Digital optical communications

- Performance metrics
  - The bit error rate
  - The eye-diagram
  - The L×B figure of merit
- Transmission impairments
  - Attenuation & noise
  - ISI, bandwidth and dispersion
  - Jitter
- Fundamental limits:
  - Quantum limit
  - Dispersion limit
- Capacity
  - First-generation: 850 nm
  - Second-generation: 1300 nm
  - Third-generation: 1550 nm

Performance metrics

- The Bit Error Rate (BER):
- The primary measure of performance of a digital system

- The probability that an error will be made in the detection of a received bit
  - BER < 10^{-9}, for telecommunications
  - BER < 10^{-12}, for data transmission

- Measured by counting the number of errors occurring during transmission over a long period of time:
  - BER = (# bit errors)/(total # of bits transmitted)

Performance metrics

The Bit Error Rate (BER):

– BER = P_{err} (Probability of Error)

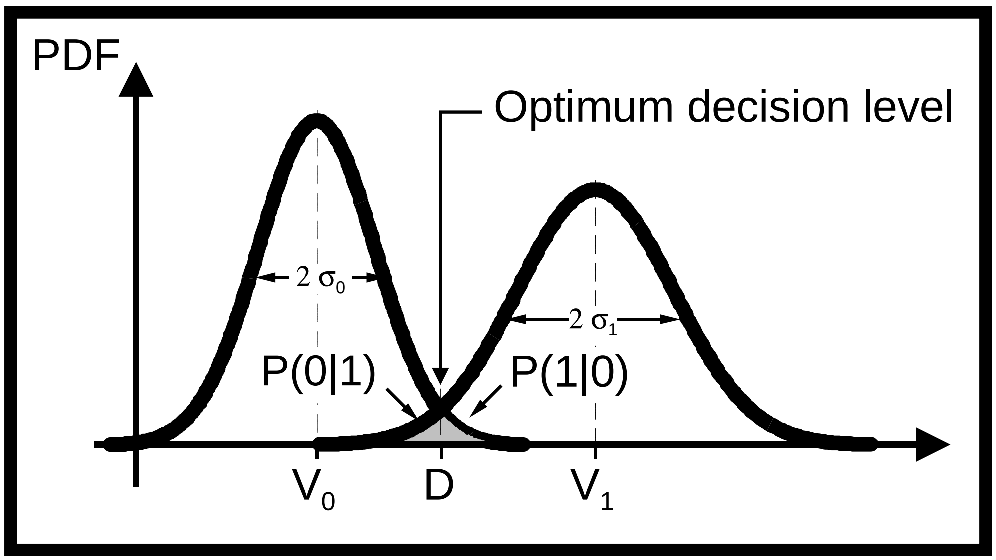
$$P_{err} = P(0|1)P(1) + P(1|0)P(0)$$

$$P(0|1) = \frac{1}{\sqrt{2\pi}} \frac{e^{-\mathrm{SNR}_1^2}}{\mathrm{SNR}_1}, \quad P(1|0) = \frac{1}{\sqrt{2\pi}} \frac{e^{-\mathrm{SNR}_0^2}}{\mathrm{SNR}_0}$$

$$\mathrm{SNR}_1 = \frac{V_1 - D}{\sigma_1}, \quad \mathrm{SNR}_0 = \frac{D - V_0}{\sigma_0}$$

– BER is a strong function of SNR_i:

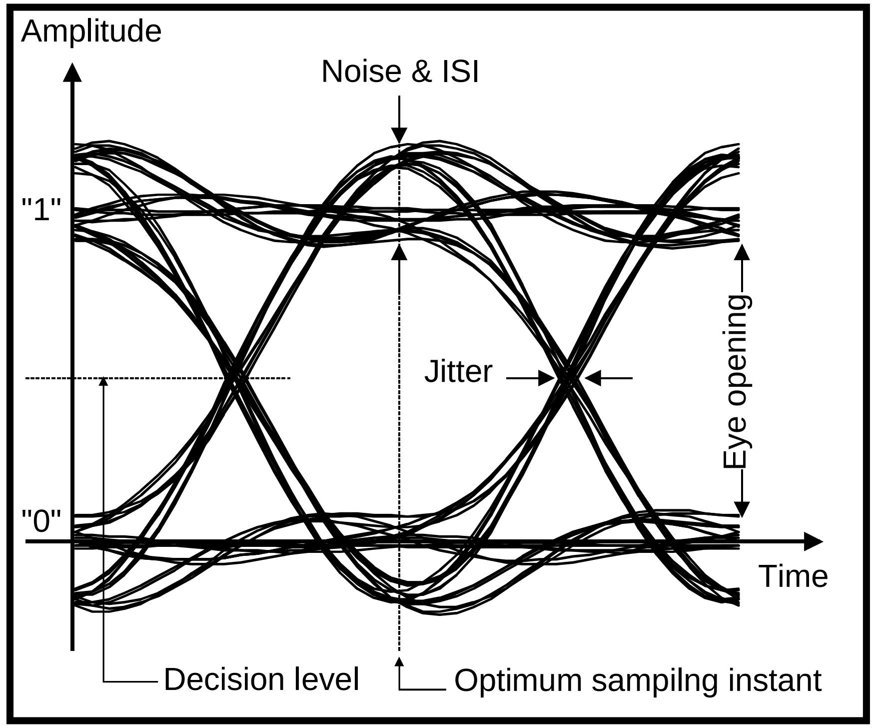
- BER(SNR = 6) = 10^{-9}
- BER(SNR = 7.9) = 10^{-15}



