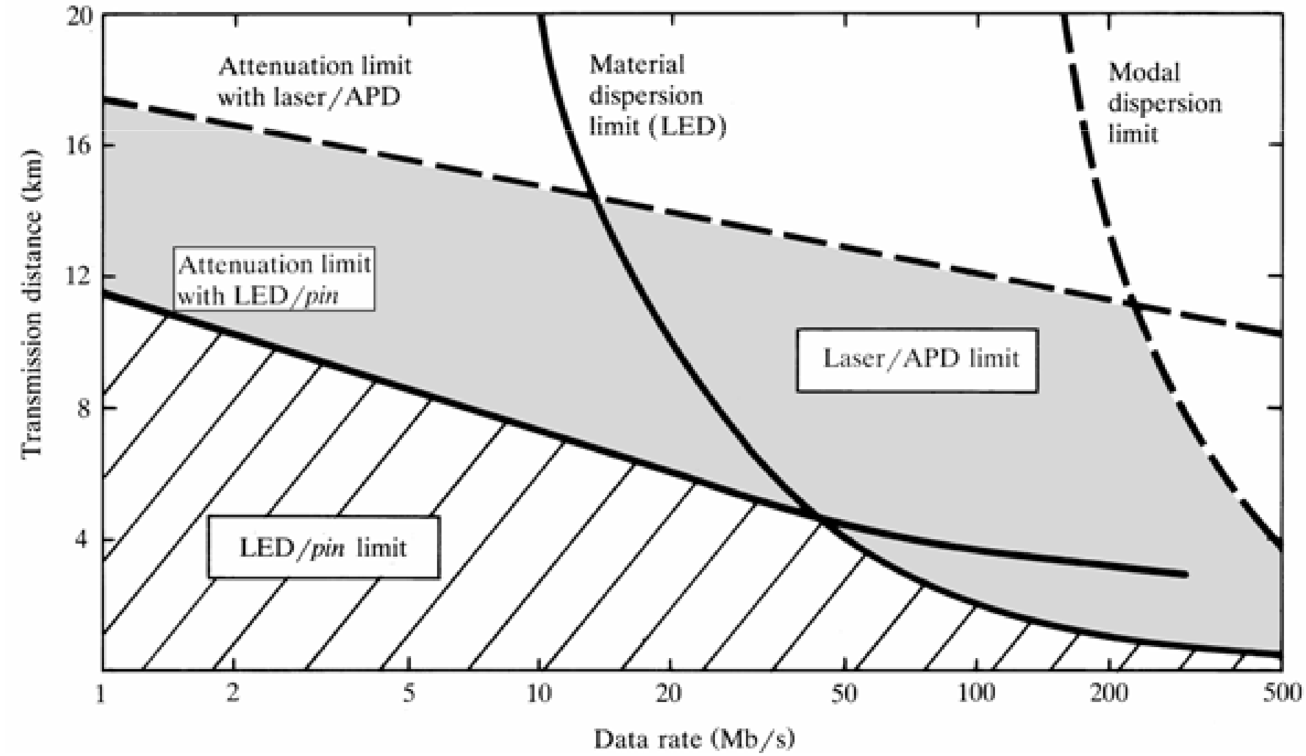
Example 8.4: Laser Tx has a rise-time of 25 ps at 1550 nm and spectral width of 0.1 nm. Length of fiber is 60 km with dispersion 2 ps/(nm.km). The InGaAs APD has a 2.5 GHz BW. The rise-time budget (required) of the system for NRZ signaling is 0.28 ns whereas the total rise-time due to components is 0.14 ns. (The system is designed for 20 Mb/s).

The total rise time is 142.7 ps

For a 2.5 Gb/s NRZ system, $T_{b,NRZ} = 400$ ps. Thus, $t_{sys} < .7T_{b,NRZ}$ and the rise-time requirement is met.

