Lecture 03

ECE 423

Optical Communications

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Transmission characteristics of optical fibers

Like any communication system there are some important factors affecting performance of optical fibers as a transmission medium.

The most interest are those attenuation and bandwidth.

Attenuation

Is the ratio of the input (transmitted) optical power into the fiber to output (received) optical power from the fiber

$$\boxed{\alpha_{dB} L = 10 \log\left(\frac{P_{in}}{P_{out}}\right)}$$

example: Signal's input power is 400W and the power at the receiver is 100W. The length of the fiber is 1Km.
attenuation = 10/1 * log(400/100) = 6 dB / Km

Bandwidth of the fiber

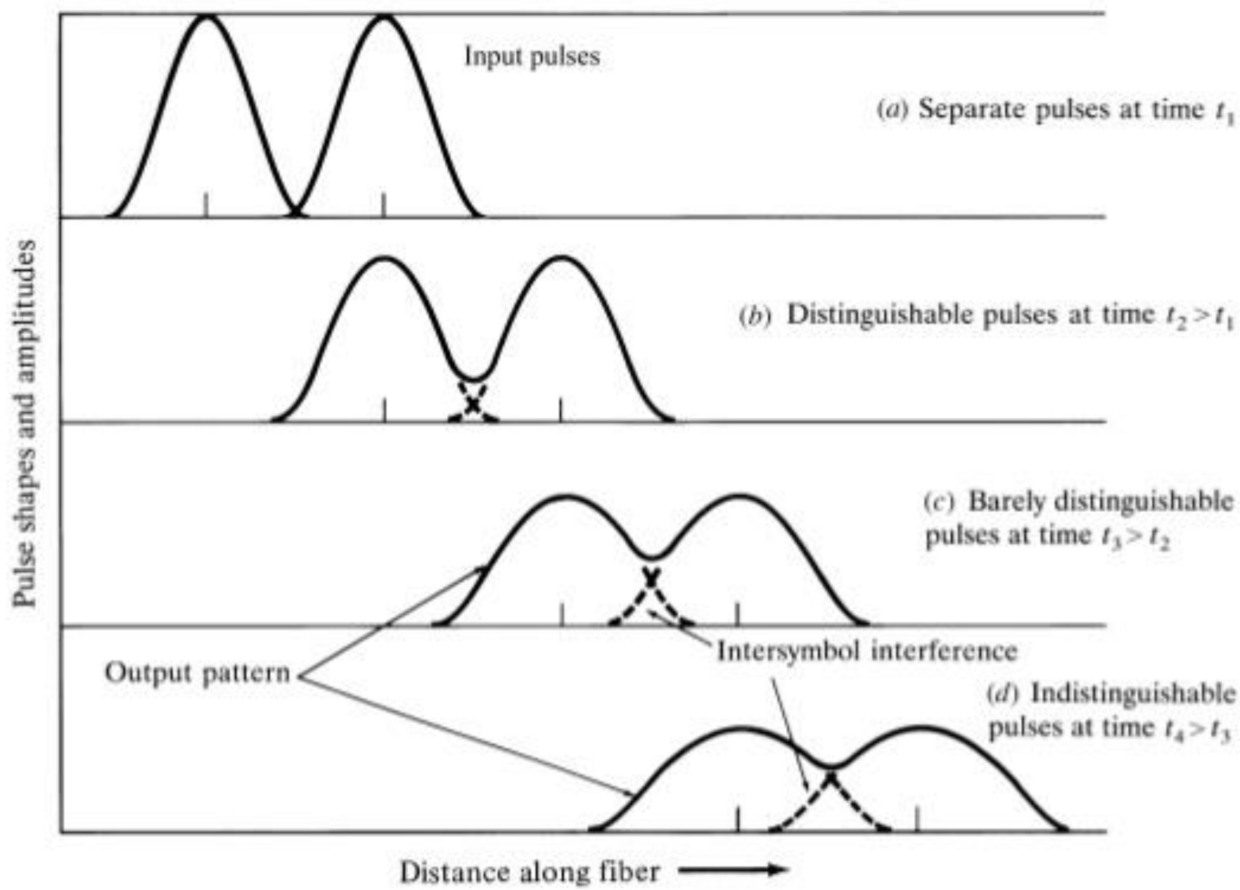
The other characteristic of primary interest is the bandwidth of the fiber which is limited by the signal dispersion within the fiber.

Dispersion

Dispersion with the fiber cause broadening of the transmitted light pulses as they travel along the channel.

During an optical transmission of a digitally modulated signal, dispersion with the fiber cause broadening of the transmitted light pulses as they travel along the channel. As a result if we have a stream of digital pulses , each pulse broadens and overlapped with its neighbors and becomes indistinguishable at the receiver input.

Since the broadening increases with the distance traveled along the fiber, we define the parameter BW x length of the fiber.



