William Stallings
Data and Computer Communications

Chapter 4

Transmission Media

Part I: Guided Transmission Media

Overview

- **Guided** - wire
- **Unguided** - wireless

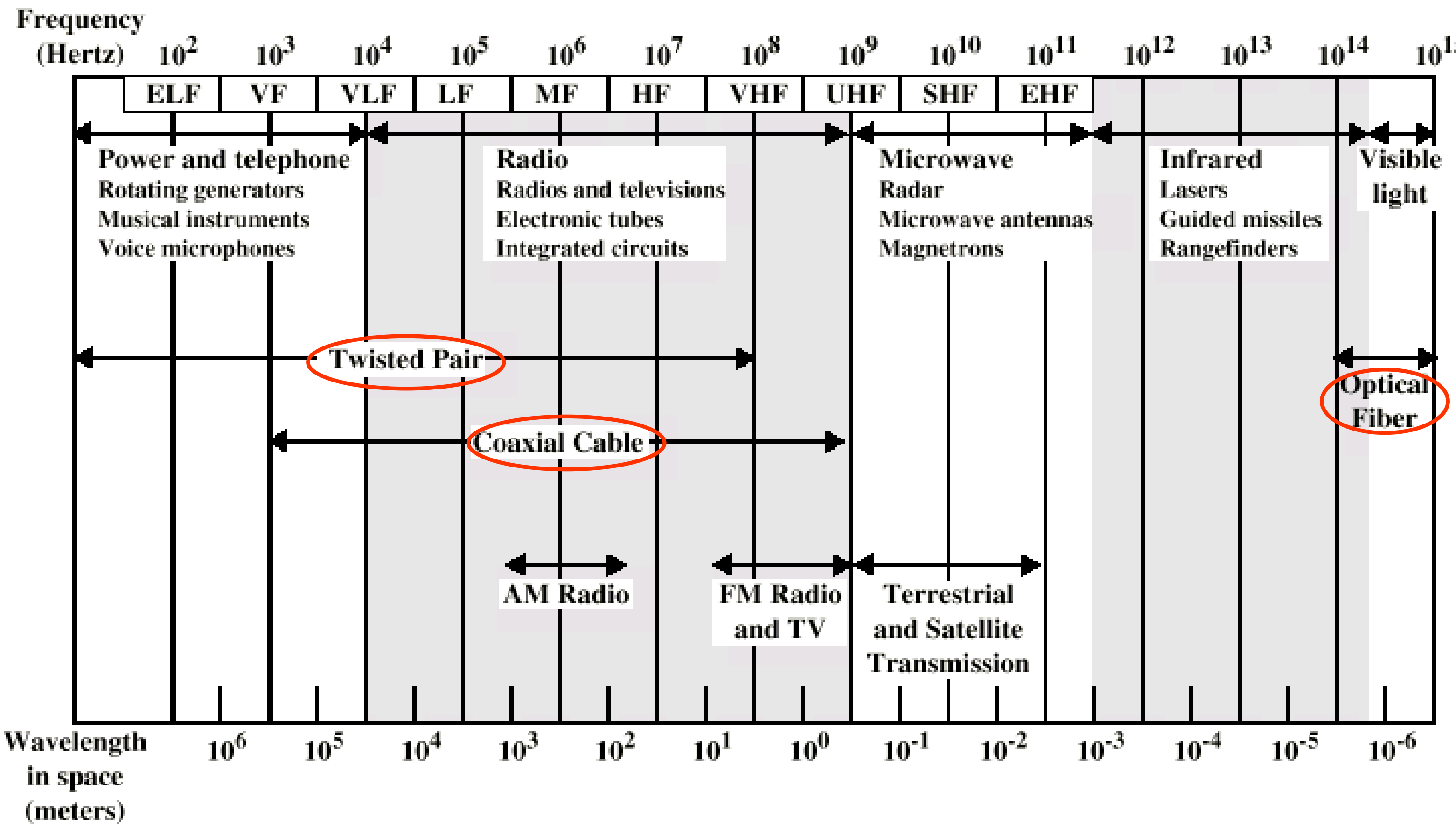
- Key concerns are **data rate** and **distance**
  - The **greater** the data rate and distance → **the better**

Design Factors

A number of design factors relating to transmission medium and signal:

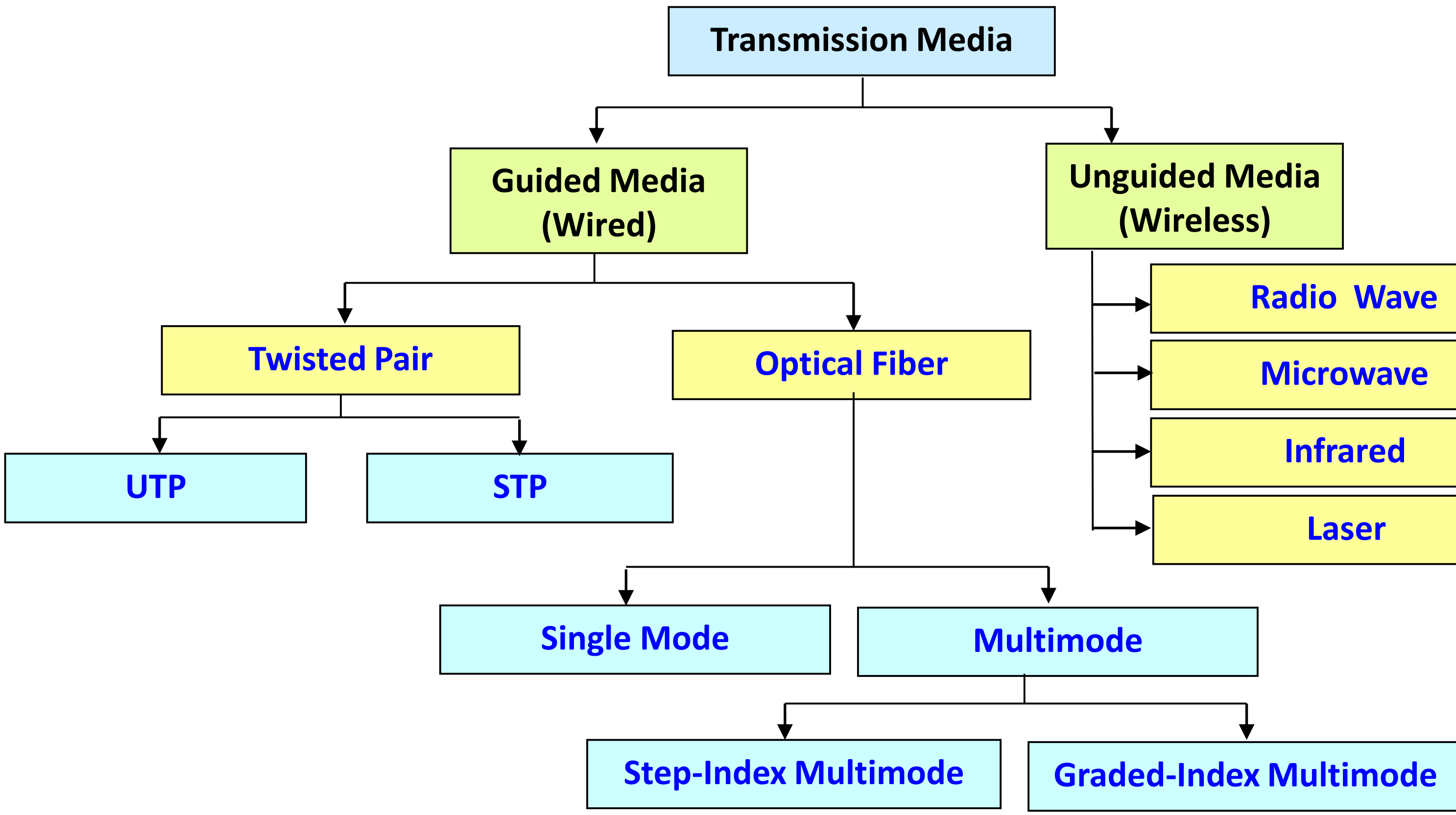
- **Bandwidth**
  - Higher bandwidth of a signal gives higher data rate
- **Transmission impairments**
  - Attenuation
- **Interference**
  - In guided media, interference can be caused by emanations from nearby cables or from unguided transmissions.
    - Proper shielding of a guided medium can minimize the problem.
- **Number of receivers**
  - In guided media
  - More receivers (multi-point) introduce more attenuation

Electromagnetic Spectrum



ELF = Extremely low frequency
VF = Voice frequency
VLF = Very low frequency
LF = Low frequency
MF = Medium frequency
HF = High frequency
VHF = Very high frequency
UHF = Ultrahigh frequency
SHF = Superhigh frequency
EHF = Extremely high frequency

Transmission Media

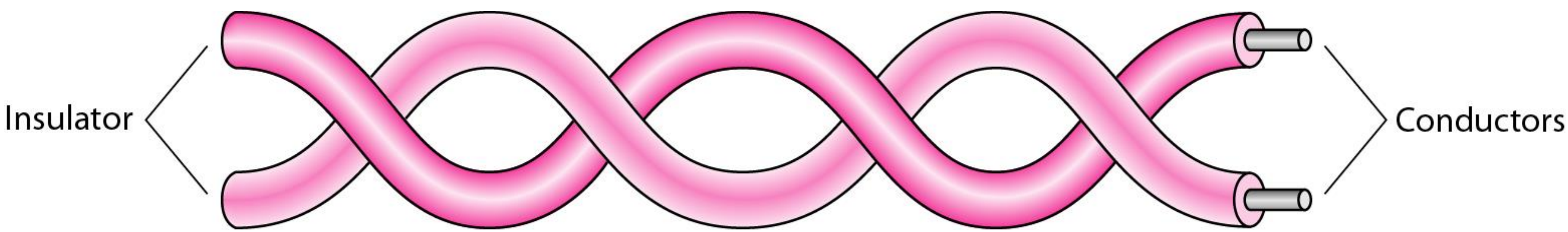


Guided Transmission Media

- **Twisted Pair**
- **Coaxial cable**
- **Optical fiber**

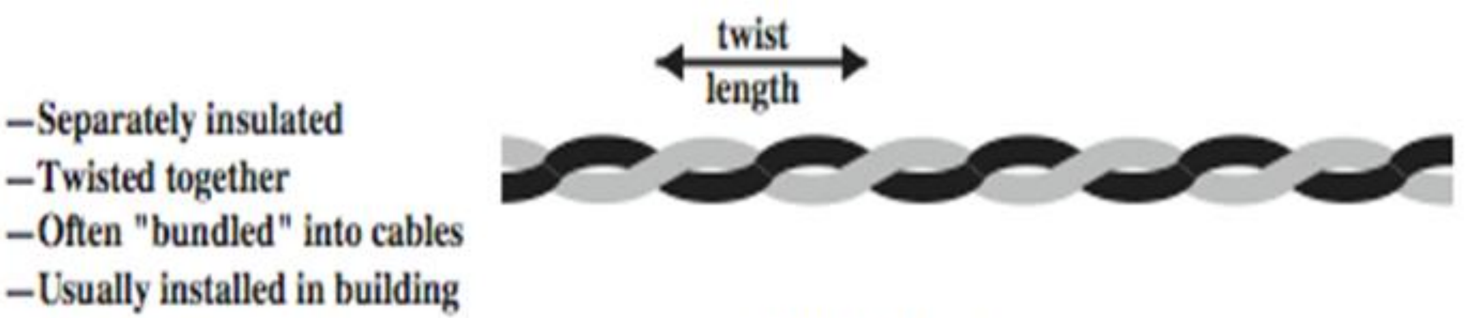
Twisted Pair

- A **twisted pair** consists of *two insulated copper wires arranged in a regular spiral pattern.*
- A wire pair acts as a single communication link.
- Typically, a number of these pairs are bundled together into a cable by wrapping them in a tough protective sheath.



Twisted Pair

- The twisting tends to decrease the **crosstalk** interference between adjacent pairs in a cable.
- *Neighboring pairs in a bundle typically have somewhat different **twist lengths** to reduce the crosstalk interference.*
- On long-distance links, the **twist length** typically varies from 5 to 15 cm.
- The wires in a pair have **thicknesses** of from 0.4 to 0.9 mm.



(a) Twisted pair

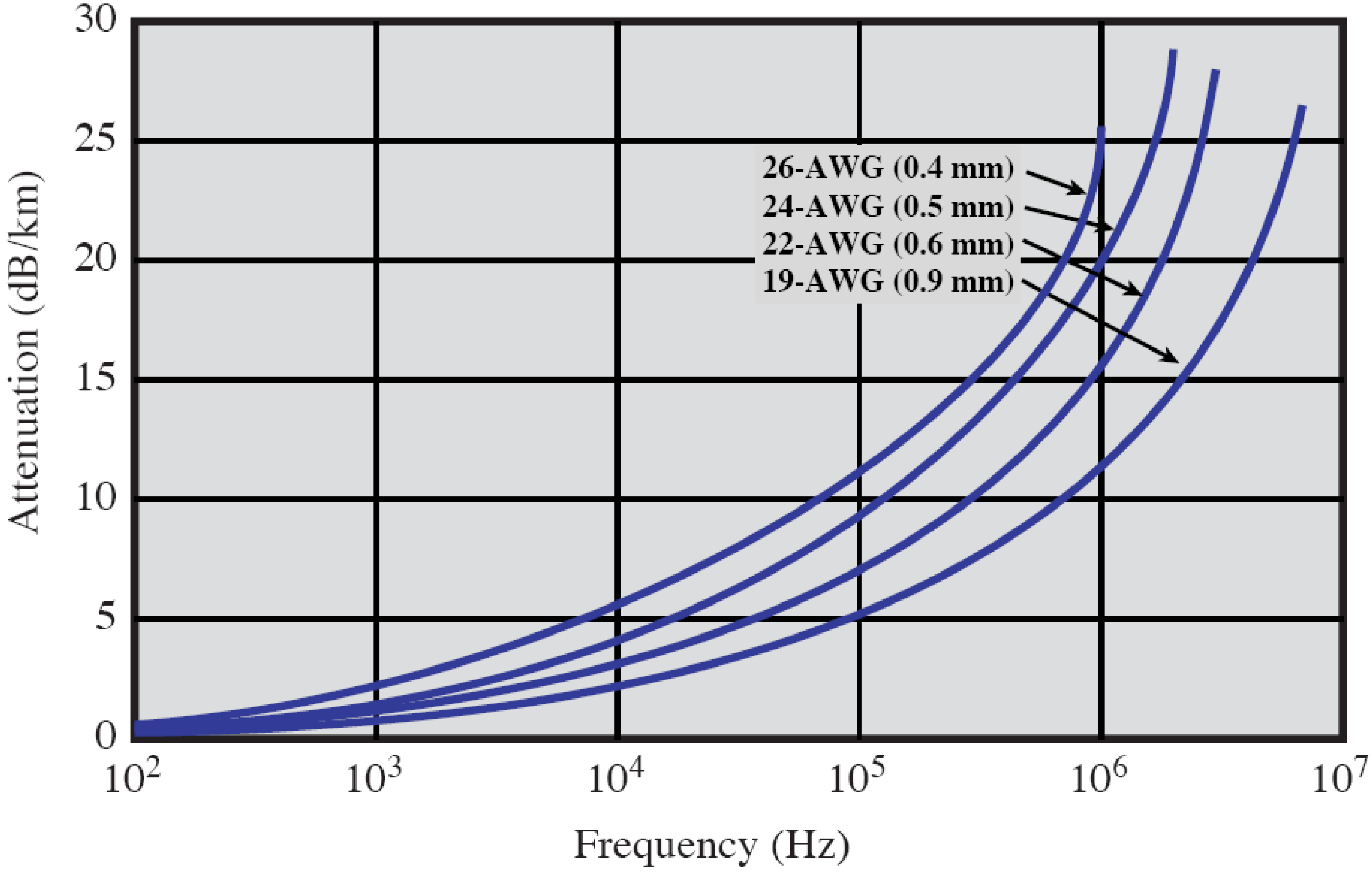
Twisted Pair - Applications

- Most common medium
- **Telephone network**
  - Between house and local exchange (subscriber loop)
- **Within buildings**
  - To private branch exchange (PBX)
- **For local area networks (LAN)**
  - 10Mbps or 100Mbps