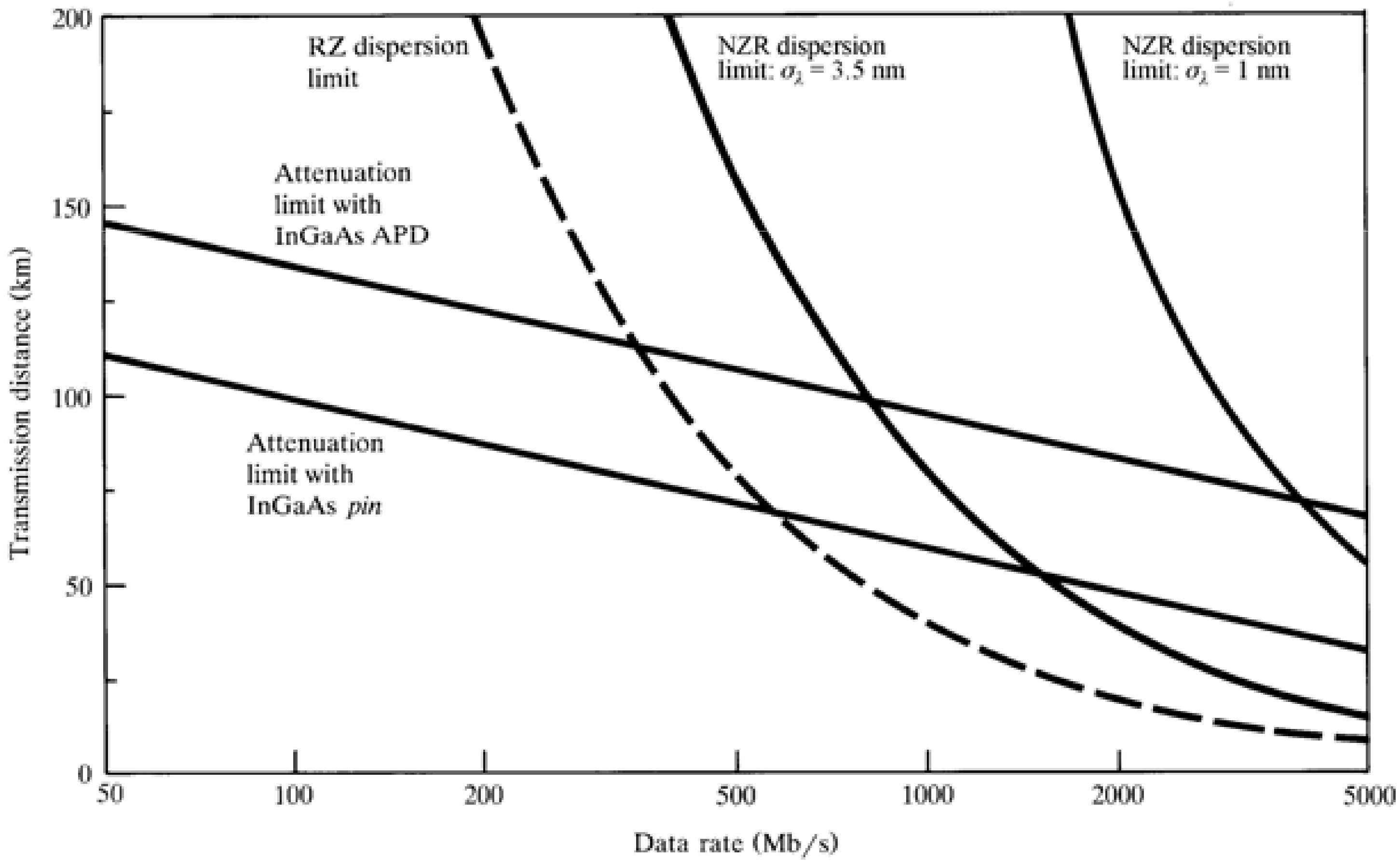
Transmission Distance for MM-Fiber in short-wavelength band