Broadening and attenuation of two adjacent pulses as they travel along a fibre. The overlapping of pulses limits the information capacity of a fibre.

This limits the maximum bit rate B to be carried by the optical fiber.

A conservative estimate of which assumes a pulse duration of τ and that pulse spreading can be up to τ (broadening) is given by (no overlap at all):

$$B \leq \frac{1}{2\tau}$$

$$\text{maximum data rate} \;\Rightarrow\; \mathrm{B} = \frac{0.5}{\Delta\tau}$$

$$\text{Chromatic Dispersion} \;\Rightarrow \frac{\Delta\tau}{L} = D_{ch}\Delta\lambda$$

$$\boxed{\therefore BL \approx \frac{0.5}{D_{ch}\Delta\lambda}}$$

$$D_{ch} = D_m + D_w$$

Example

A multimode graded index fiber exhibits total pulse broadening of 0.1us over a distance of 15km. Estimate:

a) The max. possible BW assuming no inter symbol interference;

b) The pulse dispersion per unit length;

c) The BW-length product of the fiber.

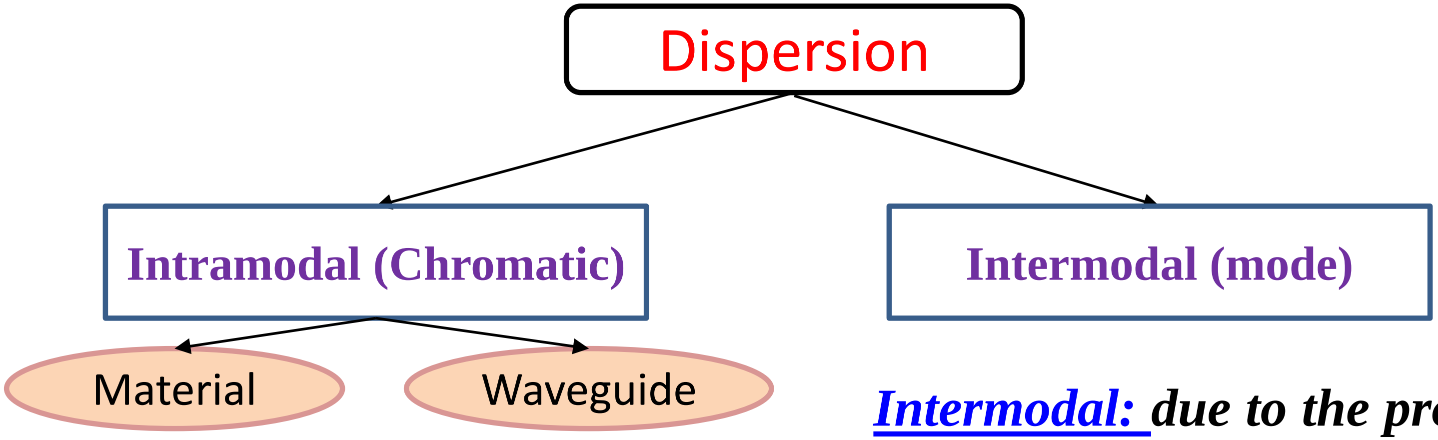
Solution

a) $$B \leq \frac{1}{2\tau} = \frac{1}{2(0.1\times10^{-6})} = 5\text{MHz}$$

b) Dispersion per unit length = $0.1\text{x}10^{-6}$ / 15 = 6.67 ns.km^{-1}

c) BW x length = 5 MHz x 15 km = 75 MHz km

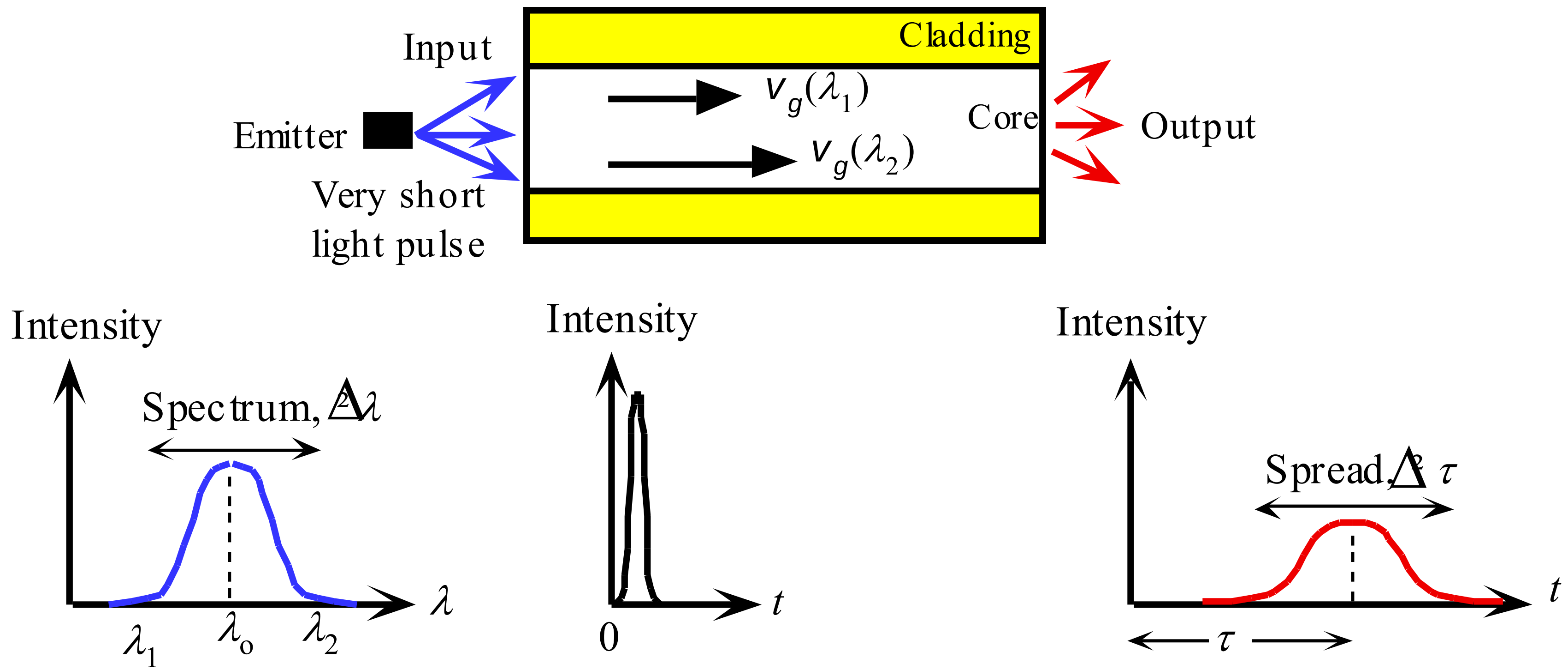
Types of dispersion



Intramodal: ***due to finite spectral line width of the optical source. The optical source emits a band of frequencies. There will be a propagation delay differences between the different spectral components of the transmitted signal which in turn causes broadening of each transmitted mode and hence intramodal dispersion***