Twisted Pair - Transmission Characteristics

- **Analog**
  - Amplifiers every 5km to 6km
- **Digital**
  - Use either analog or digital signals
  - repeater every 2km or 3km
- **Cheap**
- **Easy to work with**
- **Limited distance**
- **Limited bandwidth**
- **Limited data rate**
- **Susceptible to interference and noise**
- **Attenuation is strong function of frequency**

Transmission Characteristics



Transmission Characteristics

Example:

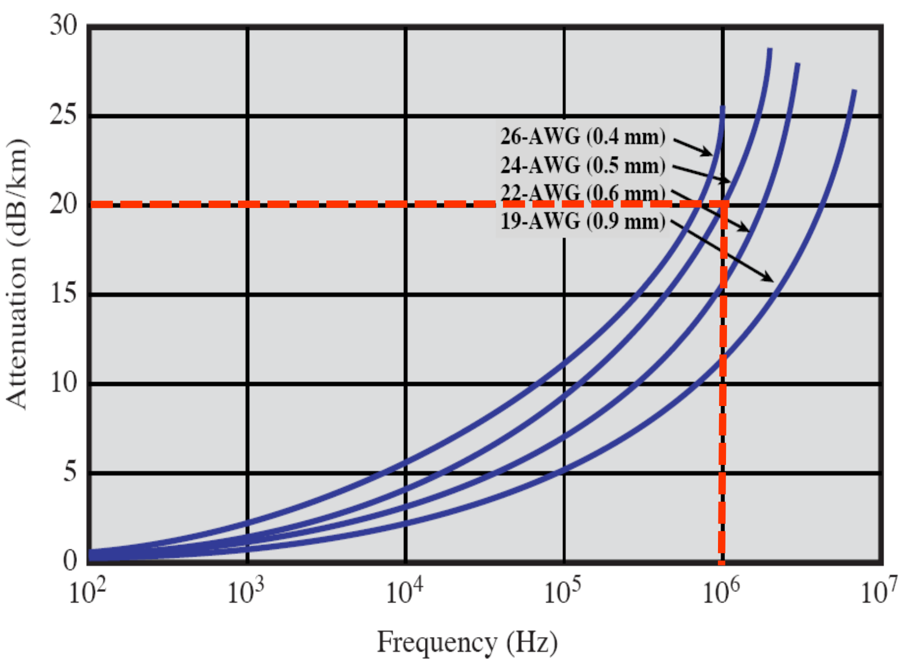
- Assume that the Allowable power loss = 20 dB
- Consider 24-gauge (0.5 mm) twisted pair operating at 1MHz

→ Attenuation = 20 dB/km

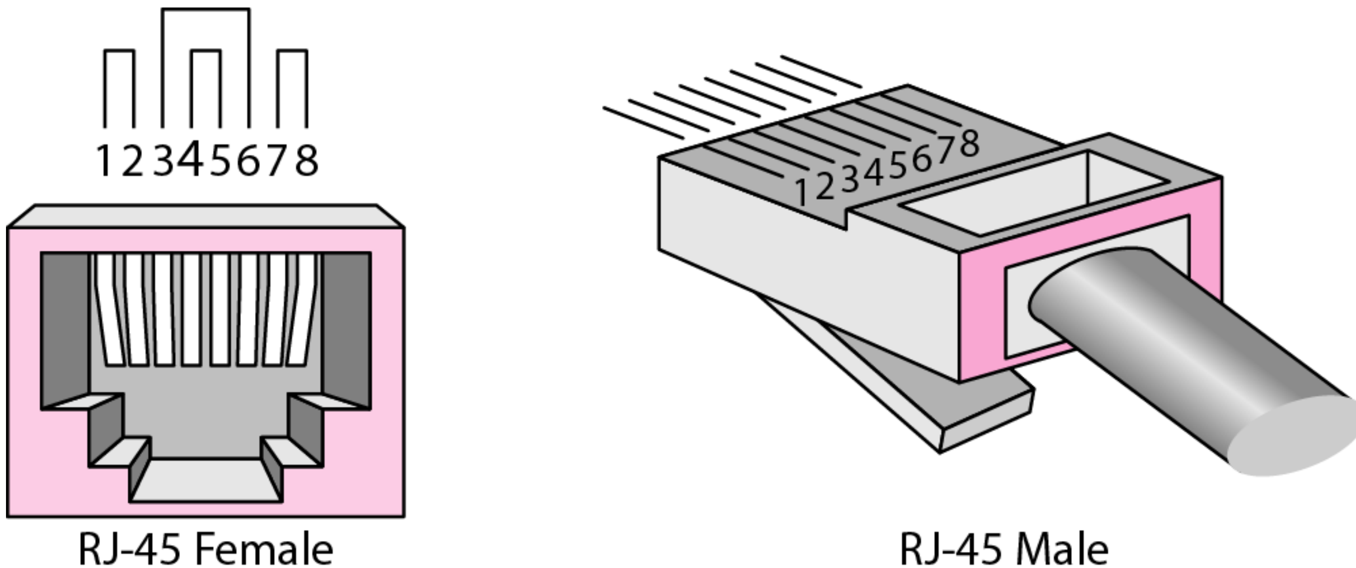
$$\text{Cable Length} = \frac{\text{Allowable Power Loss in dB}}{\text{Attenuation in dB/km}}$$