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;



Transmission Distance for a SM Fiber Link

- 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;



Power Penalties

- Power penalty is the reduction in SNR due to signal impairments in optical fiber transmission systems.
- For example, interactions between spectral variations and imperfections in a dispersive fiber can produce time-varying changes in the light at the receiver, which can lead to receiver output noise.
- It is defined as

$$PP_x = -10 \log \frac{\mathrm{SNR}_{\mathrm{impair}}}{\mathrm{SNR}_{\mathrm{ideal}}}$$

Chromatic Dispersion Penalty

- Chromatic dispersion = each wavelength travels at a different velocity in a fiber.
- Causes pulse spreading.
- Total dispersion must be kept under some "tolerance" or dispersion compensation must be employed.
- ITU-T Recommendation for SDH : for a 1-dB power penalty the accumulated dispersion should be less than 0.306 of a bit period, i.e.,

$$\left|D_{CD}\right| L \sigma_{\lambda} < \varepsilon T_b \rightarrow \left|D_{CD}\right| L \sigma_{\lambda} B < \varepsilon = 0.306$$

- For example, D_{CD} = 8 ps/(nm·km), B = 2.5 Gb/s, σ_{λ} = 0.2 nm, then the maximum allowed length L = 76.5 km.

Polarization-Mode Dispersion Penalty

- Light signal at a given wavelength in a single-mode occupies two orthogonal polarization modes.
- Each mode can travel with different velocity resulting in pulse spreading.
- PMD fluctuates with temperature variations and stress changes, and varies as the square root of distance.
- To have a power penalty below 1 dB, the pulse spreading must be less than 10% of a bit period, i.e.,

$$\Delta\tau_{PMD} = D_{PMD}\sqrt{L} < 0.1T_b$$

- For example, D_{PMD} = 0.5 ps/km$^{1/2}$, L = 100 km, $\Delta\tau_{PMD}$ = 5 ps. The maximum data rate $B = 1/T_b$ = (50ps)$^{-1}$ = 20 Gb/s.

Extinction Ratio Penalty

- The extinction ratio r_e in a laser = ratio of optical power level P_1 for logic 1 to that for logic 0, P_0 .
- Ideally, $P_1 = 2\ P_{\text{ave}}$ and $P_0 = 0$, but practically, the ratio is finite to reduce the rise time.
- Assume a non-zero $P_{\text{0-ER}}$, then $r_e = P_{\text{1-ER}}/P_{\text{0-ER}}$ and

$$P_{ave} = \frac{P_{1-ER} + P_{0-ER}}{2} = P_{1-ER}\frac{r_e + 1}{2}$$

- When receiver thermal noise dominates, 1 and 0 noise powers are equal and independent of signal level. Here, let $P_0 = 0$ and $P_1 = 2\ P_{\text{ave}}$, then

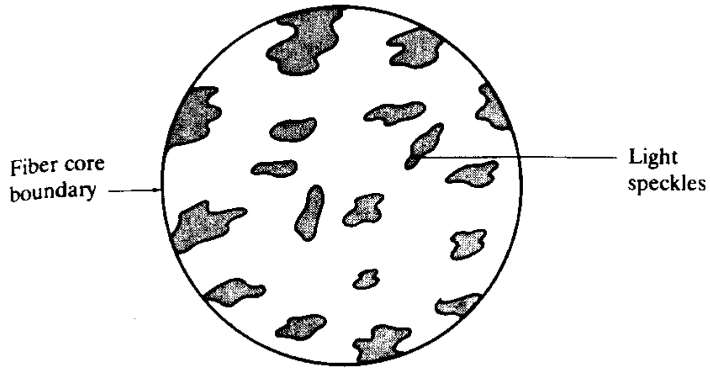
$$PP_{ER} = -10\log\frac{P_{1-ER} - P_{0-ER}}{P_1 - P_0} = -10\log\frac{r_e - 1}{r_e + 1}$$

- r_e = [7,10] -> PP_{ER} = [1.25,0.87] dB; r_e = 18 is needed for 0.5 dB power penalty.