Intermodal: ***due to the propagation delay differences between the modes within a multimode fiber. (MMSI fiber exhibits a large amount of mode dispersion which gives the greatest pulse broadening). The single mode operation does not give intermodal dispersion and therefore pulse broadening is solely due to the intramodal dispersion.***

Material Dispersion



All excitation sources are inherently non-monochromatic and emit within a spectrum, $\Delta\lambda$, of wavelengths. Waves in the guide with different free space wavelengths travel at different group velocities due to the wavelength dependence of n_1. The waves arrive at the end of the fiber at different times and hence result in a broadened output pulse.

Material Dispersion

- The refractive index of the material varies as a function of wavelength, $n(\lambda)$
- Material-induced dispersion for a plane wave propagation in homogeneous medium of refractive index *n*:

$$\tau_m = L\frac{d\beta}{d\omega} = -\frac{\lambda^2}{2\pi c}L\frac{d\beta}{d\lambda} = -\frac{\lambda^2}{2\pi c}L\frac{d}{d\lambda}\left[\frac{2\pi}{\lambda}n(\lambda)\right]$$

$$= \frac{L}{c}\left(n - \lambda\frac{dn}{d\lambda}\right)$$

- The pulse spread due to material dispersion is therefore:

$$\Delta\tau_g \approx \left|\frac{d\tau_m}{d\lambda}\right|\Delta\lambda = \frac{L\Delta\lambda}{c}\left|\lambda\frac{d^2 n_{eff}}{d\lambda^2}\right| = L\Delta\lambda\left|D_m(\lambda)\right|$$

$D_m(\lambda)$ is material dispersion

$$\boxed{\left|D_m(\lambda)\right| = -\frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2}}$$

$$n_{eff} = \frac{\beta}{k_o}$$

Waveguide Dispersion

- Waveguide dispersion is quite involved and it is due to the dependency of the group velocity of the fundamental mode as well as other modes on the fiber structure (V number).