Performance metrics

The Eye-Diagram:

- It is the overlay of all possible states of a sequence
- Powerful diagnostic:
  - Jitter
  - Noise
  - Inter-Symbol Interference (ISI)
  - Patterning effects
  - Bit errors



Performance metrics

Bit Rate-Distance Product:

- To compare different systems a figure of merit is necessary
- The product:

  (Bit Rate) × (Distance), is a measure of the information carrying capacity of a link
- "Distance":
  - is the maximum distance that can be achieved without the use of repeaters between the transmitter and the receiver
- Optimize a link capacity $\Leftrightarrow$ increase $B \times L$

Transmission Impairments

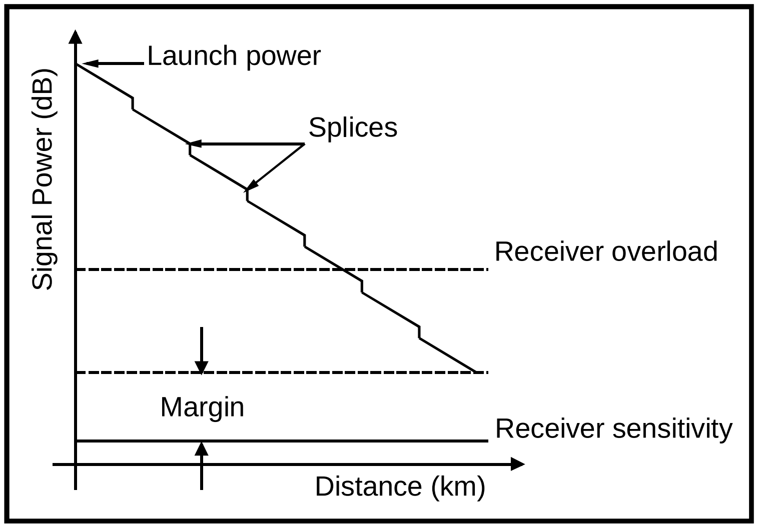
Attenuation & Noise:

- As a signal travels along a fiber (or cable) it is attenuated:

$$P(L) = P_T \cdot 10^{-\frac{A \cdot L}{10}}$$

- Due to receiver noise, a minimum power has to be detected by the receiver in order to achieve the desired BER
- The maximum distance over which a signal can travel before it is to week to be detected is:

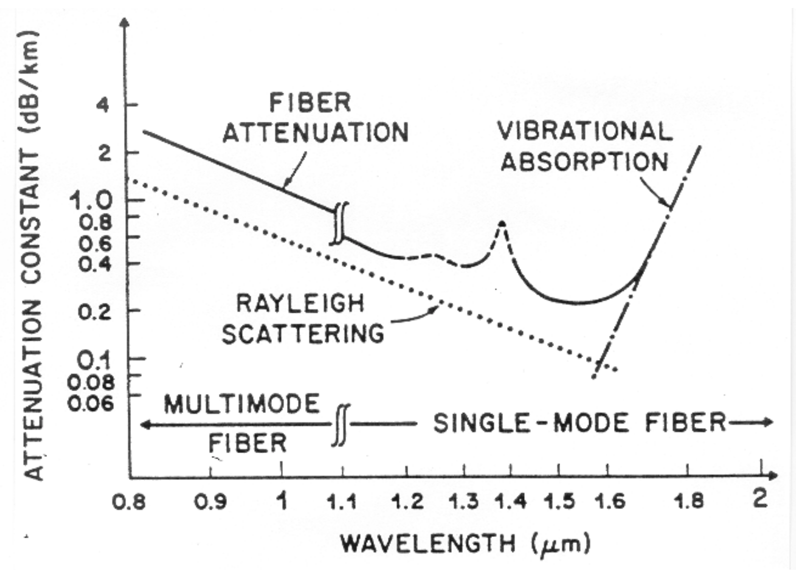
$$L_{max} = \frac{10}{A} \log\left(\frac{P_T}{P_R}\right)$$