Modal Noise

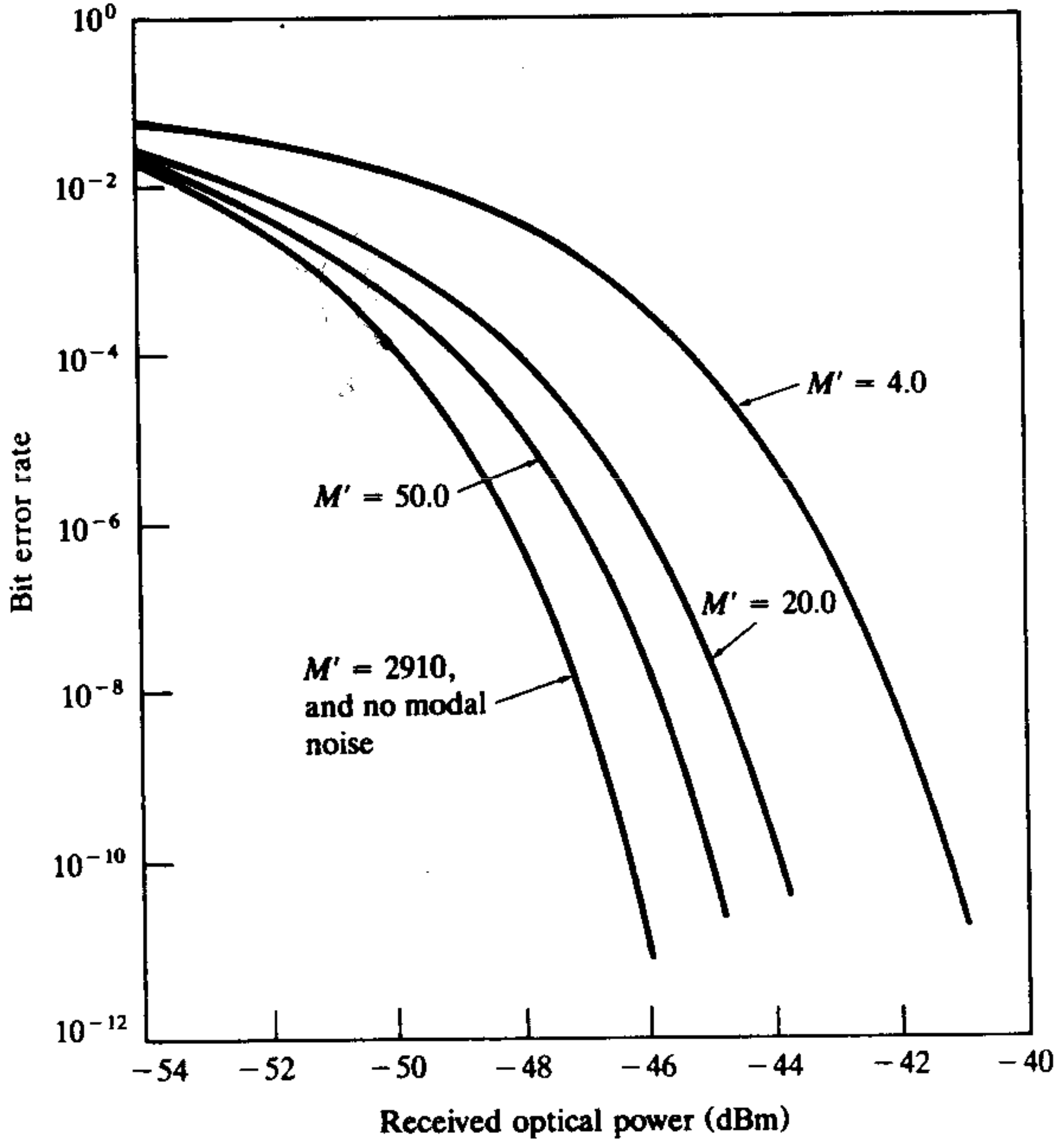
- In MM fiber, more than one mode propagating -> speckle pattern; # of speckles ≈ # of modes.
- Mode-dependent losses, changes in phase between modes, fluctuations in the distributions of energy among modes -> different speckle pattern
- Modal (Speckle) Noise : Speckle-pattern dependent loss.
- Fluctuations in frequency also causes intermodal delays. If coherence time > intermodal dispersion -> speckle pattern.
- If $1/\delta\nu$ (coherence time) $<<$ δT (intermodal dispersion time), modal dispersion due to interference between 2 modes -> sinusoidal ripple with frequency