$$\Delta\tau_w \approx \left|\frac{d\tau_w}{d\lambda}\right|\Delta\lambda$$

$$D_w(\lambda) = -\frac{n_2\Delta}{c\lambda}V\frac{d^2(Vb)}{dV^2}$$

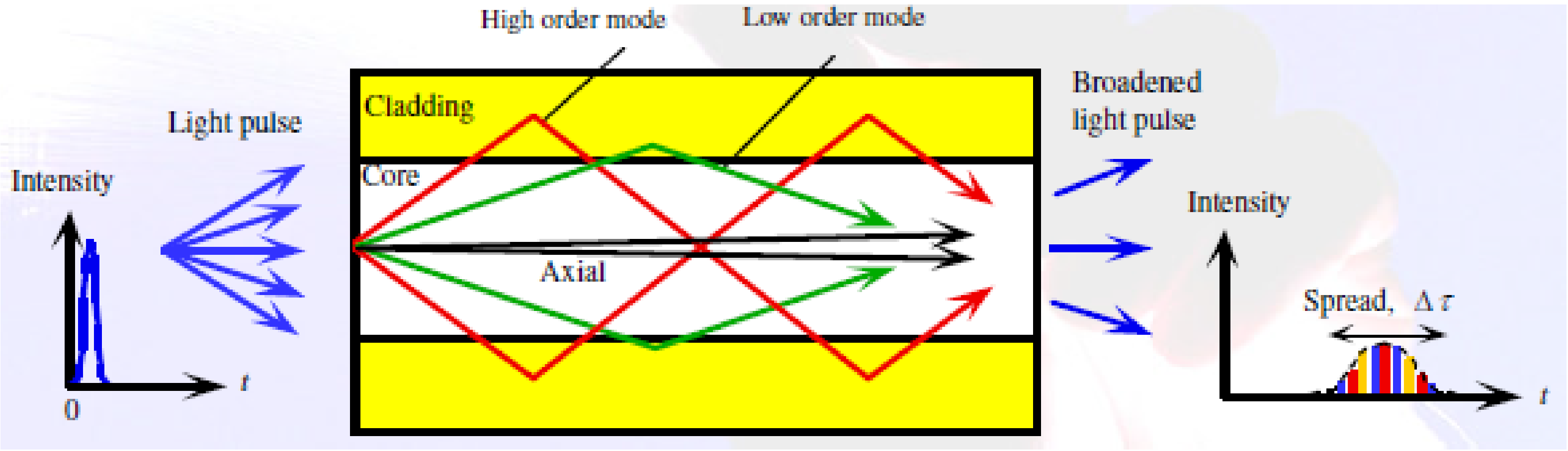
Where $$V\frac{d^2(Vb)}{dV^2} \approx 0.08 + 0.549(2.834 - V)^2$$

$$b = \frac{\beta^2/k^2 - n_2^{\ 2}}{n_1^{\ 2} - n_2^{\ 2}} \approx \frac{\beta/k - n_2}{n_1 - n_2}$$

Normalized propagation constant

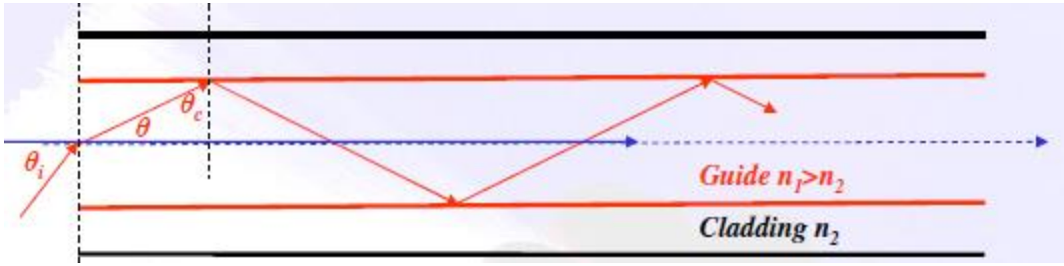
Intermodal dispersion

Due to propagation delay differences between modes within the fiber. It has a greatest effect of pulse broadening in step index multimode fibers.



Intermodal dispersion

Assume the length of the fiber is L; The pulse spread due to intermodal dispersion is due to the difference in time between the two extreme rays shown in the previous figure :



$$\Delta T = T_{\max} - T_{\min} = \frac{L/\cos\theta}{c/n_1} - \frac{Ln_1}{c} \quad \text{but} \quad \cos\theta = \sin\theta_c = \frac{n_2}{n_1}$$

$$\Delta T = \frac{Ln_1^2}{cn_2}\left(\frac{n_1 - n_2}{n_1}\right) = \frac{Ln_1^2}{cn_2}\Delta \approx \frac{Ln_1}{c}\Delta$$

$$\Delta T = \frac{L(NA)^2}{2cn_1}$$

$$\boxed{B.L = \frac{c}{2(n_1 - n_2)}}$$

Important

Attenuation

- Attenuation is the loss of power as the light travels inside the fiber. It is caused by:
  - Light absorption
  - Light scattering
  - Bending losses

$$attenuation = \frac{10}{L}\log\left(\frac{P_i}{P_o}\right)$$

L: Fiber's length in km.
Pi: Signal's power in the input.
Po: Signal's power in the output.