Transmission Impairments

fiber attenuation

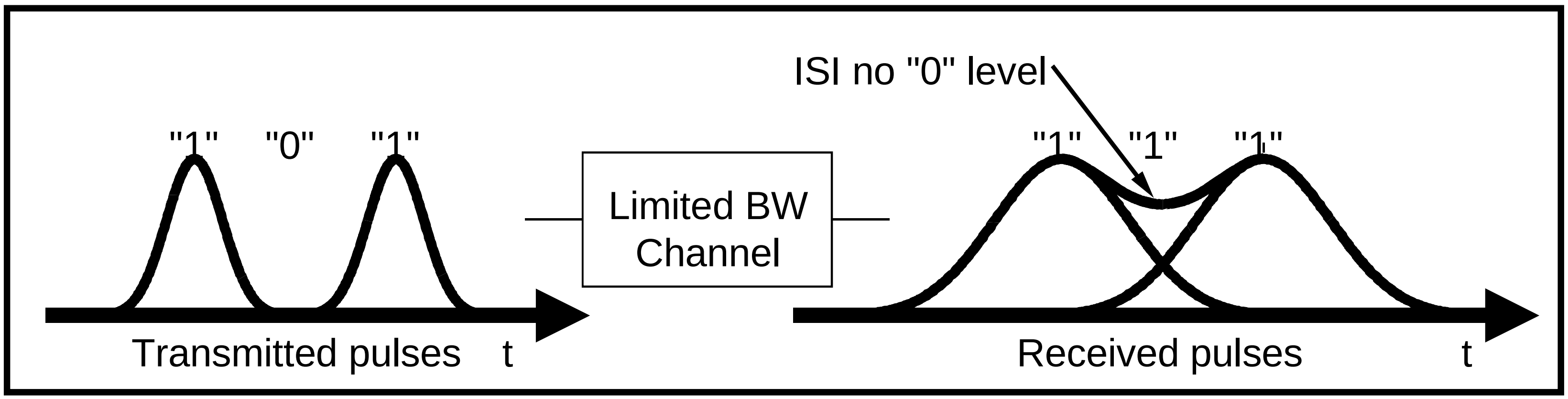
- Attenuation in optical fibers is caused by:
  - Rayleigh scattering: dominant at the “shorter” wavelengths (<1600nm): $A \sim 0.6/\lambda^4$ dB/km
  - Silica vibrational absorption: dominant at “longer” wavelengths (>1600nm)
  - Both phenomena combine to produce a low-loss “window” with absolute loss minimum at 1550nm
  - Absorption peak caused by OH ions (~1400nm)



Transmission Impairments

ISI, Dispersion and Bandwidth

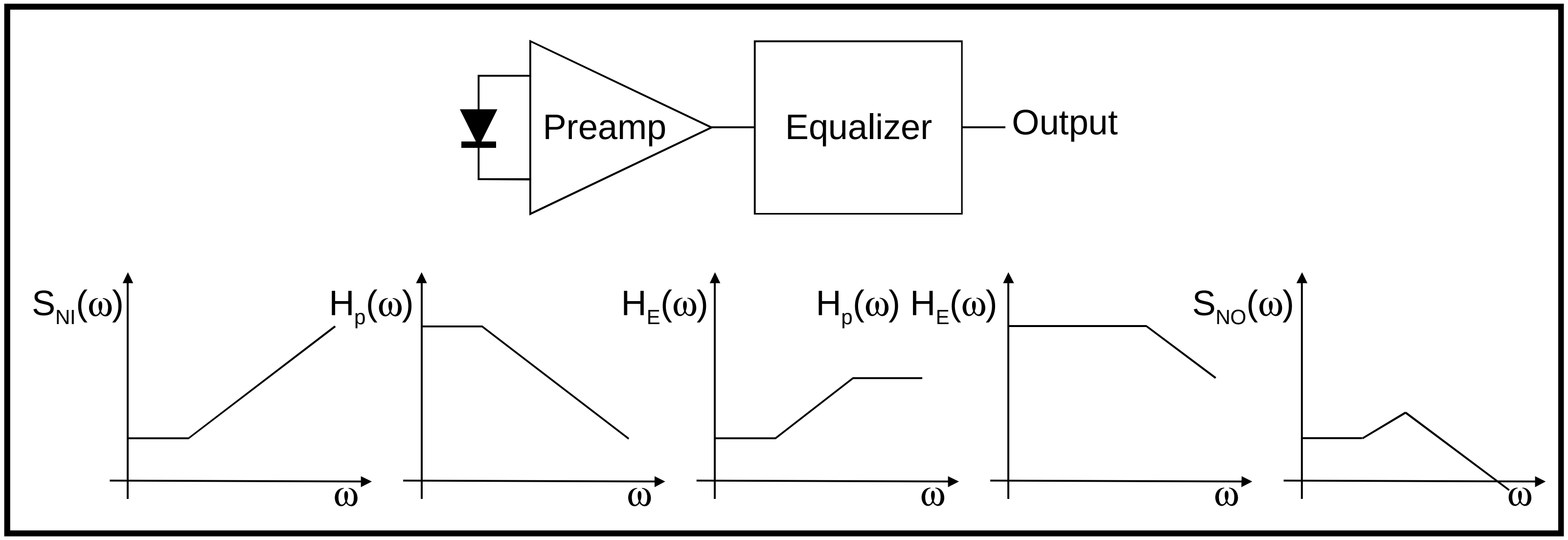
- In a physical link, the available bandwidth is limited
- As the symbol rate approaches the bandwidth limit the received pulses become broadened versions of the transmitted pulses
- For moderate to sever bandwidth limitations the received pulses start to overlap
- This overlap is called Intersymbol Interference (ISI)
- Bandwidth limitations and fiber dispersion are the common causes of ISI
- Large amounts of ISI can not be simply corrected by increasing the received signal power



Transmission Impairments

Bandwidth:

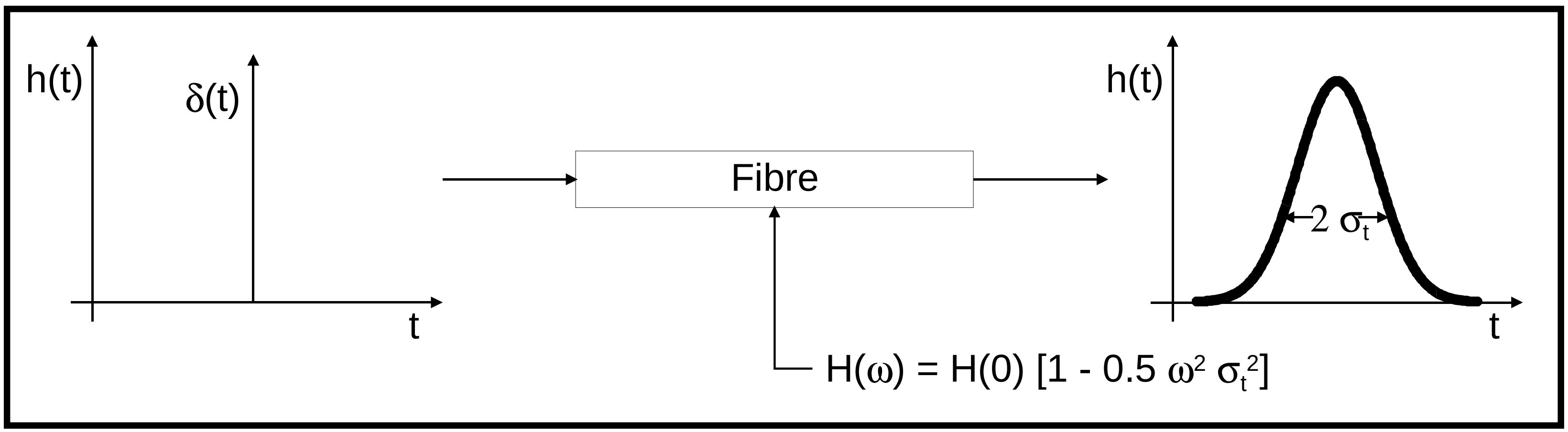
- Electronic circuits have finite bandwidths
- Bandwidth limitations can be equalized
- Equalization increases the receiver high frequency noise
  - This increases the BER
  - The BER can be restored by increasing the received signal power
  - The increase in power necessary to restore the BER is called the ***Power Penalty***



Transmission Impairments

Dispersion:

- As signal pulses travel along a fiber they spread and start to overlap
- Dispersion effects result in: reduction of the high frequency response of the system
- Small amounts of dispersion can be corrected by equalization
- Equalization has an associated power penalty
- Systems operate typically with dispersion penalties less than 1dB
- To maintain the dispersion penalty less than 1dB the RMS pulse spread has to be less than one-quarter of T: $\boldsymbol{\sigma_t < T/4}$



Transmission Impairments

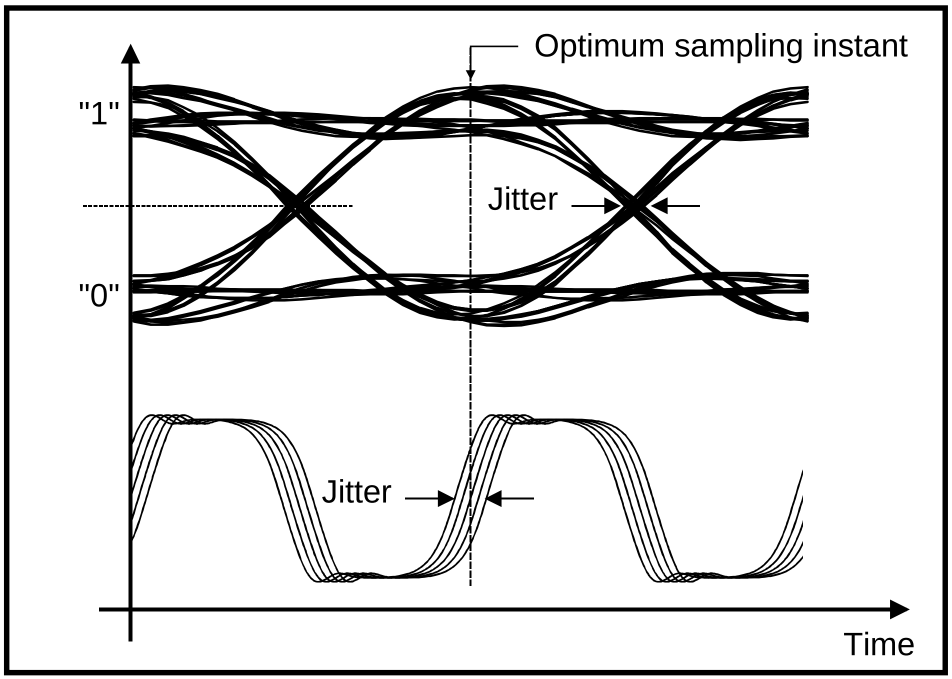
<u>Dispersion:</u>

- Since, σ_t increases with fiber length
- And, a power penalty less that 1 dB requires $\sigma_t < T/4$
- The maximum fiber length that satisfies $\sigma_t < T/4$ is called the <u>*dispersion-limited transmission distance*</u>
- Dispersion-limited transmission depends on:
  - The fiber length
  - The bit rate
  - The fiber material characteristics
  - The fiber waveguide structure
  - It is <u>independent of fiber loss</u>