→ Cable length = 20 dB / 20 dB/km

→ Cable length = 1 km



UTP Connector

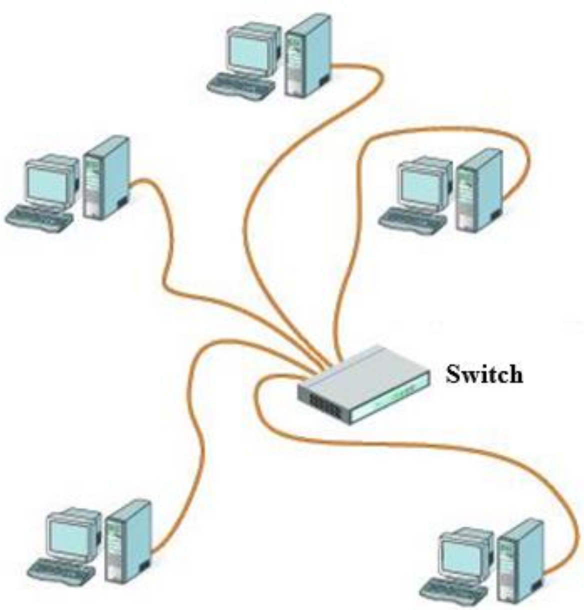


UTP Standard – 1000BaseT

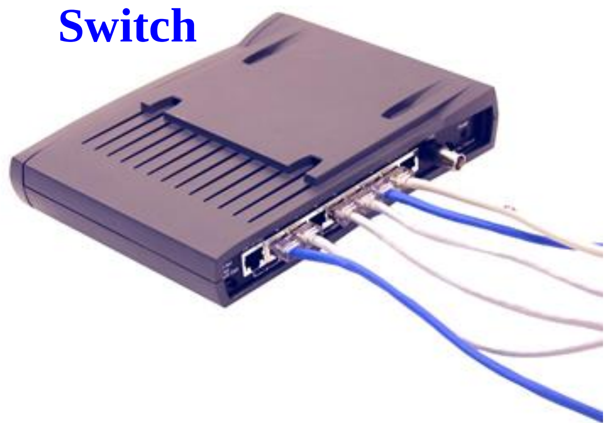
Max. 1 PC on each segment

Max. segment length is 100 meters

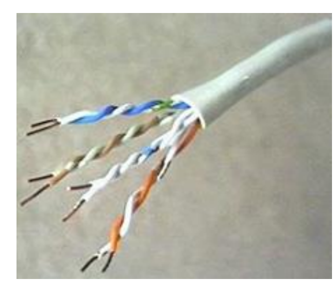
Max. 1024 PCs per hub or switch



Switch

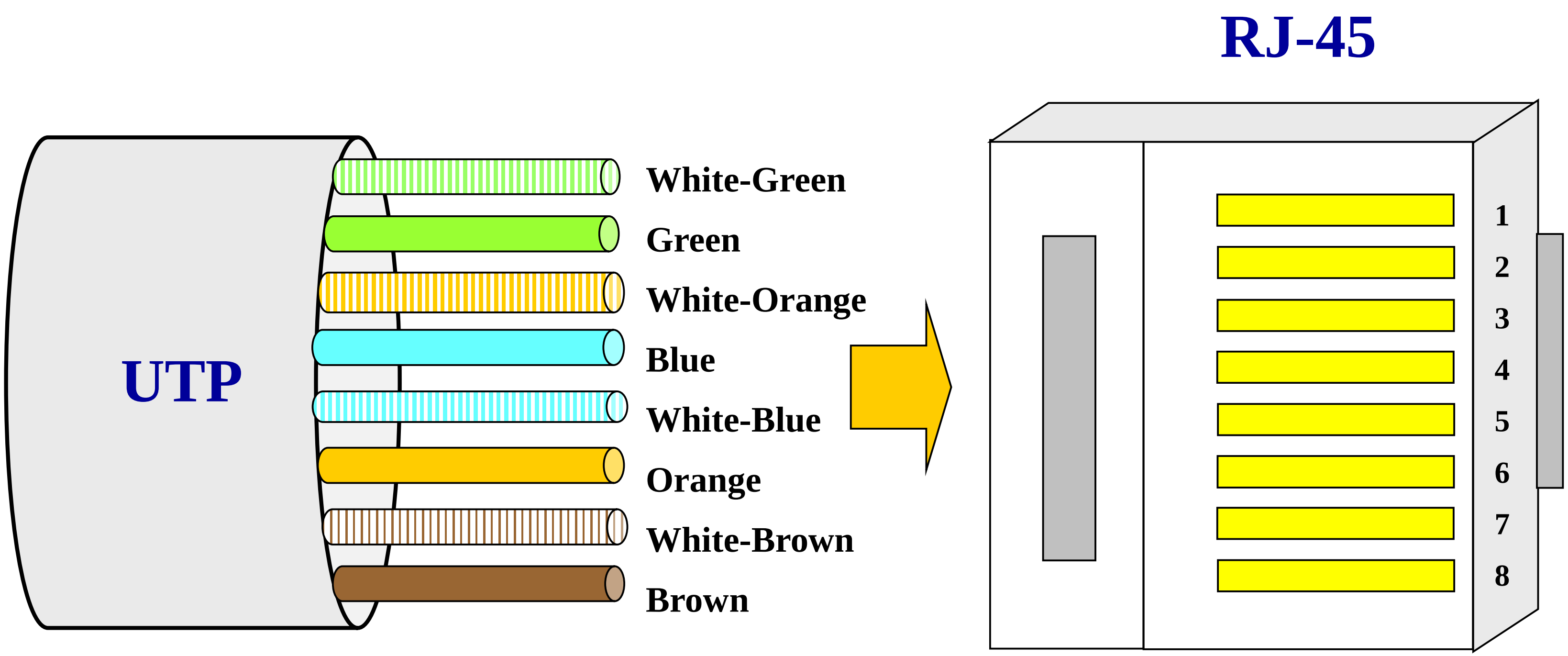


RJ-45

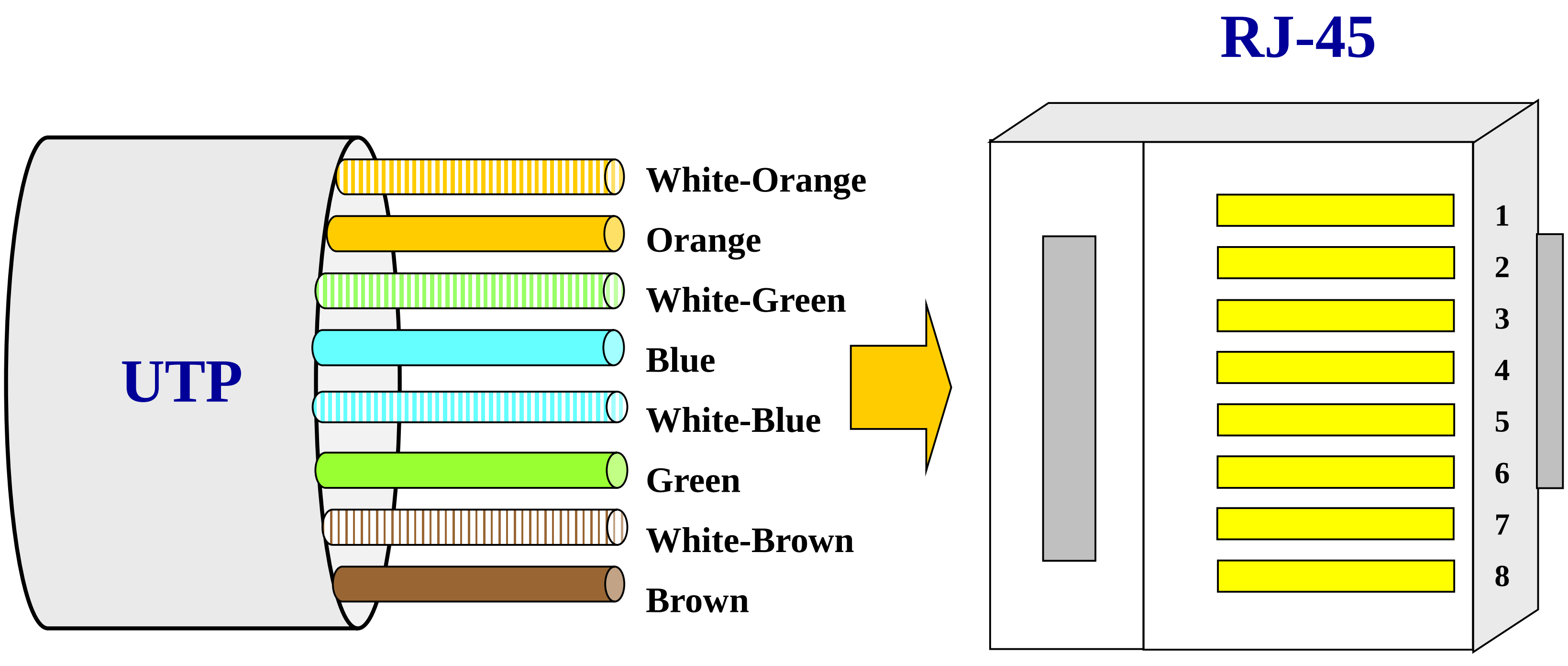


UTP

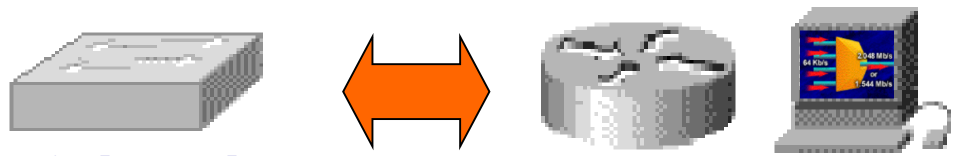
RJ-45 Termination — EIA/TIA-568A



RJ-45 Termination — EIA/TIA-568B



UTP Implementation: Straight-Through



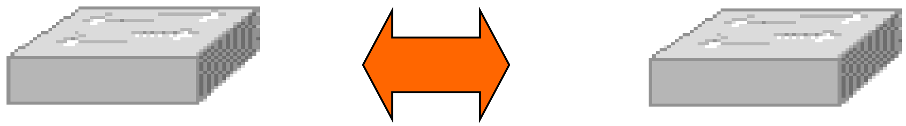
Switch / Hub

Router / Server

Pin	Function
1	RD+
2	RD-
3	TD+
4	NC
5	NC
6	TD-
7	NC
8	NC

Pin	Function
1	TD+
2	TD-
3	RD+
4	NC
5	NC
6	RD-
7	NC
8	NC

UTP Implementation: Crossover



Switch / Hub

Switch / Hub

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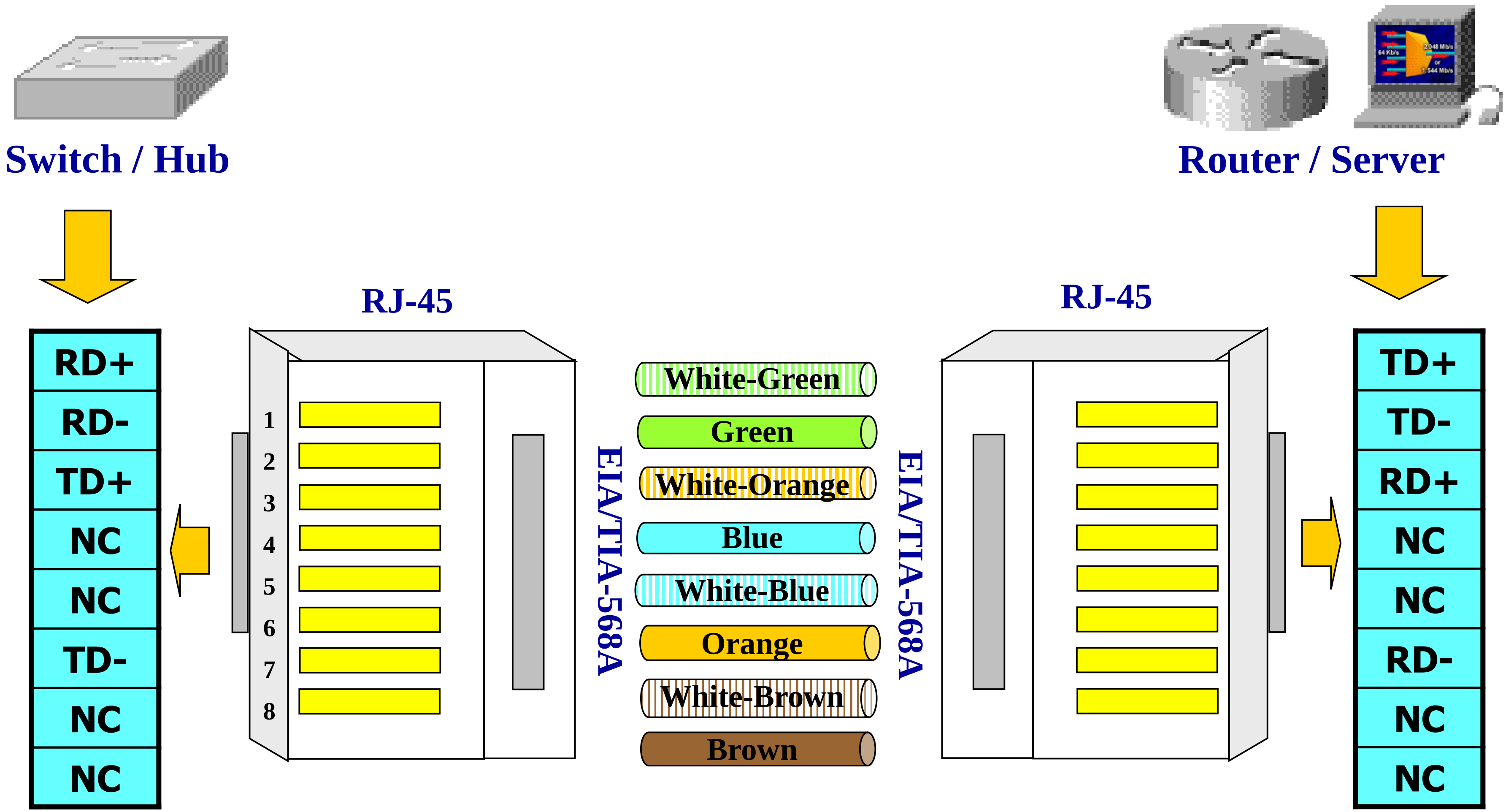

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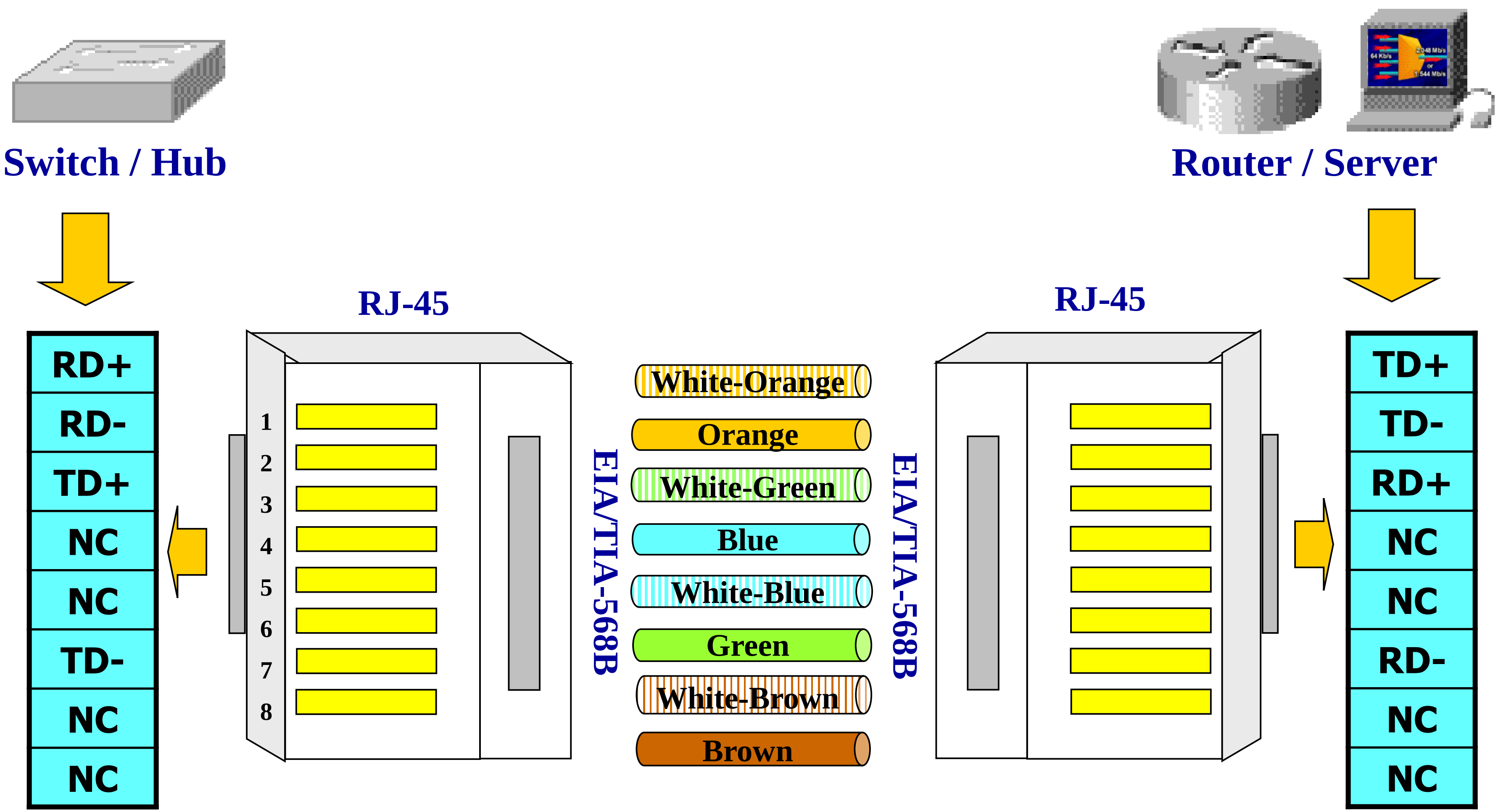