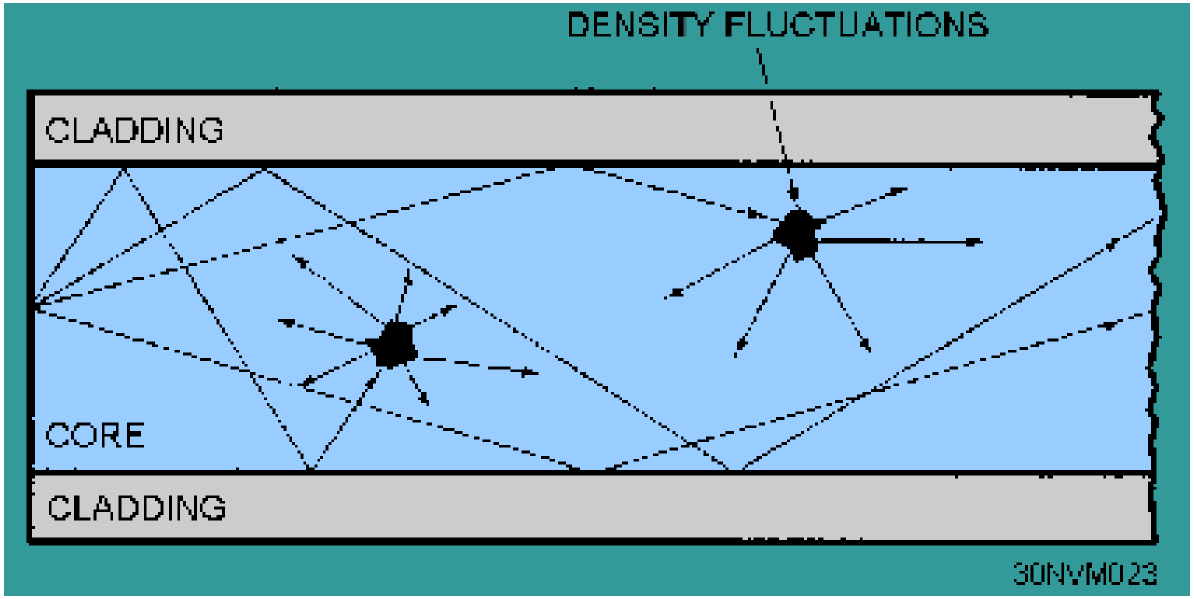
attenuation units: dB/Km

Light Absorption

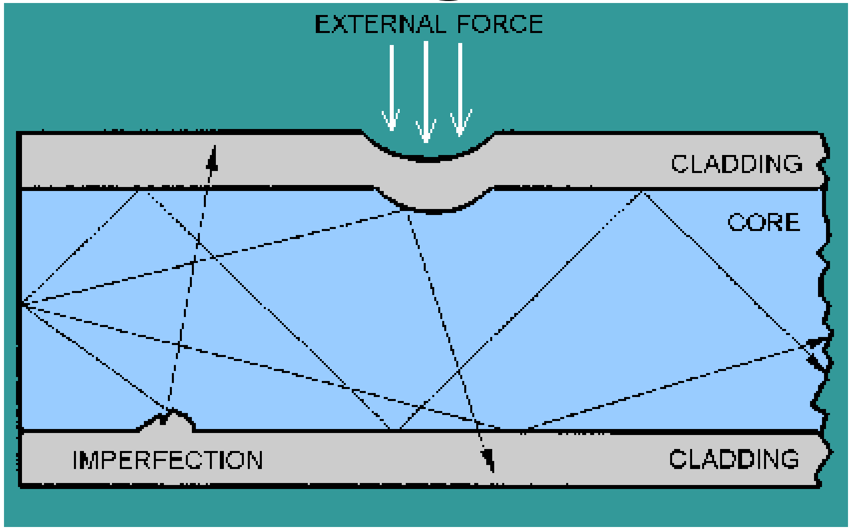
- Absorption is the conversion of optical power into another energy form, such as heat.
- Due to photon absorption in interaction with atoms or molecules of the material. It happens due to material composition and fabrication process impurities which causes attenuation in the transmitted optical power in the form of heat due to absorption.
  - The intrinsic type
    - Photons are absorbed by electrons and excites them to higher energy levels. ***due to interaction with the main components of the glass***
  - The extrinsic type
    - Impurities in the atomic structure of the silicon (e.g. iron, nickel, chromium) results in the absorption of photons by the electrons of these metal and electrons excitation to higher energy levels.

Light Scattering

- Scattering is the result of density fluctuations in the fiber structure.
  - During the fabrication process of the fiber, there are areas where the density of the molecular structure is higher or lower.