Transmission Impairments

<u>Jitter:</u>

- In a band limited system phase noise (jitter) leads to a degradation of the SNR.
- Since the BER is a strong function of the SNR jitter can lead to a quick degradation of the BER
- The effects of excessive amounts of jitter <u>can not</u> be corrected by increasing the signal power



Fundamental Limits

Quantum Limit:

- The quantum noise limit is obtained when all the system noise contributions are reduced to zero.
- In this case the detection of a single electron is sufficient to identify a transmitted “1”
- However, light detection is a statistical process it self. There is a finite probability that a given amount of power will generate zero electrons
- To reduce this probability to 10^{-9} the received mean power has to be bigger than:

$$\langle P \rangle \geq 10 \cdot h\nu \cdot B$$

- The quantum limit is thus proportional to:
  - The photon energy ($h\nu$)
  - The bit rate (B)

Ex. For a 10Gbits/s transmission system operating at 1550nn the quantum limit is: -48.9dBm

Fundamental Limits

Dispersion Limit

- Optical dispersion is proportional to the transmitted spectral width
- If the light source spectral width was reduced to zero the transmitted signal would still have a finite spectral width due to the signal bandwidth:

$$\sigma_{\lambda} \cong \frac{\lambda^2}{c}\frac{B}{2}$$

- That sets the ultimate dispersion limit to the fiber length:

$$L \leq \frac{c}{2D\lambda^2}\frac{1}{B^2}$$

Ex. For a 10 Gbit/s transmission system operating at 1550 nm with D = 15 ps/nm/km the dispersion limit constrains the fiber length to less than 40 km

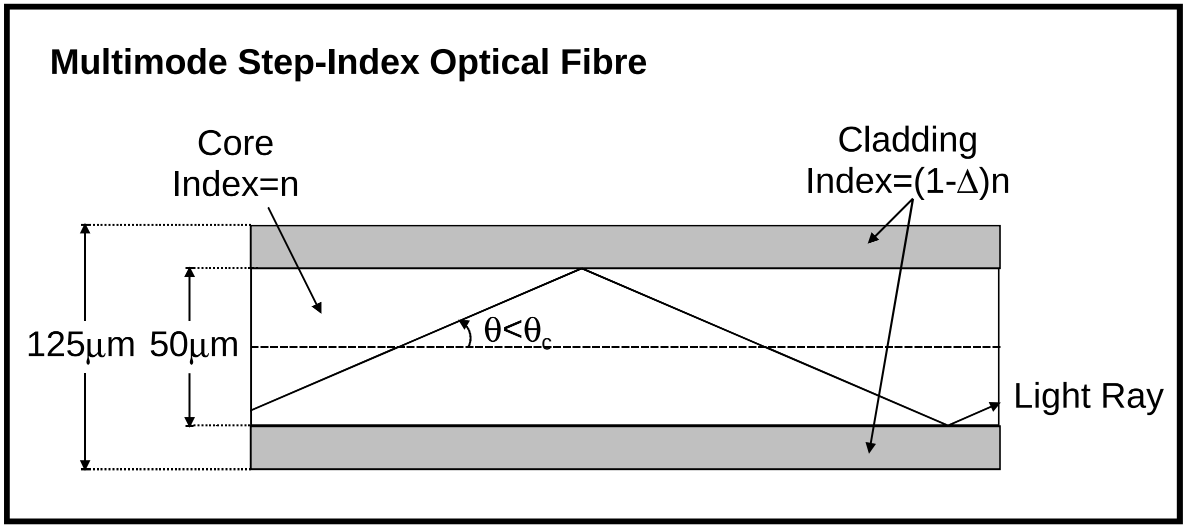
First-generation optical systems

- Wavelength: λ = 850 nm
- Fiber: multimode, step-index and graded-index
- Light sources: GaAs/AlGaAs lasers and LED's
- Detectors: Si PIN's and APD's
- ***Loss limit:***
  - Receiver sensitivity: for a typical Si APD based receiver about 300 photons/bit are necessary to achieve a BER of 10-9

$$P_R = -131.6 + 10\log(B) \quad (\text{in dBm})$$

Ex. For a 100 Mbit/s system operating at λ = 850 nm with A = 2.5 dB/km, P_T = 1 mW and P_R = -51.6 dBm the loss limited transmission distance is L_{max} = 20.6 km

First-generation optical systems



Multimode Step-Index fiber:

- Composed of:
  - A core, having index of refraction *n*
  - A cladding, having a lower index (1-Δ)*n*
- The index step acts to confine the optical energy in the fiber core:
  - "Light rays" with $\theta \leq \sqrt{2\Delta}$ are confined to the core by total internal reflection
  - "Rays" at larger angles are partially reflected and rapidly attenuated

First-generation optical systems

Dispersion limit:

- Modal dispersion is the dominant dispersive mechanism:
  - Rays propagating at different angles have different flight times

$$\tau = \frac{Ln}{c\cos(\theta)}, \quad \text{for} \quad 0 \le \theta \le \sqrt{2\Delta}$$