$$\nu = \delta T \frac{d\nu_{source}}{dt}$$

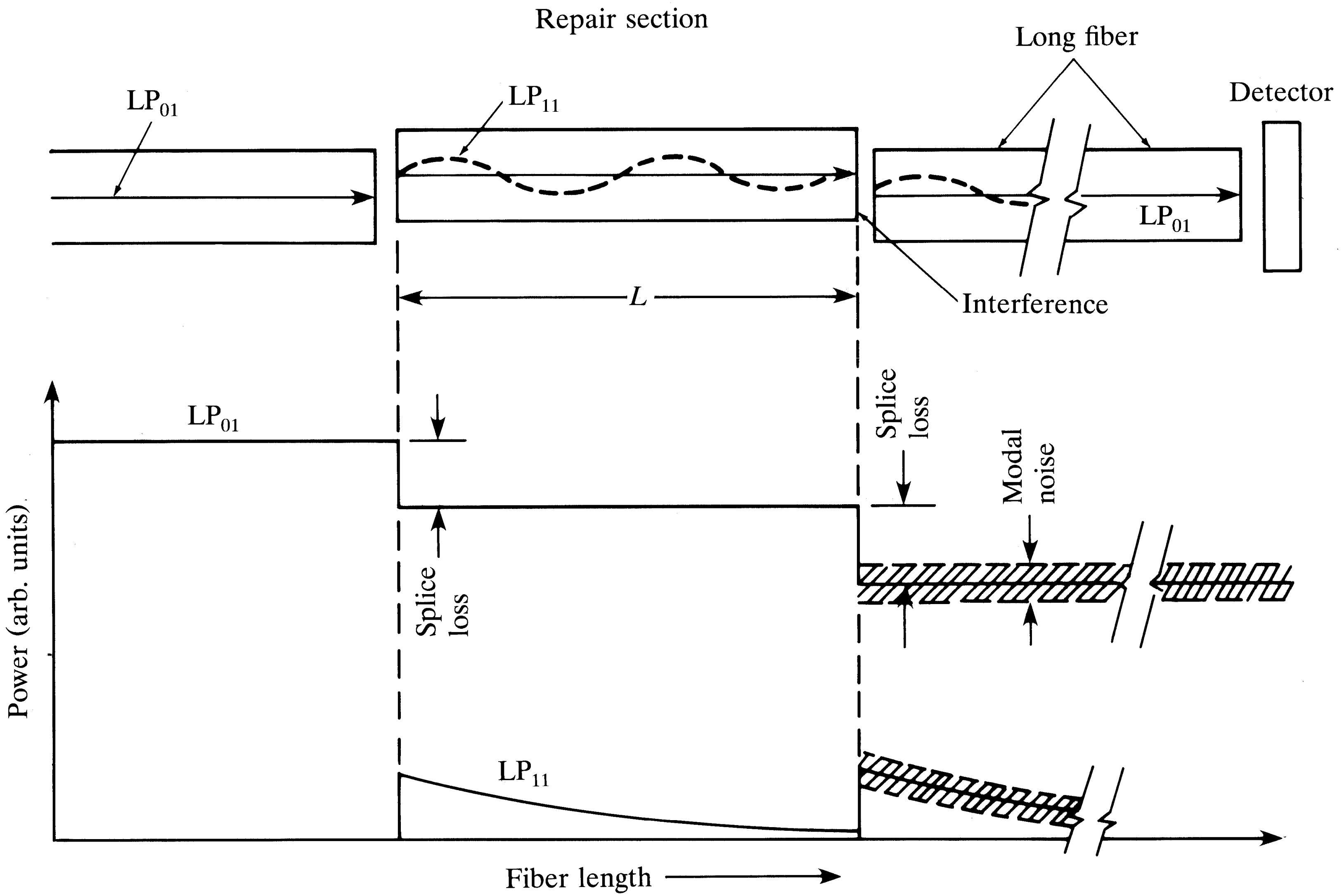


Modal Noise (2)

- To avoid modal noise,
  - Use LED with MMF
  - Use a laser with large number of modes
  - Use a MMF with large NA
  - Use single mode fiber with laser