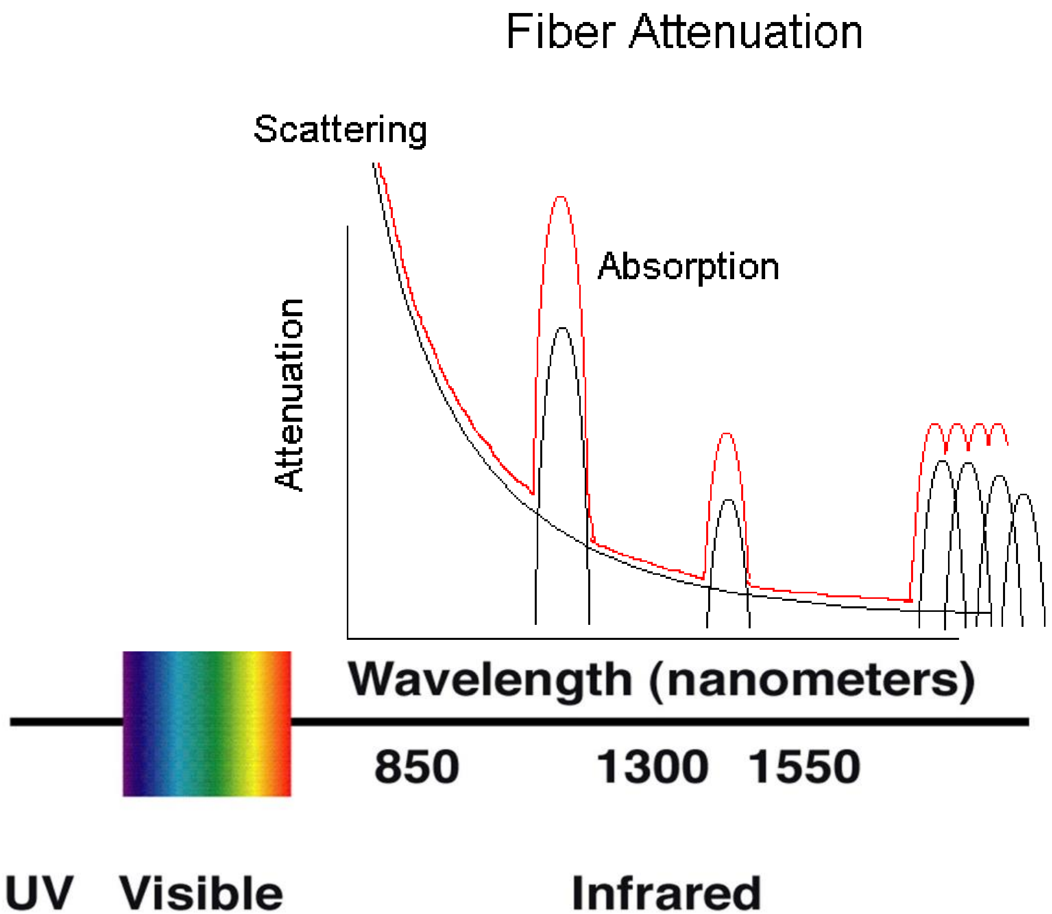


Bending losses

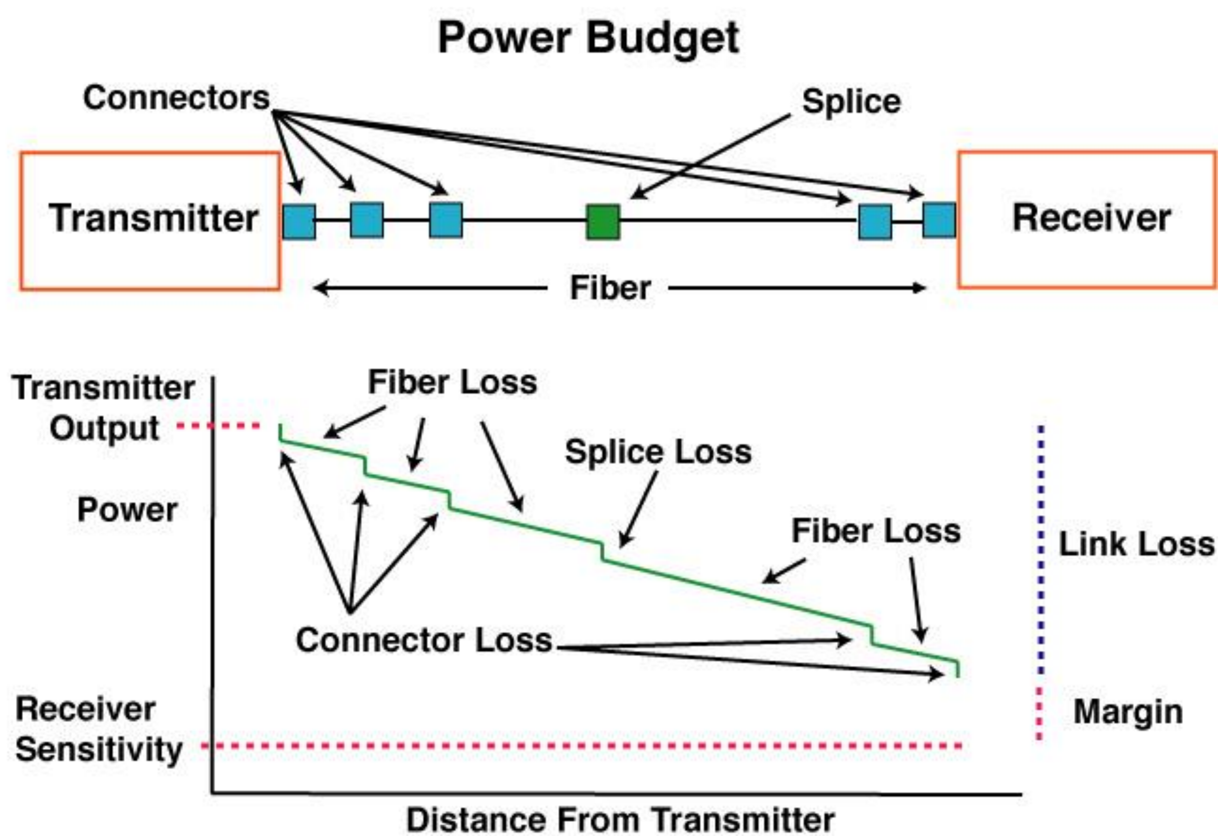


- Bending losses:
  - **Macrobends**: Too sharp bend.
    - A part of the mode is converted to a higher order mode, which is lost inside the cladding.
  - **Microbends**: Imperfections in the fiber or external force which deforms the cable.

Fiber Attenuation



Fiber Optic Link Power Budget



Decibel Units

- Any ratio converted into dB as R (in dB) $= 10\log_{10} R$.
- $R = 1$ corresponds to 0 dB: Ratios smaller than 1 are negative.
- Signal-to-noise ratio is defined as

$$\mathrm{SNR} = 10\log_{10}(P_S/P_N).$$

- Loss of an optical fiber is expressed in dB units.
- If a 1-mW signal reduces to 1 μW after 100 km of fiber, 30-dB loss translates into a loss of 0.3 dB/km.
- Power (in dBm) $= 10\log_{10}\left(\frac{\text{power}}{1\ \text{mW}}\right)$.
- 1 mW corresponds to 0 dBm on the decibel scale.
- 1 μW power corresponds to -30 dBm.

Link loss budgets

Overview

Link loss budgeting, also known as link engineering, is used to determine if the optical fiber cabling system being designed will work as expected. It is used to evaluate the total optical losses of the cabling system.

Link loss budgeting is a three step process, described as follows:

1. Determine the difference between the transmit power of the light source and the sensitivity of the receiver. This is known as the System Gain or the Dynamic Operating Range.

   System Gain = Transmitter Power - Receiver Sensitivity

2. Determine the total attenuation losses for the cabling system. These are passive losses attributed to the cable, connectors and splices.

   Optical fiber Loss = Length of cable (in km) x Loss per km

   Connector Loss = Number of connector pairs x Loss per connector pair