  - The pulse spread after fiber length L is

$$\sigma_t = \frac{Ln}{2c}\Delta$$

  - *Dispersion-limited transmission distance:*

$$L_{max} = \frac{c}{2n\Delta}\frac{1}{B}$$

Ex. For a 100 Mbit/s system operating at λ = 850 nm using multimode step-index fiber with n = 1.46 and Δ = 0.01 the dispersion limited distance is 0.1km

First-generation optical systems

Multimode Graded-Index fiber:

- Similar structure to step-index fiber <u>but</u> the core refractive index has a parabolic profile: high in the center and gradually decreasing towards the cladding:
  - light rays staying close to the core center travel relatively slow ("high *n*")
  - light rays making wide excursions towards the cladding travel relatively faster
  - Control of the index profile allows to make the travel times for all rays to be nearly equal
- **Dispersion limit:**
  - The pulse spread after the distance L is

$$\sigma_t = \frac{L\ n}{8\ c}\Delta^2$$

  - *Dispersion limited transmitted distance*

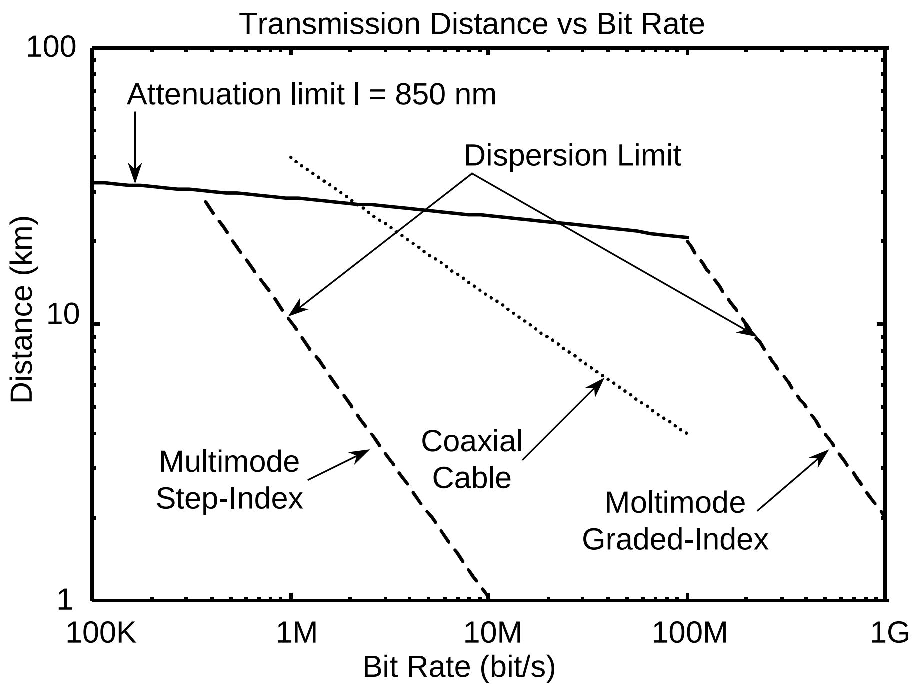
$$L_{max} = \frac{2\ c}{n\ \Delta^2}\frac{1}{B}$$

First-generation optical systems

Ex. For a 100 Mbit/s system operating at λ = 850 nm using multimode graded-index fiber with n = 1.46 and Δ = 0.014 the dispersion limited distance is 20 km

First-generation system: B = 100Mbit/s

- L_{max}(attenuation) = 20.6 km
- L_{max}(dispersion) = 0.1 km (step-index)
- L_{max}(dispersion) = 20.9 km (graded-index)