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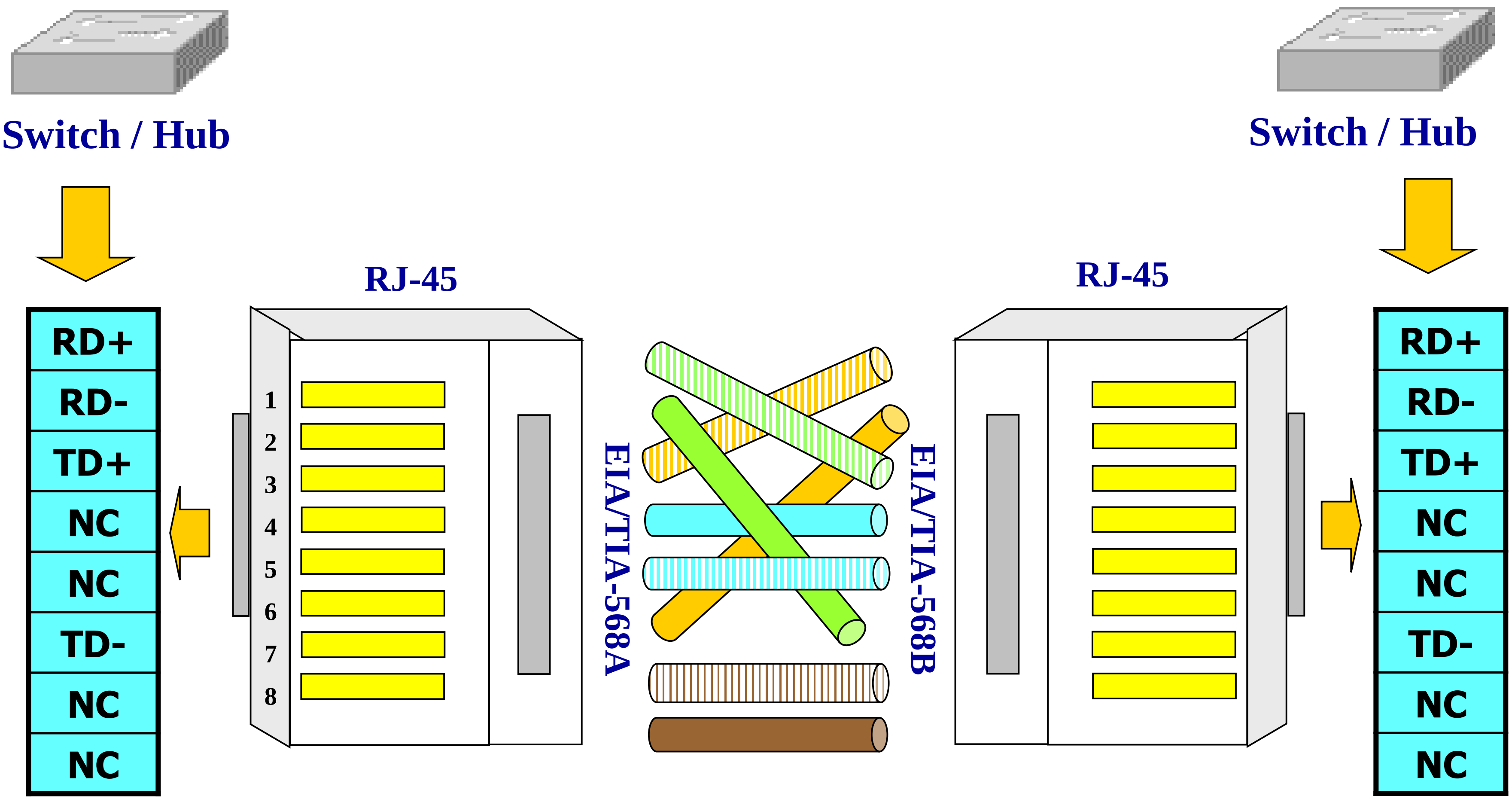
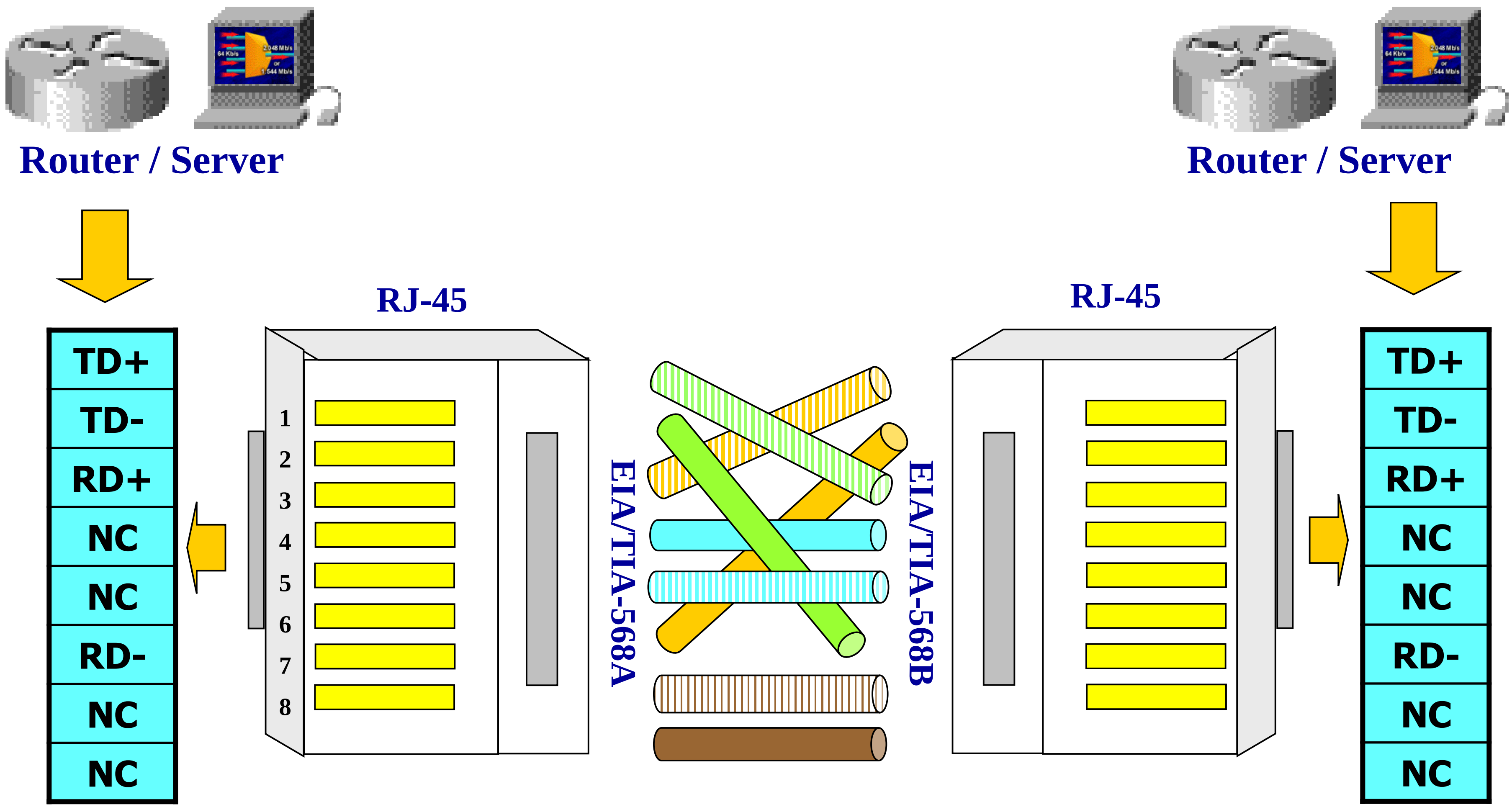
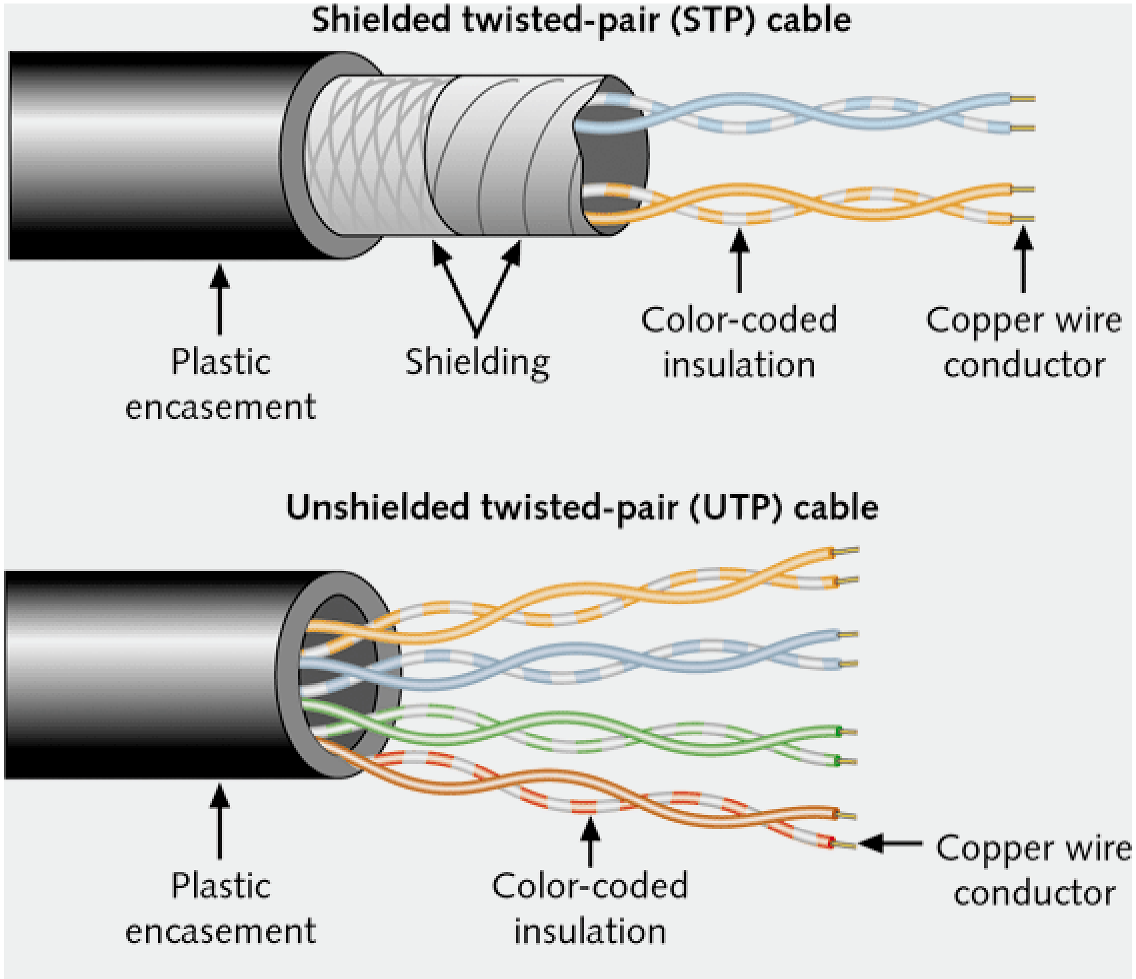


UTP Implementation: Crossover



Unshielded and Shielded TP



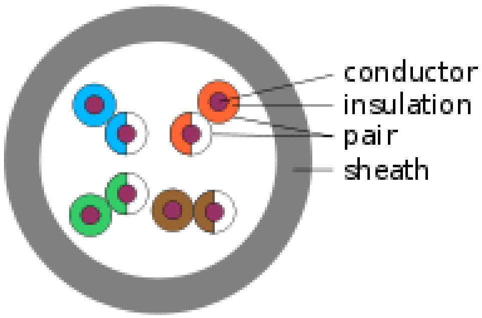
STP and UTP cable

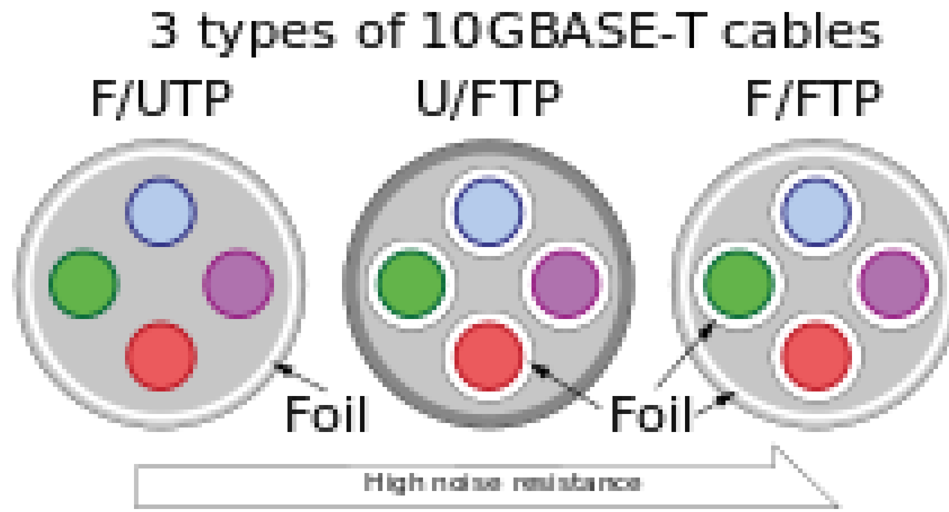
Unshielded and Shielded TP

- **Unshielded Twisted Pair (UTP)**
  - **Ordinary telephone wire**
  - **Cheapest**
  - **Easiest to install**
  - **Suffers from external EM interference**
- **Shielded Twisted Pair (STP)**
  - **Metal braid or sheathing that reduces interference**
  - **More expensive**
  - **Harder to handle (thick, heavy)**