   Splice Loss = Number of splices x Loss per splice

   Other Loss = Loss due to other components + Margin for component aging

   Total Loss = Optical fiber Loss + Connector Loss + Splice Loss + Other Loss

3. Verify that the System Gain exceeds the total passive cabling system losses. The amount by which the System Gain exceed the total losses represents the safety margin, which should be sufficient to account for any errors made in estimating losses or gains.

   System Gain > Total Loss

   Safety Margin = System Gain - Total Loss

The following example will be used to illustrate how link loss budgets are calculated.

EXAMPLE 10.1: LINK LOSS BUDGETING

An optical fiber campus backbone is to be installed between a main cross-connect and an intermediate cross-connect. The system will use 62.5/125 μm multimode optical fiber and operate at an 850 nm operating wavelength.

The following information is known about the cabling system:

- The total length of optical fiber cable used—including all patch cords—between the two points is 1500 m (4920 ft).
- There are a total of 6 mated pairs of connectors.
- A total of 4 splices will be used.
- A 2-dB margin is provided for component aging.

The following information has been provided by the equipment manufacturers:

- The transmitter power of the light source, operating at 850 nm is -9dBm.
- The sensitivity of the receiver is -28 dBm.

The first step is to calculate the System Gain.

System Gain = Transmitter Power - Receiver Sensitivity

System Gain = -9dBm - (-28 dBm) = 19 dB

The second step is to determine the passive cabling system losses. The loss values provided by ANSI/TIA/EIA-568-A will be used in calculations. Other components may require different values to be used.