Modal noise at a connection of a SMF



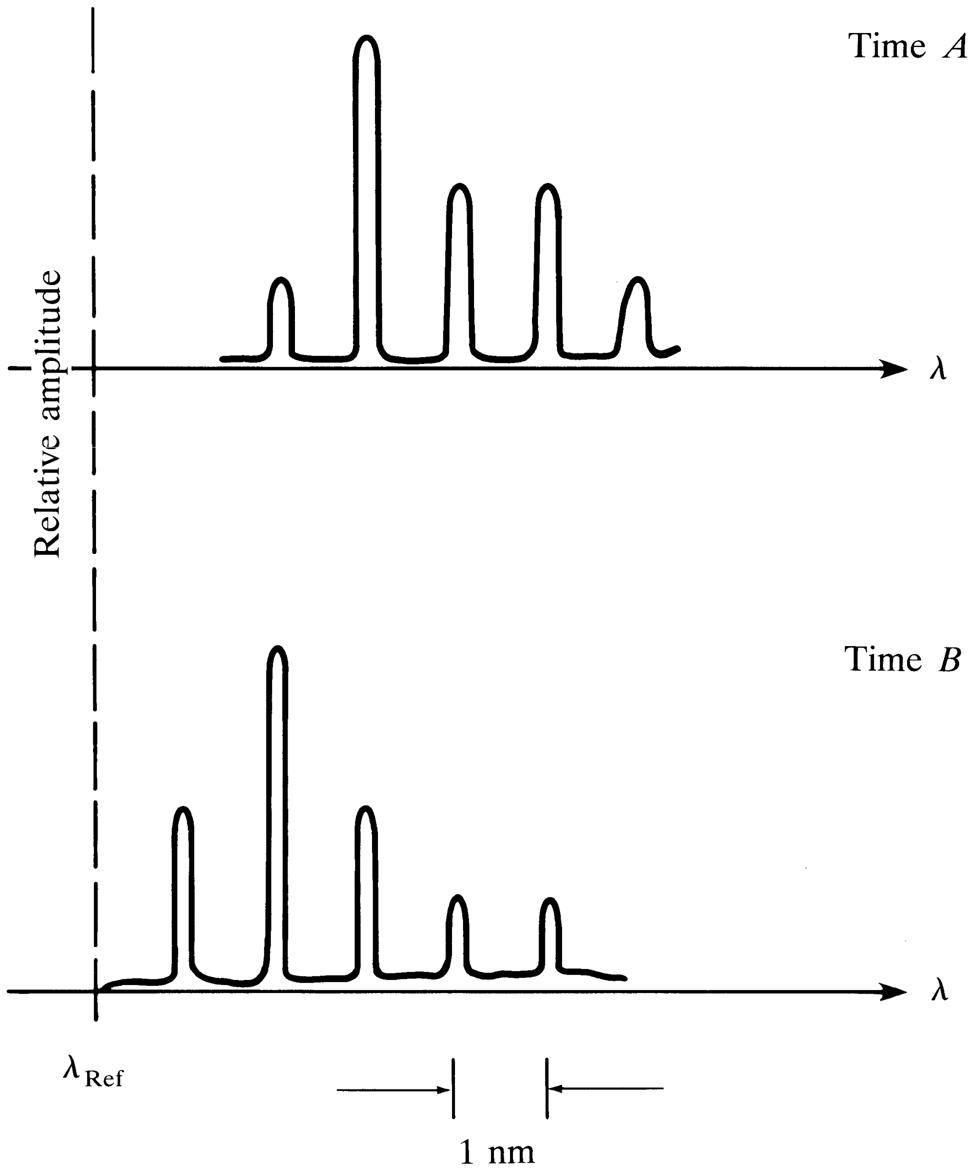
Mode Partition Noise

- This is the dominant noise in single mode fiber coupled with multimode laser
- Mode partition noise is associated with intensity fluctuations in the longitudinal modes of a laser diode
- Each longitudinal mode has different λ, power fluctuations can be large.
- The SNR due to MPN can not be improved by increasing the signal power.
- Approximation:

$$PP_{mpn} = -5\frac{x+2}{x+1}\log\left[1-\frac{k^2Q^2}{2}\left(\pi BLD\sigma_{\lambda}\right)^4\right]$$

k : mode-partition noise factor, range 0.6-0.8.