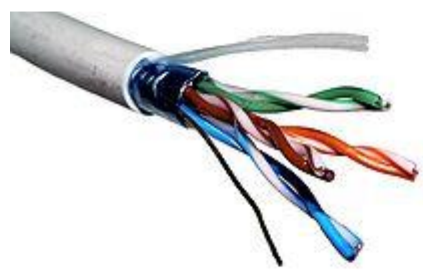
Unshielded and Shielded TP

UTP

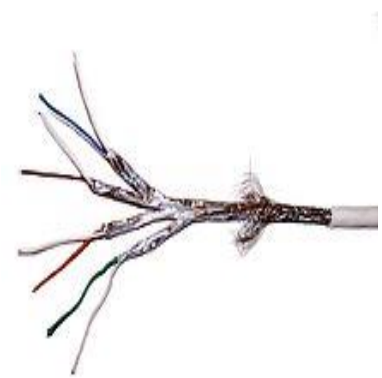




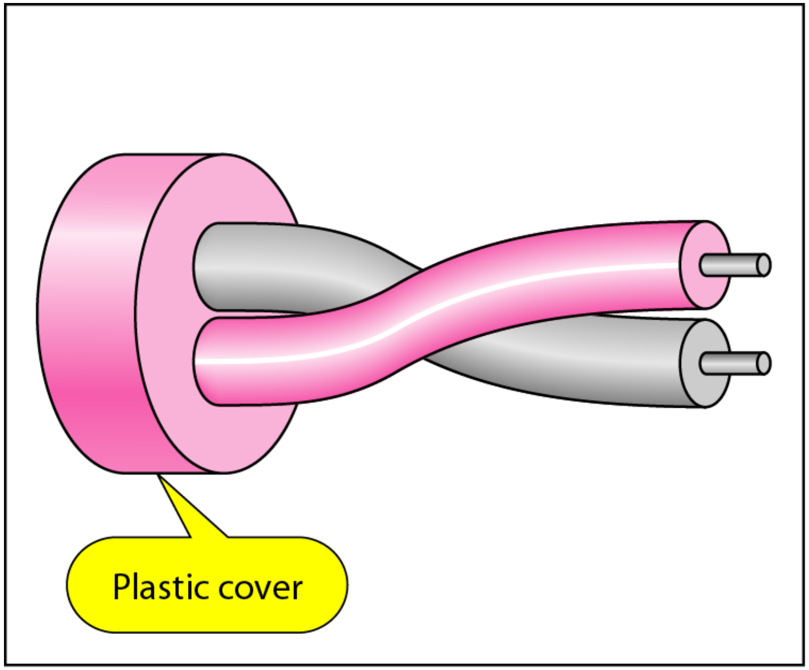
UTP



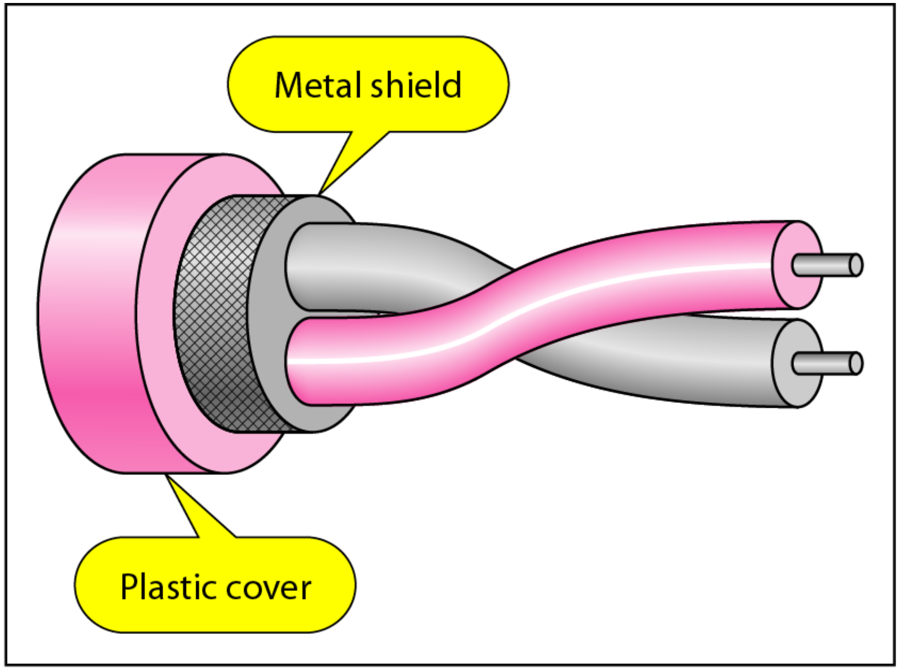
F/UTP



Unshielded and Shielded TP



a. UTP



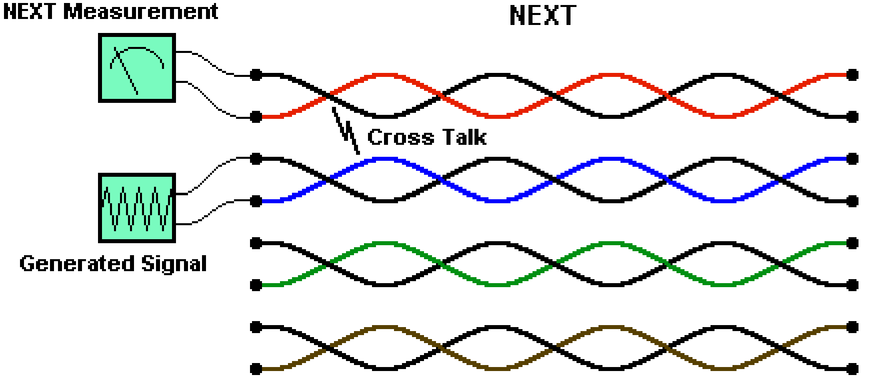
b. STP

UTP Categories

Name	Typical construction	Bandwidth	Applications	Notes
Level 1		0.4 MHz	Telephone and modem lines	Not described in EIA/TIA recommendations. Unsuitable for modern systems.[7]
Level 2		4 MHz	Older terminal systems, e.g. IBM 3270	Not described in EIA/TIA recommendations. Unsuitable for modern systems.[7]
Cat.3	UTP[8]	16 MHz[8]	10BASE-T and 100BASE-T4 Ethernet[8]	Described in EIA/TIA-568. Unsuitable for speeds above 16 Mbit/s. Now mainly for telephone cables[8]
Cat.4	UTP[8]	20 MHz[8]	16 Mbit/s[8] Token Ring	Not commonly used[8]
Cat.5	UTP[8]	100 MHz[8]	100BASE-TX & 1000BASE-T Ethernet[8]	Common in most current LANs[8]
Cat.5e	UTP[8]	100 MHz[8]	100BASE-TX & 1000BASE-T Ethernet[8]	Enhanced Cat5. Same construction as Cat5, but with better testing standards.
Cat.6	UTP[8]	250 MHz[8]	10GBASE-T Ethernet	Most commonly installed cable in Finland according to the 2002 standard. SFS-EN 50173-1
Cat.6a	U/FTP, F/UTP	500 MHz	10GBASE-T Ethernet	Adds cable shielding. ISO/IEC 11801:2002 Amendment 2.
Cat.7	F/FTP, S/FTP	600 MHz	Telephone, CCTV, 1000BASE-TX in the same cable. 10GBASE-T Ethernet.	Fully shielded cable. ISO/IEC 11801 2nd Ed.
Cat.7a	F/FTP, S/FTP	1000 MHz	Telephone, CATV, 1000BASE-TX in the same cable. 10GBASE-T Ethernet.	Uses all four pairs. ISO/IEC 11801 2nd Ed. Am. 2.
Cat.8.1	U/FTP, F/UTP	1600-2000 MHz	Telephone, CATV, 1000BASE-TX in the same cable. 40GBASE-T Ethernet.	In development.
Cat.8.2	F/FTP, S/FTP	1600-2000 MHz	Telephone, CATV, 1000BASE-TX in the same cable. 40GBASE-T Ethernet.	In development.

Near End Crosstalk

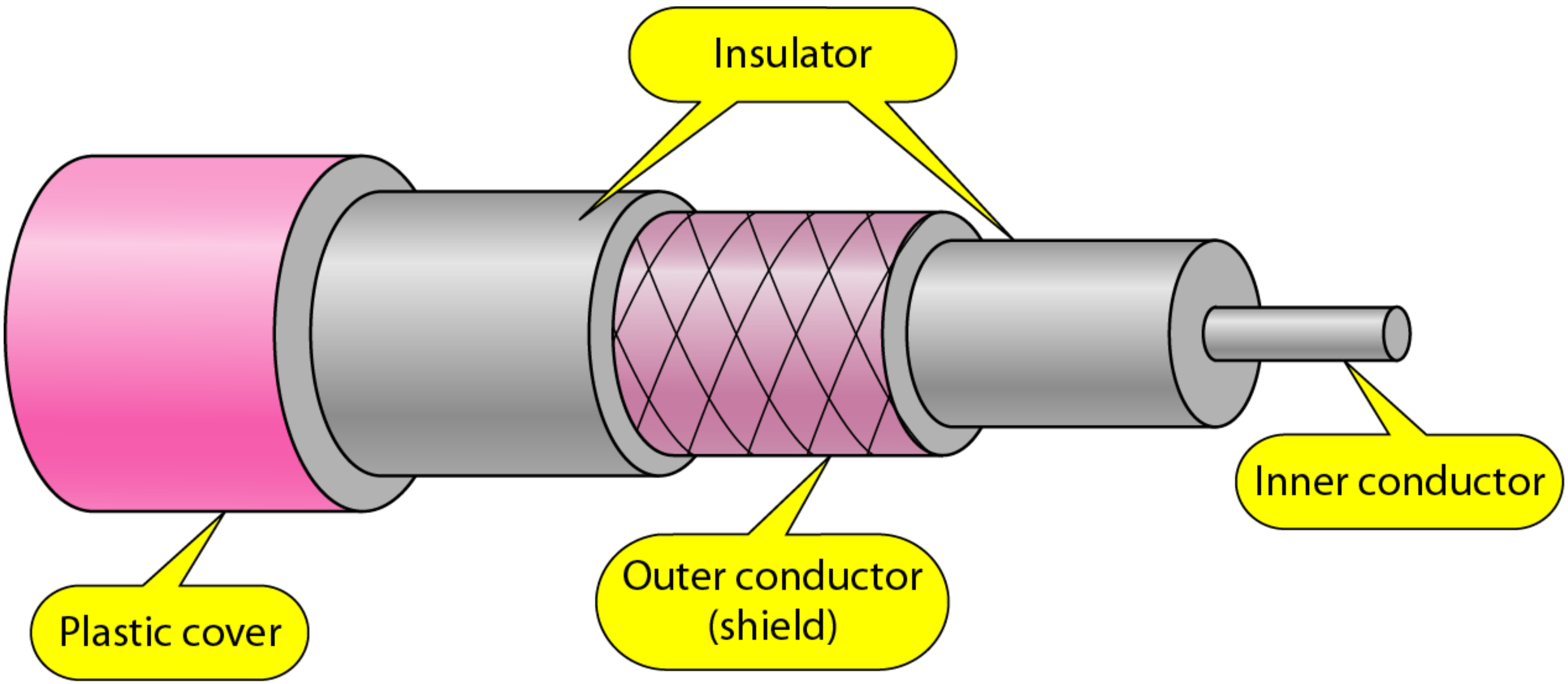
- Coupling of signal from one pair to another
- Coupling takes place when transmit signal entering the link couples back to receiving pair
- i.e. near transmitted signal is picked up by near receiving pair



Comparison of Shielded and Unshielded Twisted Pair

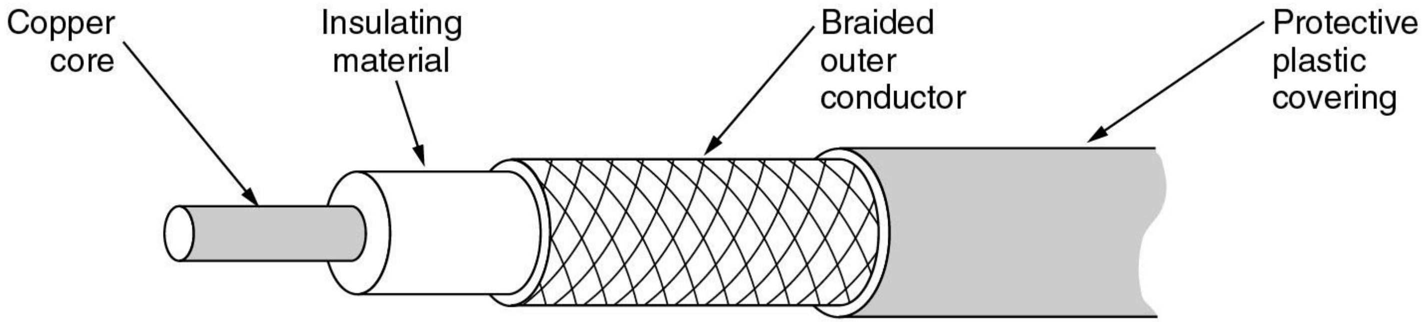
	Attenuation (dB per 100 m)			Near-end Crosstalk (dB)		
Frequency (MHz)	Category 3 UTP	Category 5 UTP	150-ohm STP	Category 3 UTP	Category 5 UTP	150-ohm STP
1	2.6	2.0	1.1	41	62	58
4	5.6	4.1	2.2	32	53	58
16	13.1	8.2	4.4	23	44	50.4
25	—	10.4	6.2	—	41	47.5
100	—	22.0	12.3	—	32	38.5
300	—	—	21.4	—	—	31.3

Coaxial Cable

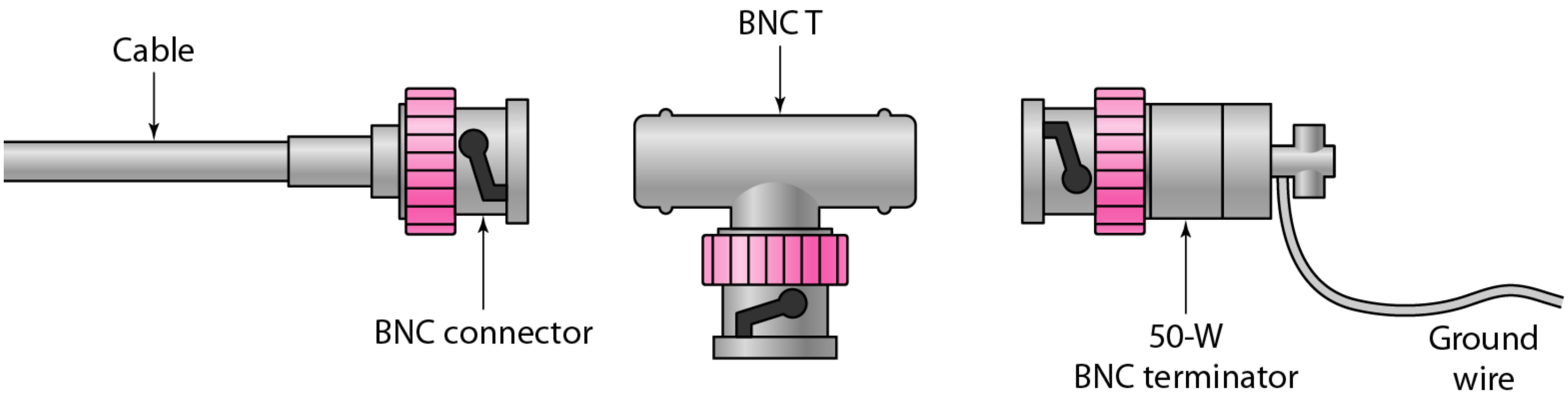


Coaxial Cable

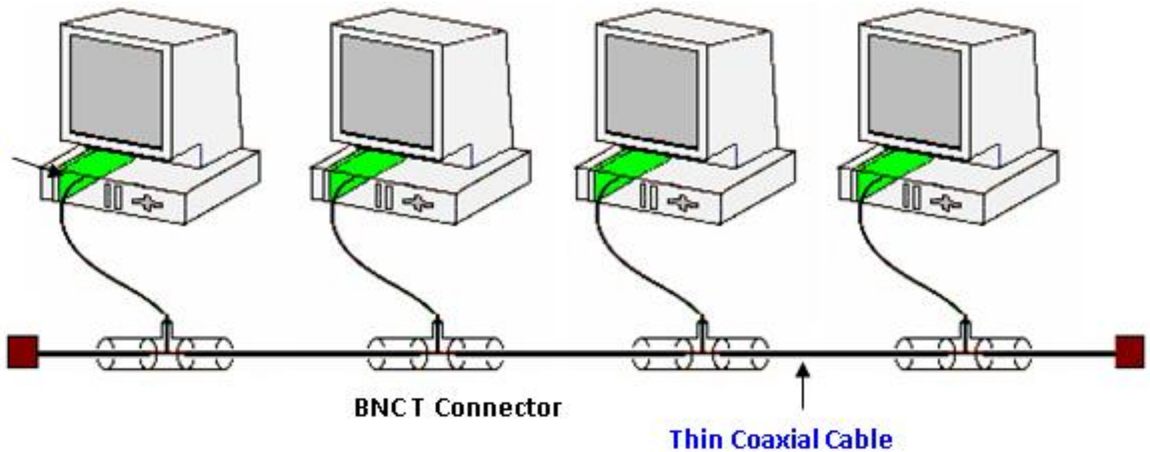
- Hollow outer cylindrical conductor that surrounds single inner wire conductor
- Inner conductor insulated by solid dielectric material
- Outer conductor covered with jacket/shield
- **Diameter between 1-2.5 cm**