Optical fiber Loss = Length of cable (in km) x Loss per km

Optical fiber Loss = 1.5 km x 3.75 dB/km = 5.62 dB

Connector Loss = Number of connector pairs x Loss per connector pair

Connector Loss = 6 pairs of connectors x 0.75 dB loss per pair = 4.5 dB

Splice Loss = Number of splices x Loss per splice

Splice Loss = 4 splices x 0.3 dB loss per splice = 1.2 dB

Other Loss = Loss due to other components + Margin for component aging

Other Losses = 2 dB margin for component aging

Total Loss = Optical fiber Loss + Connector Loss + Splice Loss + Other Loss

Total Loss = 5.62 + 4.5 + 1.2 + 2 = 13.31 dB

Finally, Total Loss is compared to the System Gain to see if the system will work.

System Gain > Total Loss ?

19 dB > 13.31 dB

Since the System Gain is greater than the Total Loss, the system will work.

Safety Margin = System Gain - Total Loss

Safety Margin = 19 dB - 13.32 dB = 5.68 dB

The system has a Safety Margin of 5.68 dB.

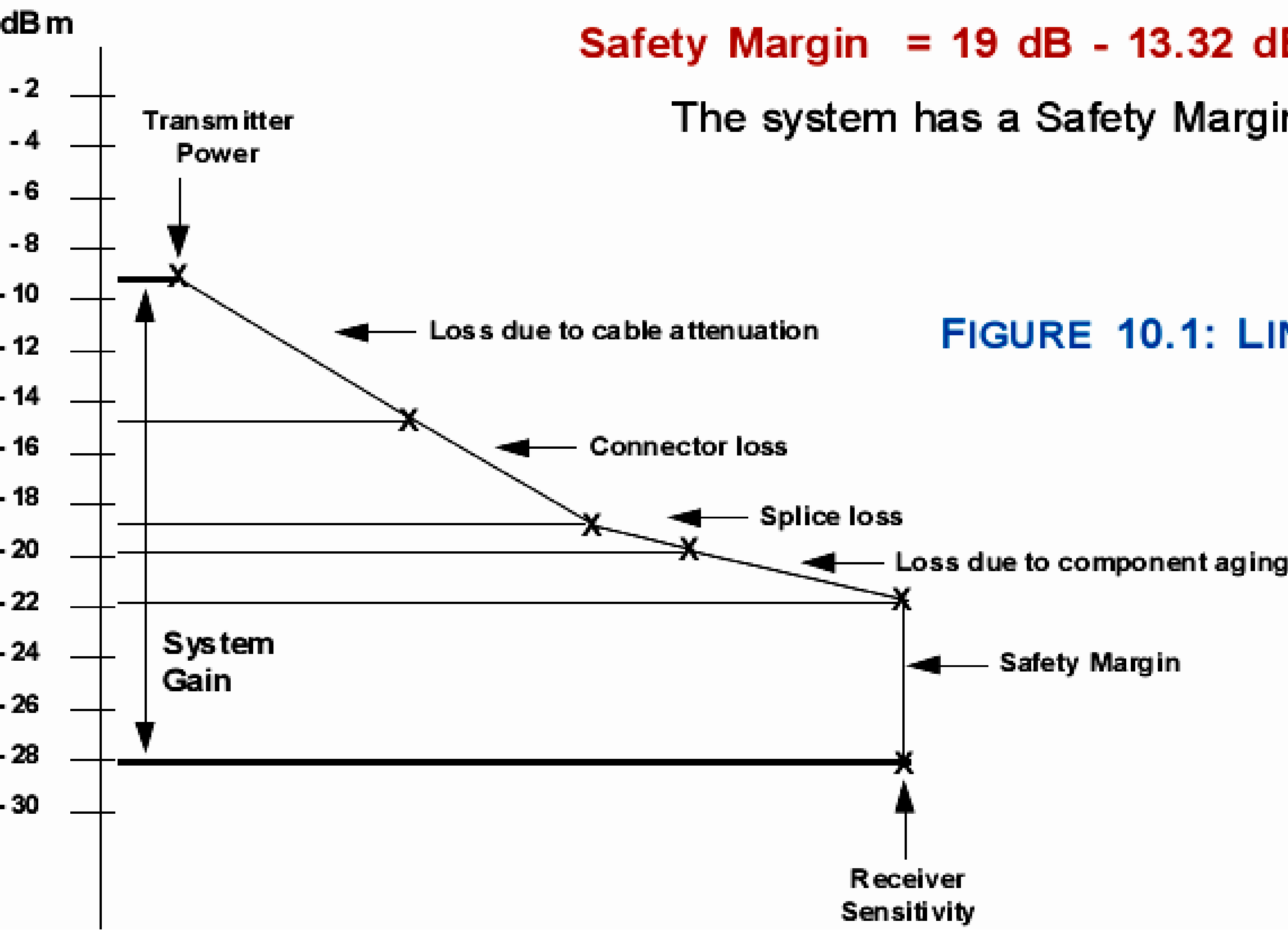


FIGURE 10.1: LINK LOSS BUDGETING

Graphically, the various system losses appear as shown.