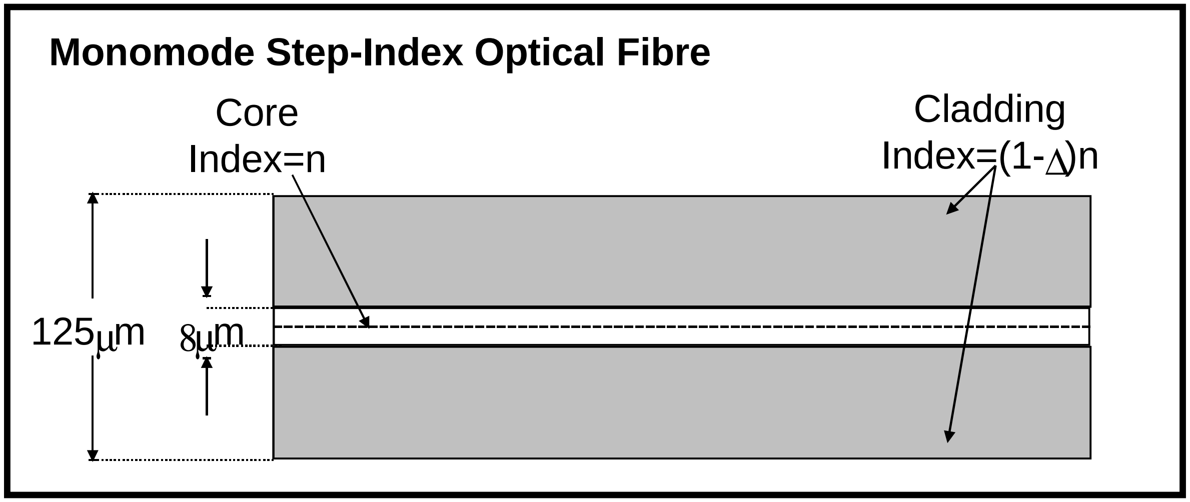
Second-generation optical systems

- Wavelength: λ = 1300 nm
- Fiber: single-mode step-index
- Light sources: InGaAs/InP Lasers
- Detectors: InGaAs/InP PIN's and Ge APD's
- **<u>Loss limit:</u>**
  - Receiver sensitivity: about 1000 photons/bit are necessary to achieve a BER of 10^{-9} for an InGaAsP/InP APD based receiver

$$P_R = -128.2 + 10\log(B) \quad (\text{in} \quad \text{dBm})$$

Ex. For a 10 Gbit/s system operating at λ = 1300 nm with A = 0.4 dB/km, P_T = 1 mW and P_R = -28.2 dBm the loss limited transmission distance is L_{max} = 70.4 km

Second-generation optical systems



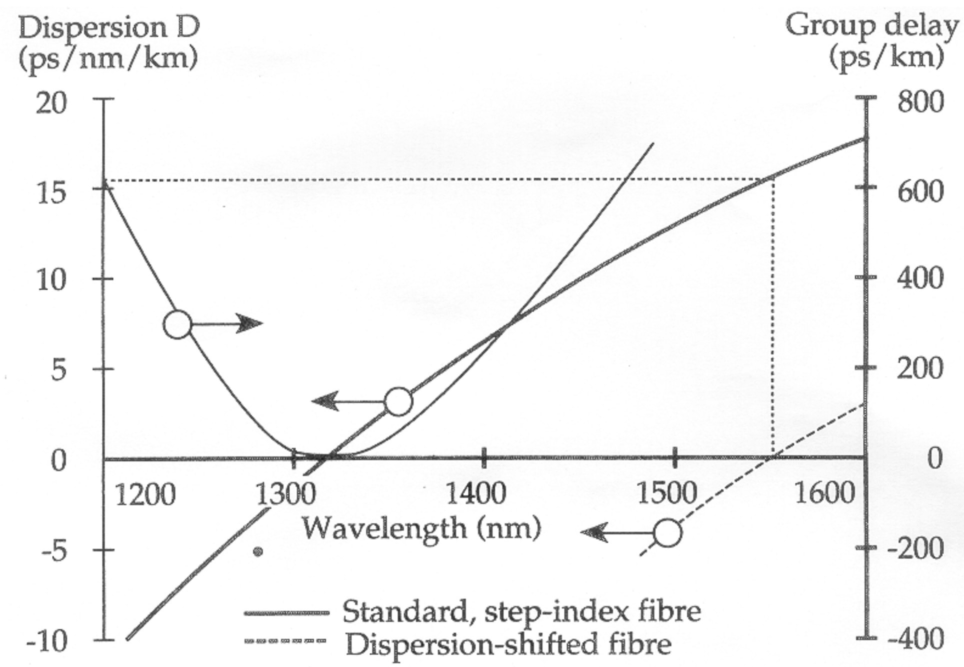
<u>Monomode Step-Index fiber:</u>

- Composed of:
  - A core, having index of refraction *n*
  - A cladding, having a lower index (1-Δ)*n*
  - *<u>Core size: monomode << multimode</u>*
- A monomode fiber supports a single wave mode
- Consequently, *<u>there is no modal dispersion</u>*
- But there is: *<u>material dispersion</u>*

Second-generation optical systems

Dispersion limit:

- Due to *material dispersion*
  - The group velocity of a propagating mode is a function of the wave length
  - The index of refraction of silica is a function of the wavelength
- The RMS pulse spreading is given by: $\sigma_t = D \cdot L \cdot \sigma_\lambda$
- Material dispersion goes through an minimum at λ = 1300 nm