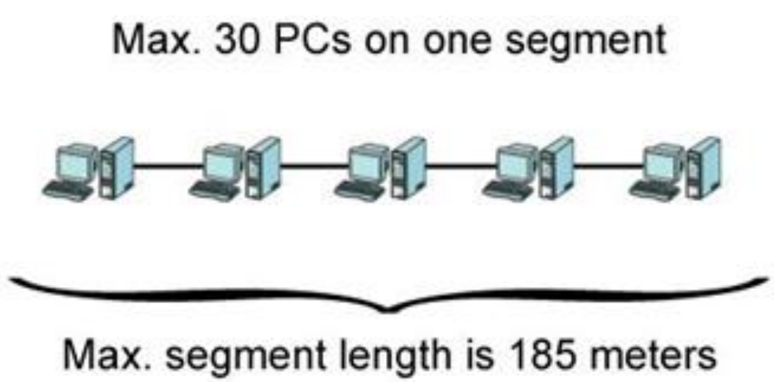


BNC Connector



Coaxial Standards – 10Base2



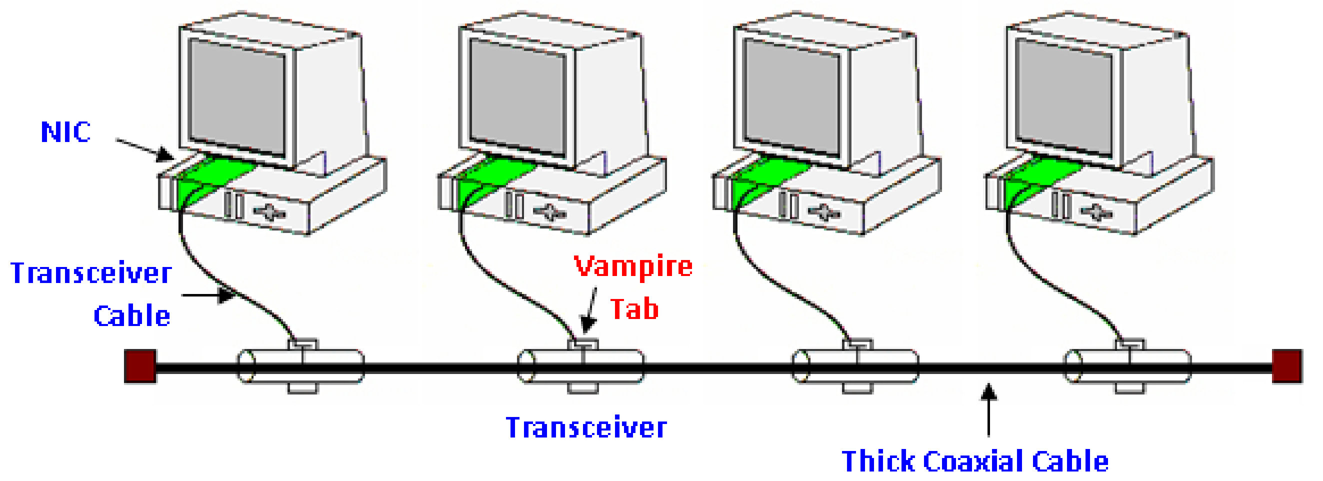


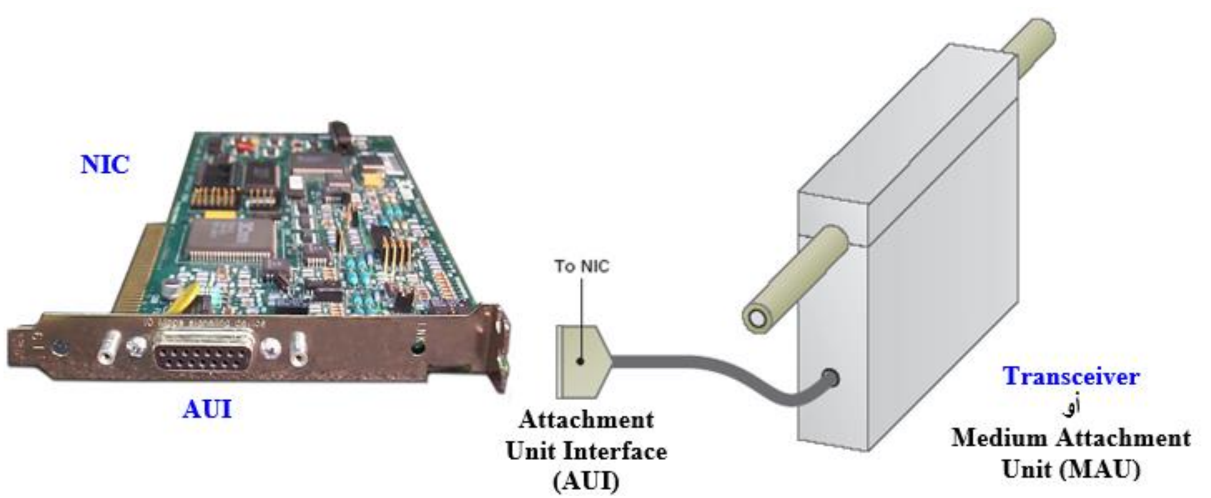
BNC

BNC T Connector

NIC

Coaxial Standards – 10Base5





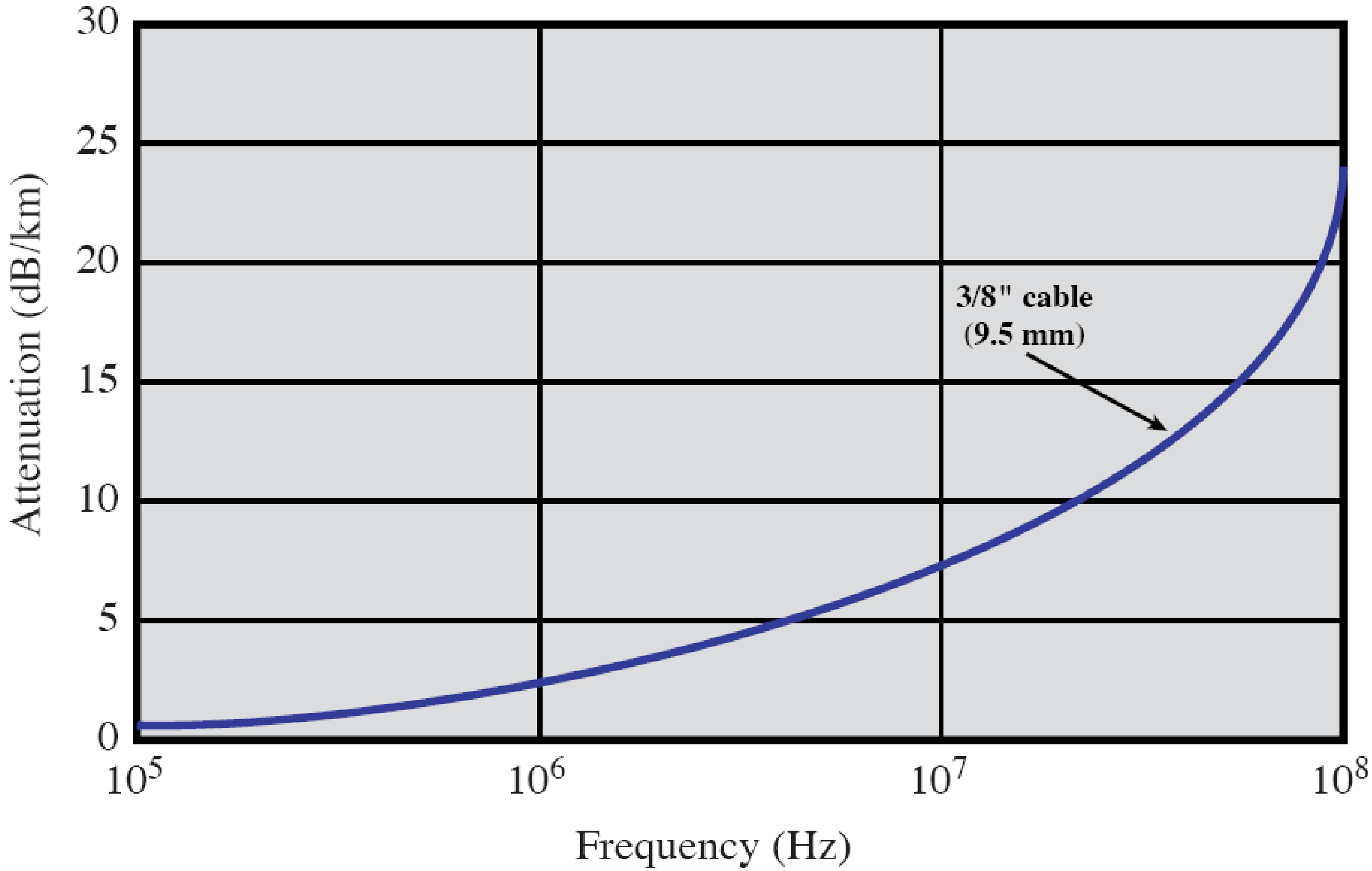
Coaxial Cable Applications

- Most versatile medium
- **Television distribution**
  - Ariel to TV
  - Cable TV
- Long distance telephone transmission
  - Can carry 10,000 voice calls simultaneously
  - Being replaced by fiber optic
- Short distance computer systems links
- Local area networks

Coaxial Cable - Transmission Characteristics

- Frequency characteristics superior to Twisted Pair
- Less susceptible to interference than Twisted Pair
- Spectrum up to 500 MHz
- Main constraint is **attenuation**
- Repeaters needed at closer distances for digital transmission at high data rates
- Analog and digital signals
- **Analog**
  - Amplifiers every few km
- **Digital**
  - Repeater every 1km

Transmission Characteristics



Transmission Characteristics Example:

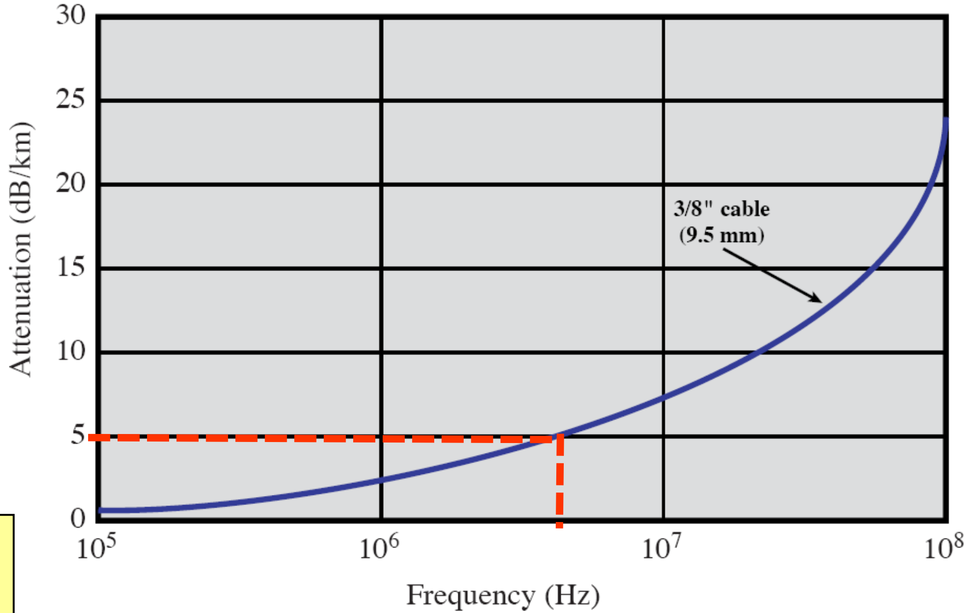
- ⌘ Assume that the Allowable power loss = 20 dB
- ⌘ Consider 0.375 inch (9.5 mm) coaxial cable operating at 7 MHz

→ Attenuation = 5dB/km

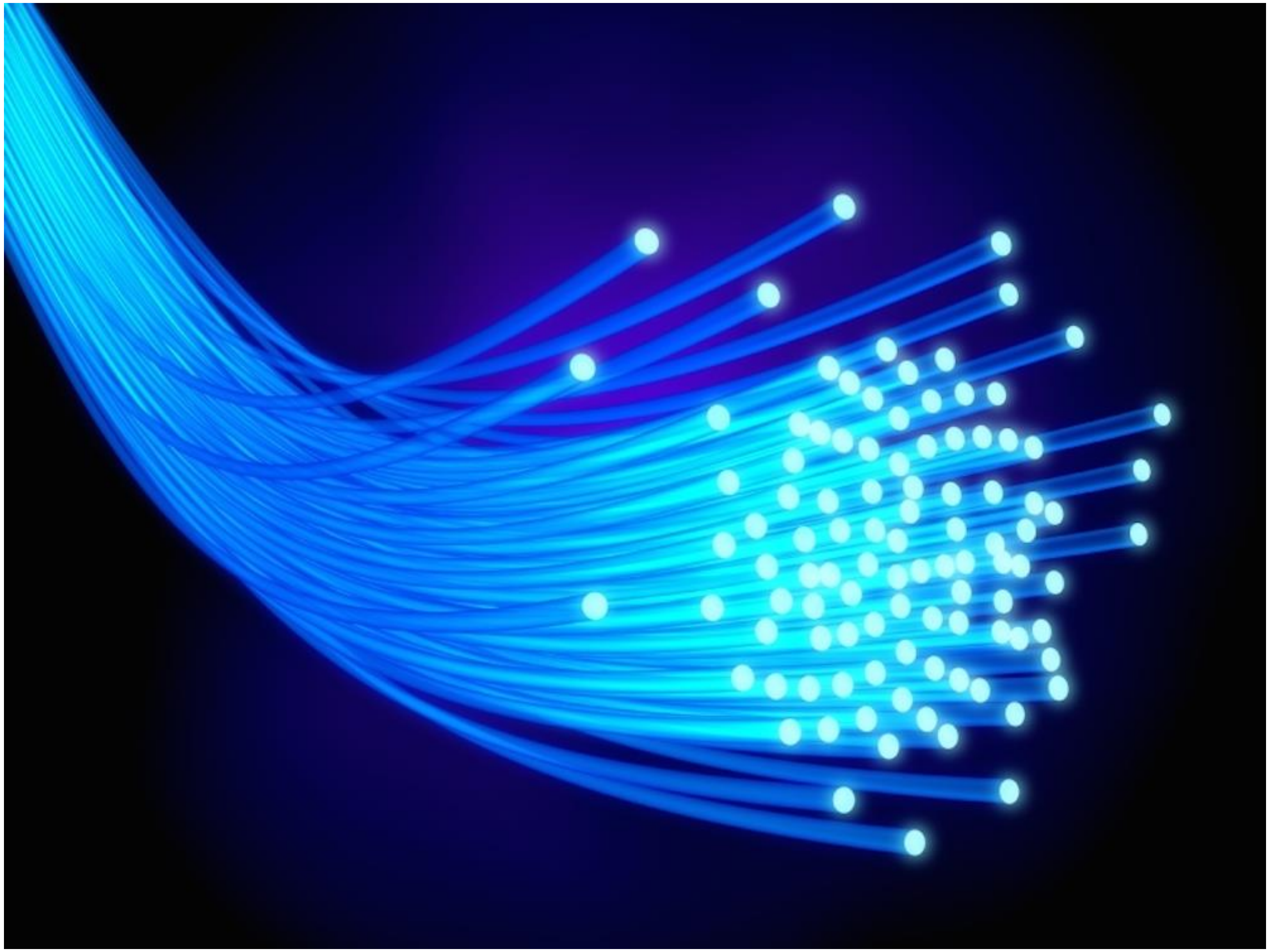
$$\text{Cable Length} = \frac{\text{Allowable Power Loss in dB}}{\text{Attenuation in dB/km}}$$