Dynamic spectra of a laser



Laser output spectrum vary with time giving **mode partition noise**

Chirping

- Chirping is a *line broadening* effect of a laser, caused by laser instability or modulation.
- The time-dependent frequency change is given by

$$\Delta\nu(t) = \frac{-\alpha}{4\pi}\left[\frac{d}{dt}\ln P(t) + \kappa P(t)\right]$$

where α is *linewidth enhancement factor* (-3.5~-5.5 for AlGaAs), κ is frequency-dependent factor.

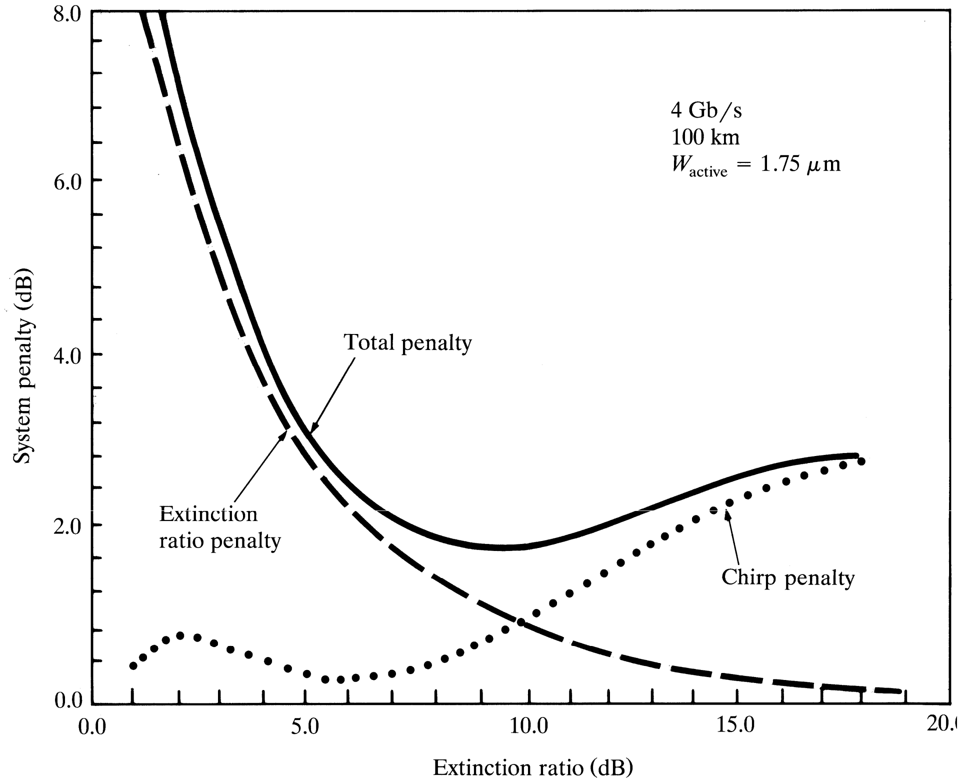
- Increase bias level -> reduce rate of change of ln $P(t)$ and $P(t)$
- Estimated power penalty