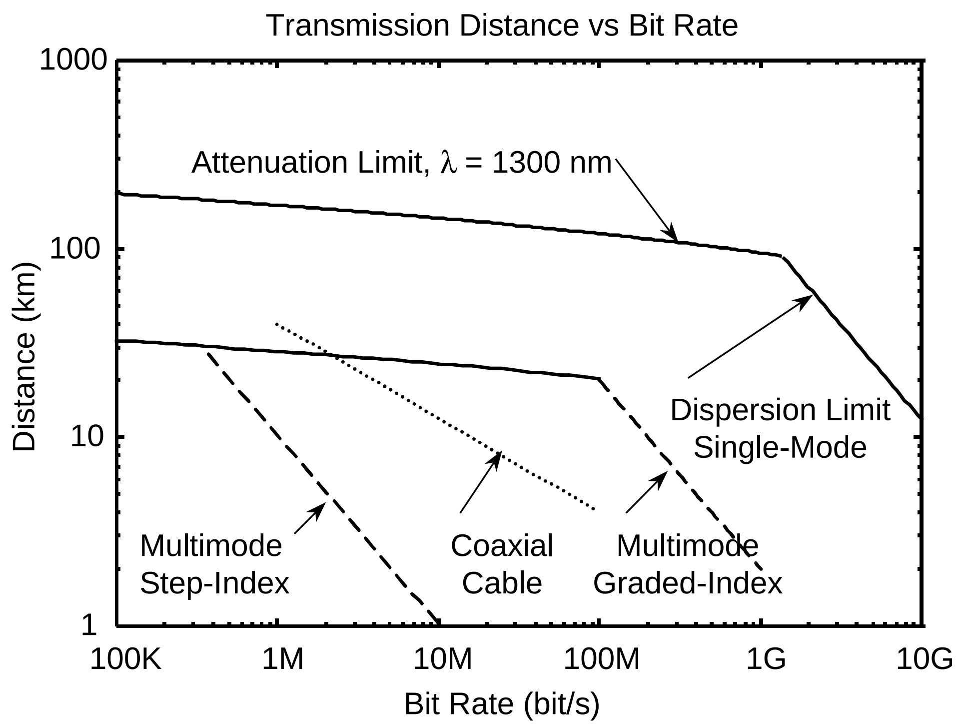


Second-generation optical systems

<u>Dispersion limit:</u> (material dispersion)

- The dispersion limited transmission distance is given by: $L_{\max} = \dfrac{1}{4 \cdot D \cdot \sigma_\lambda \cdot B}$

Ex. For a 10 Gbit/s system with an InGaAsP laser with center wavelength λ = 1300 nm (10 nm tolerance), D is around 1 ps/nm/km. For a typical spectral with of 1nm the loss limited transmission distance is L_{max} = 25 km



Third-generation optical systems

- Wavelength: λ = 1550 nm
- Fiber: single-mode and dispersion-shifted
- Light sources: GaInAsP/InP DFB Lasers
- External Modulators: MZ and EA
- Optical amplifiers: SLA's and EDFA's
- Detectors: InGaAsP/InP PIN's
- **Loss limit:**
  - Receiver sensitivity: similar to that of the second generation systems (same materials)

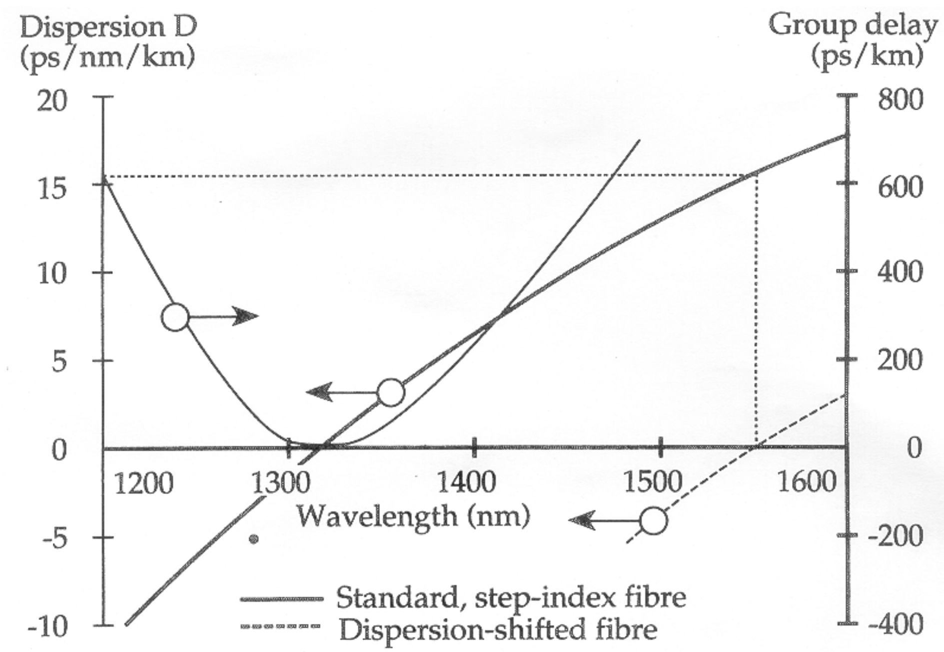
$$P_R = -128.2 + 10\log(B) \quad (\text{in} \quad \text{dBm})$$

Ex. For a 10 Gbit/s system operating at λ = 1550 nm with A = 0.25 dB/km, P_T = 1 mW and P_R = -28.2 dBm the loss limited transmission distance is L_{max} = 112.8 km

Third-generation optical systems

Dispersion limit:

- Dispersion shifted fiber
  - Standard fiber has D = 15-17 ps/nm/km dispersion at λ = 1550 nm
  - Wave guide dispersion has opposite sign to material dispersion at λ = 1550 nm
  - By fiber design material and waveguide dispersion can be made to cancel each other
  - This results in minimum attenuation and dispersion at λ = 1550 nm



Third-generation optical systems

Dispersion limit:

- Reducing the light source spectral width reduces the effects of dispersion
  - Narrow spectral width lasers DFB's
  - External modulators: MZ and EA
- Dispersion limit: $$L_{\max} = \frac{1}{4 \cdot D \cdot \sigma_\lambda \cdot B}$$
- For small values of D and extremely narrow spectral width:

$$L_{\max} \leq \frac{c}{2 D \lambda^2} \frac{1}{B^2}$$