→ Cable length = 20 dB / 5 dB/km

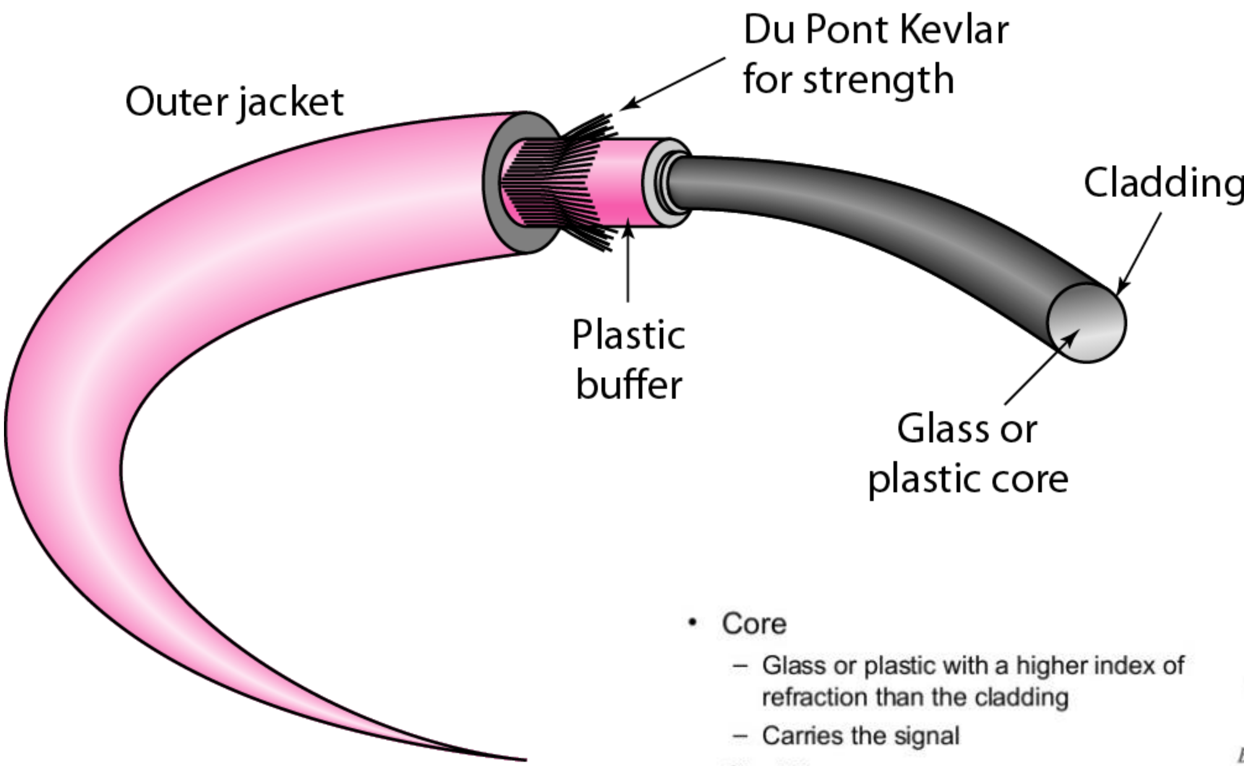
→ Cable length = 4 km



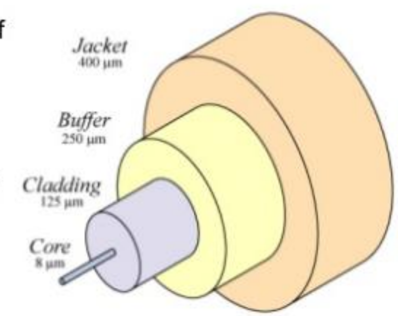
Optical Fiber



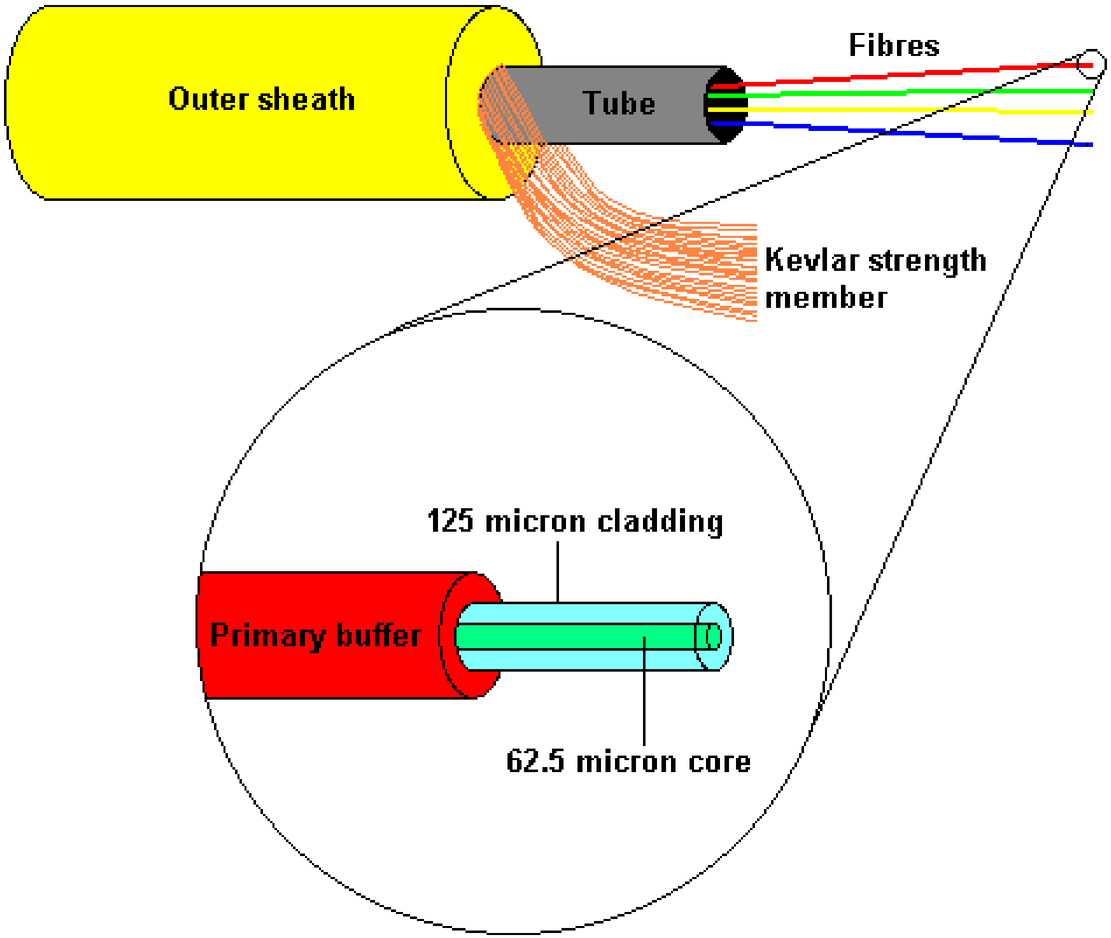
Optical Fiber



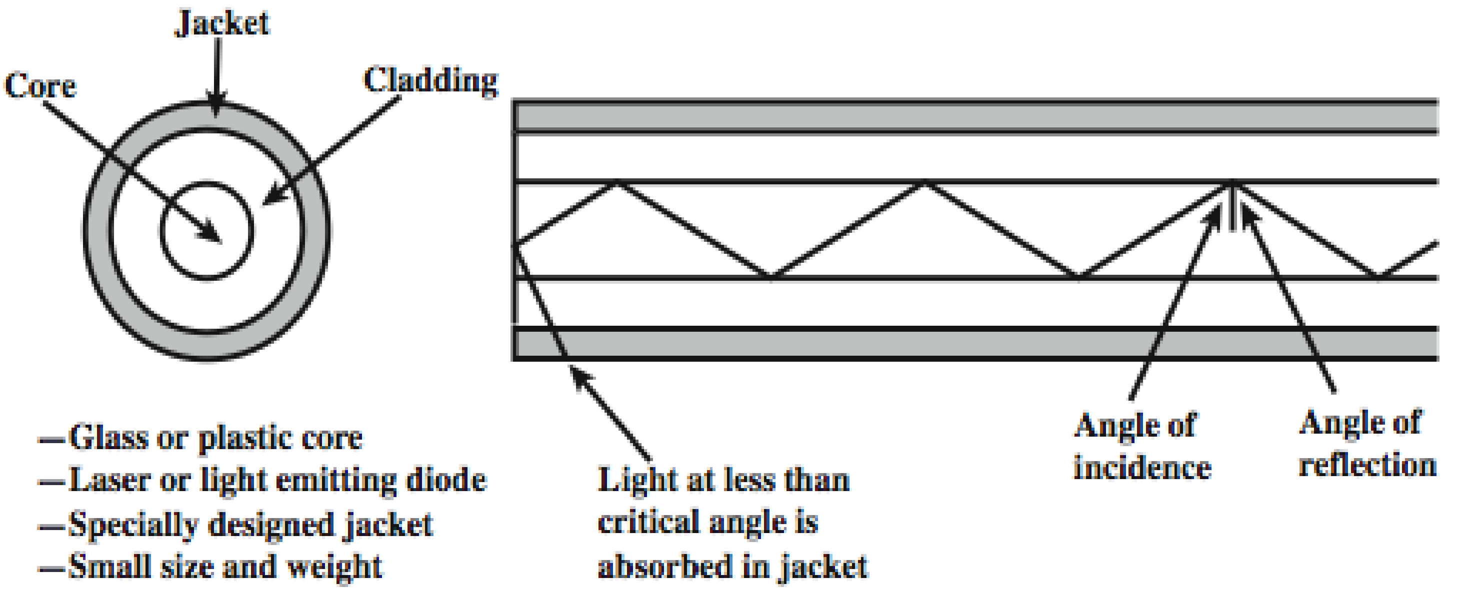
- Core
  - Glass or plastic with a higher index of refraction than the cladding
  - Carries the signal
- Cladding
  - Glass or plastic with a lower index of refraction than the core
- Buffer
  - Protects the fiber from damage and moisture
- Jacket
  - Holds one or more fibers in a cable



Optical Fiber



Optical Fiber



(c) Optical fiber

Advantages of Optical Fiber

- Greater capacity
  - Fiber: 100s of Gbps over 10s of kilometers
  - Twisted pair: 1Mbps for few kilometers, or 100 Mbps for few meters
  - Coaxial cable: 100s of Mbps for 1 km
- Smaller size and weight
- Lower attenuation

Advantages of Optical Fiber

- Electromagnetic isolation
  - not affected by external electromagnetic fields
  - do not radiate energy
- Greater security
  - difficult to tap
- Greater repeater spacing
  - 10s to 100s of kilometers

Optical Fiber - Applications

- Long-haul trunks
- Metropolitan trunks
- Rural exchange trunks
- Subscriber loops
- LANs

Optical Fiber - Light

- Light is a form of *electromagnetic* energy.

- *The speed of light depends on the density of the medium which it is travelling (the higher the density, the slower the speed)*.

- It travels at it fastest in a vacuum: 3×10^8 m/s. The speed decreases as the medium becomes denser.

Optical Fiber - Refraction

- If a ray of light travelling through one substance suddenly enters another substance, its speed changes abruptly, causing the ray to change direction. This change is called **refraction**.

- The two angles made by the beam of light in relation to the vertical axis are called I, for *incident*, and *R*, for *refracted*.

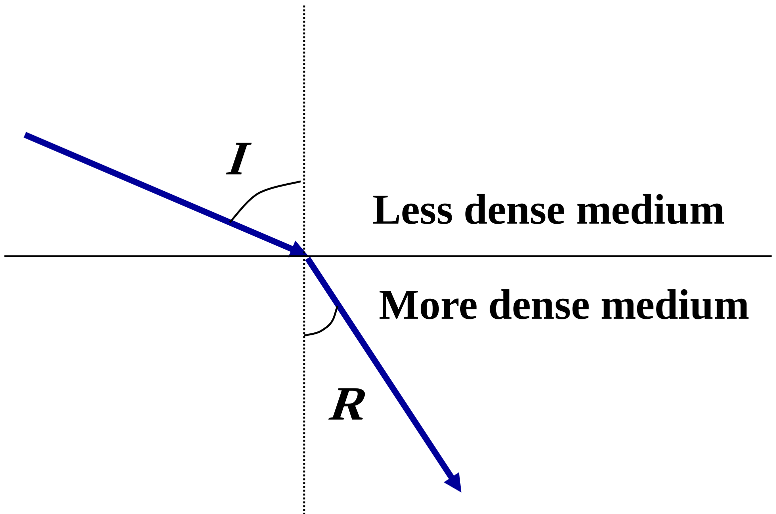
- When light travels into a **more** dense medium, *the angle of the incidence (I) is greater than the angle of refraction (R).*

- When light travels into a **less** dense medium, *the angle of the incidence (I) is less than the angle of refraction (R).*

- In the fiber-optic technology, *a glass or plastic core is surrounded by a cladding of less dense glass or plastic.*