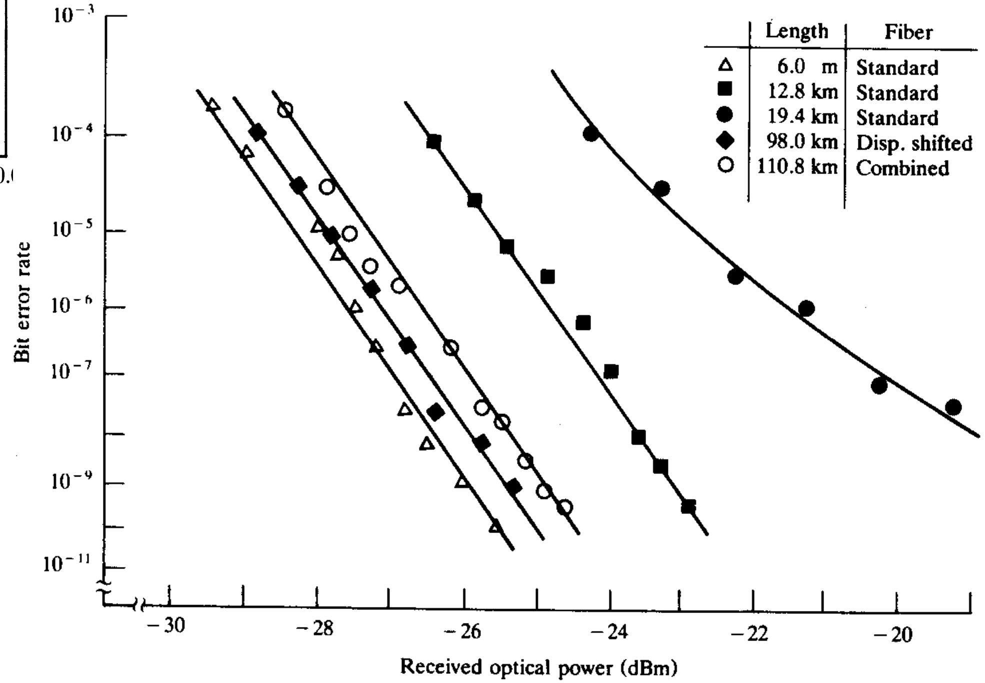
$$PP_{chirp} = -10\frac{x+2}{x+1}\log(1-\Delta)$$

where x : excess noise factor

eye closure $\Delta = \left(\frac{4}{3}\pi^2 - 8\right)t_{chirp}DLB^2\delta\lambda\left[1+\frac{2}{3}\left(DL\delta\lambda - t_{chirp}\right)\right]$

Chirping & extinction-ratio penalties; Effects of Chirping





Reflection Noise

• Reflections occur at discontinuities, e.g., splices, connectors, couplers, etc.

• Reflected power causes optical feedback leading to laser instabilities, which give rise to power fluctuations, jitter, wavelength change, etc.

• SNR changed -> Intensity noise + Intersymbol interference

• Keeping return losses below -15 to -32 dB for 500 Mb/s to 4 Gb/s.