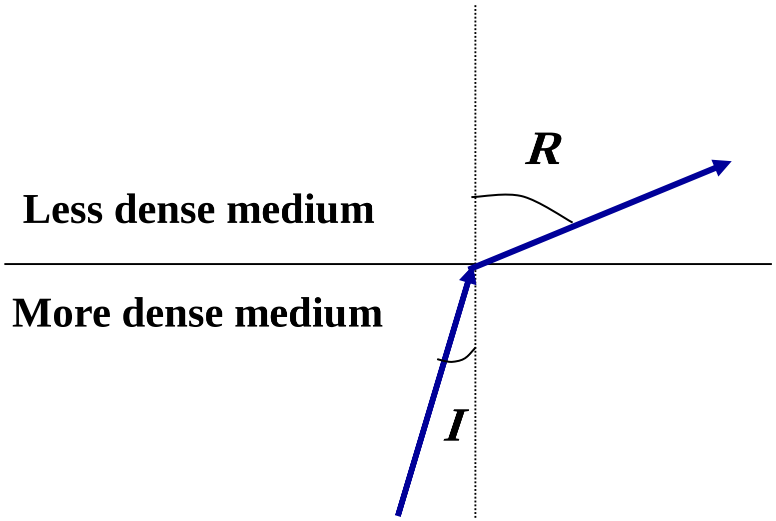
Optical Fiber - Refraction

Case 1: Refraction from less dense to more dense medium



I > *R*

Case 2: Refraction from more dense to less dense medium



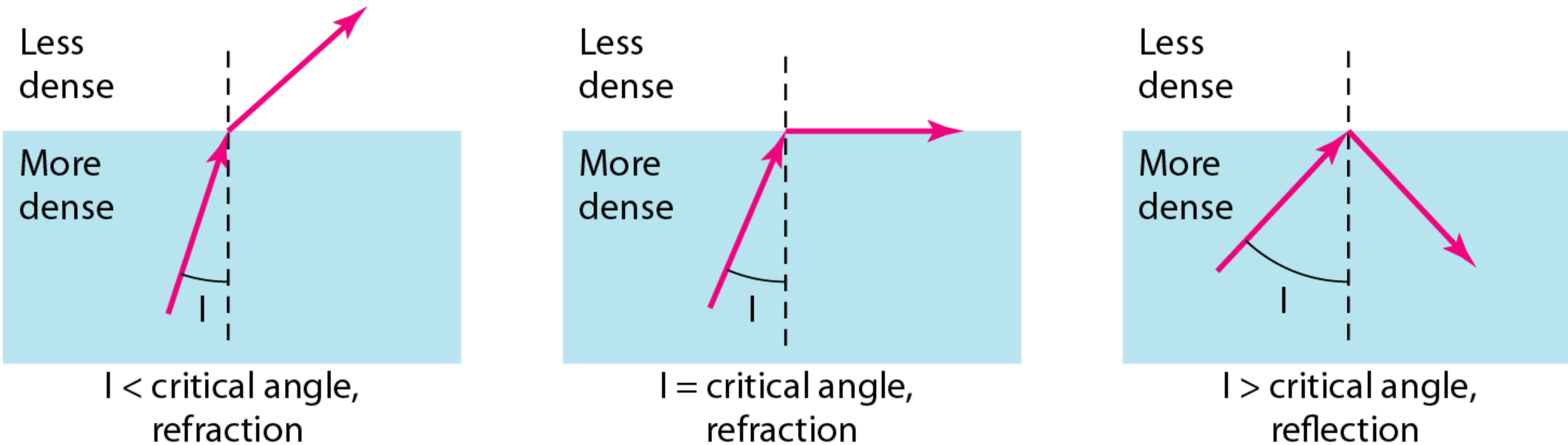
R > *I*

Optical Fiber – Critical Angle

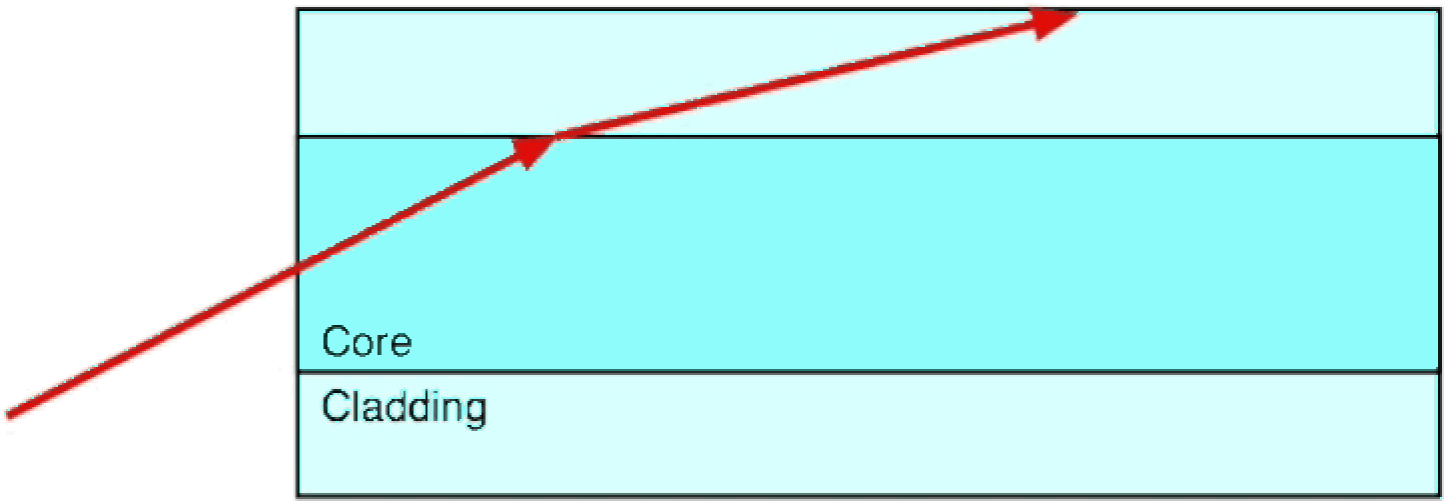
- For a beam of light travels from a more dense into a less dense medium, as the angle of incidence (*I*) increases, so does the angle of refraction (*R*). It moves away from the vertical and closer to the horizontal.

- The change in the incident angle (*I*) results in a refracted angle (*R*) of 90 degrees. The refracted beam now lying along the horizontal. This incident angle is known as the *critical angle*.

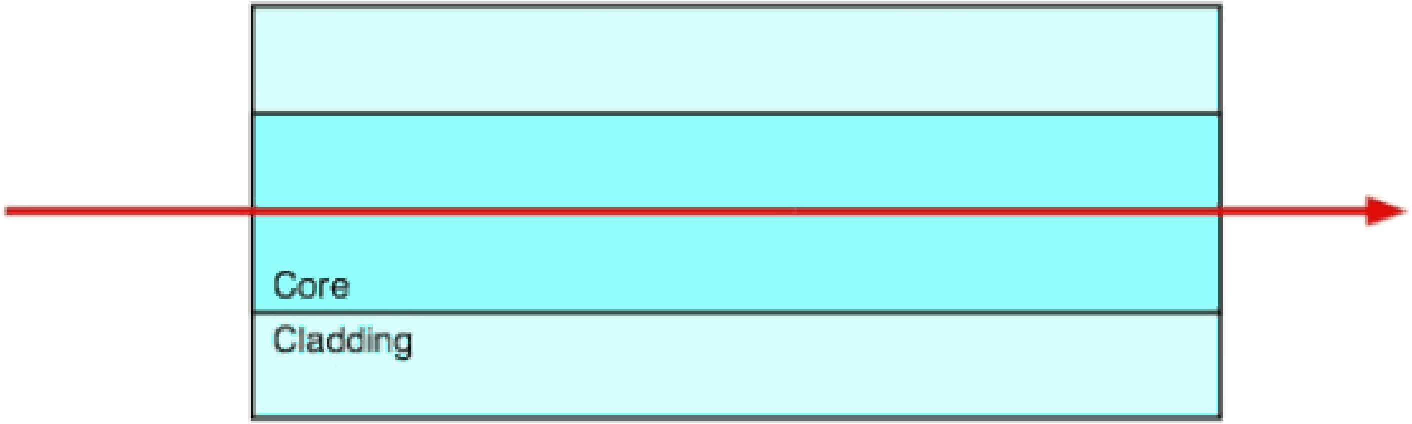
Optical Fiber – Critical Angle



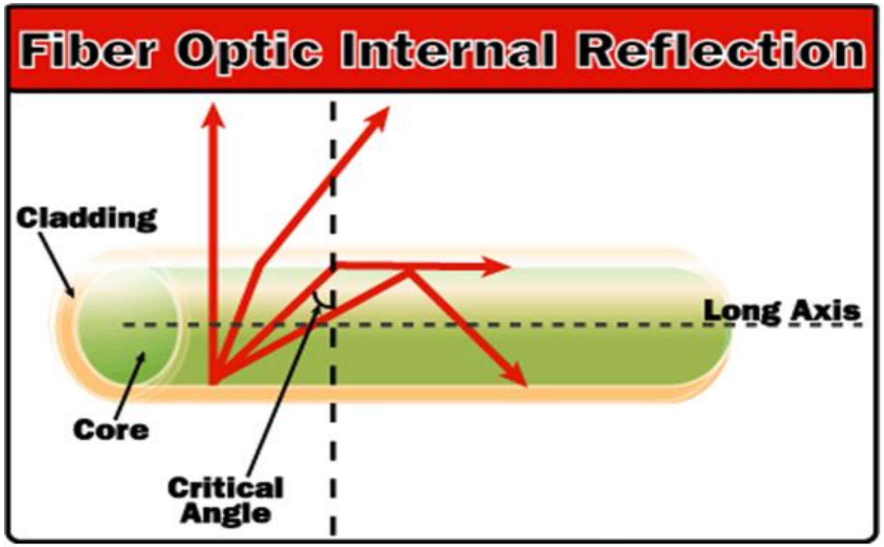
Optical Fiber

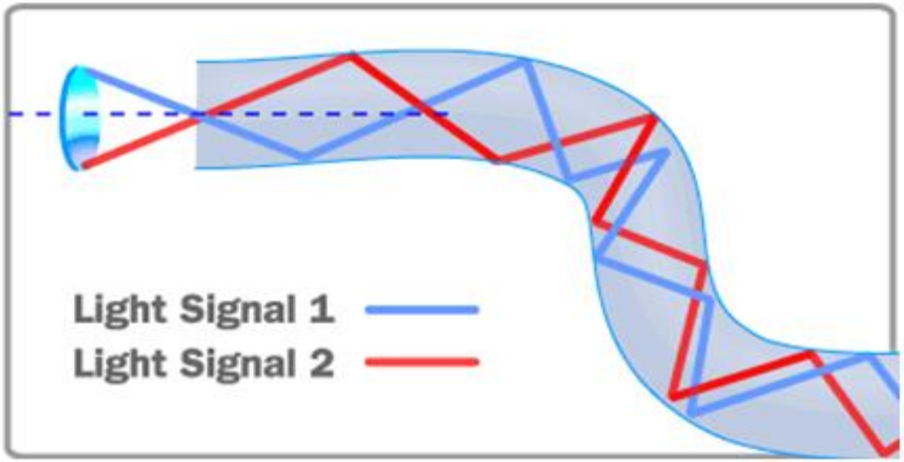


Optical Fiber



Optical Fiber

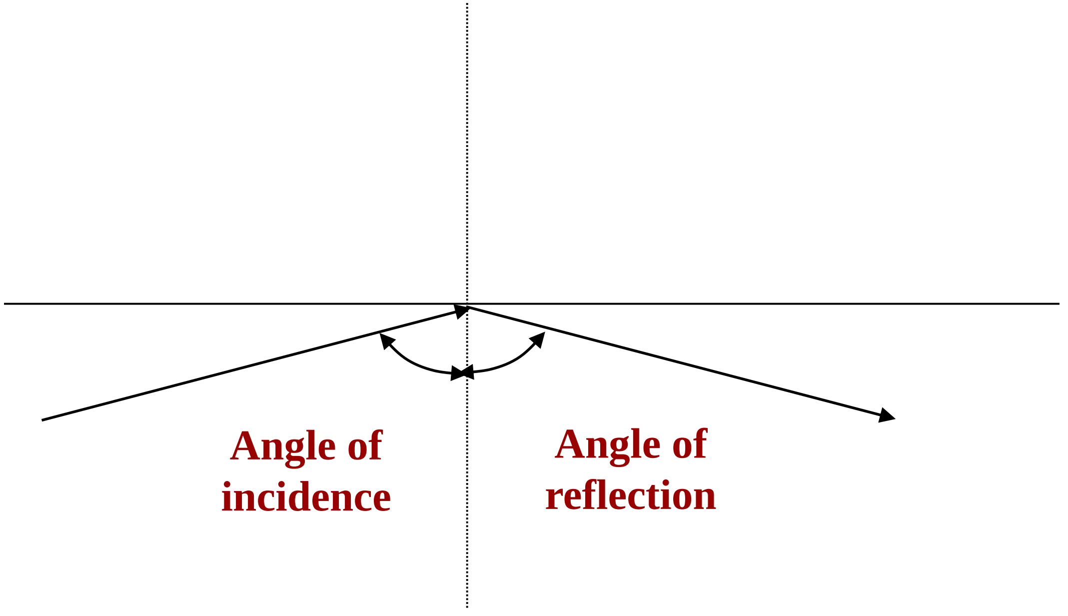




Optical Fiber – Reflection

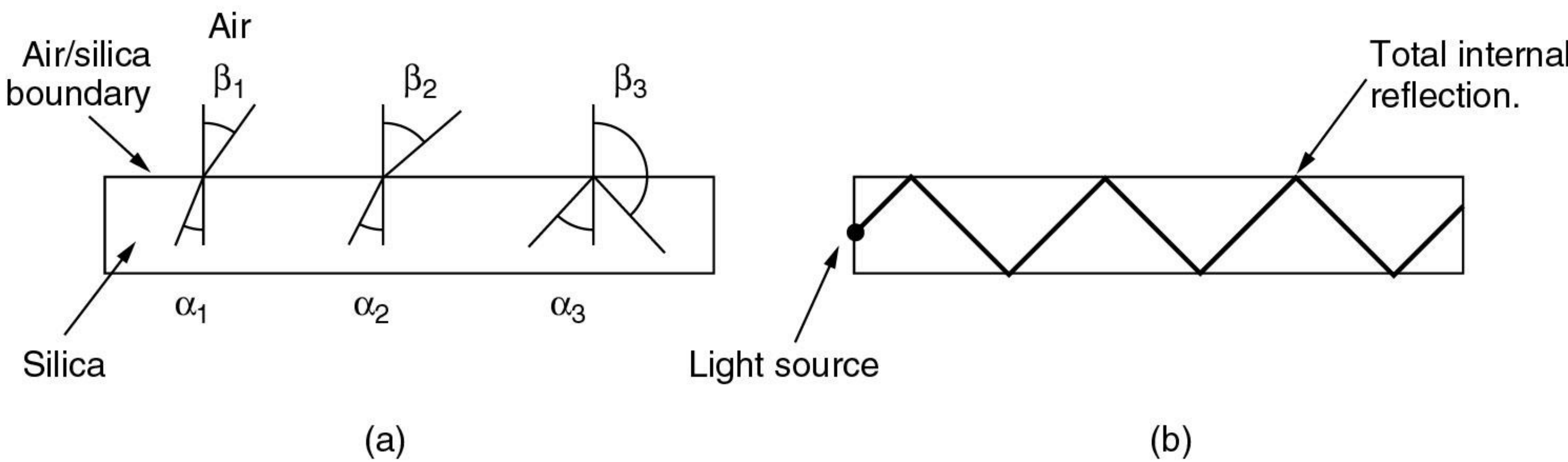
- *When the angle of incidence (I) becomes greater than the critical angle,* a *reflection* occurs. Light no longer passes into the less dense medium (cladding).
- In this case, the *angle of incidence is equal to the angle of reflection.*
- Optical fibers use reflections to *guide* light through a glass or plastic core, which is surrounded by a cladding of less dense glass or plastic.

Optical Fiber – Reflection

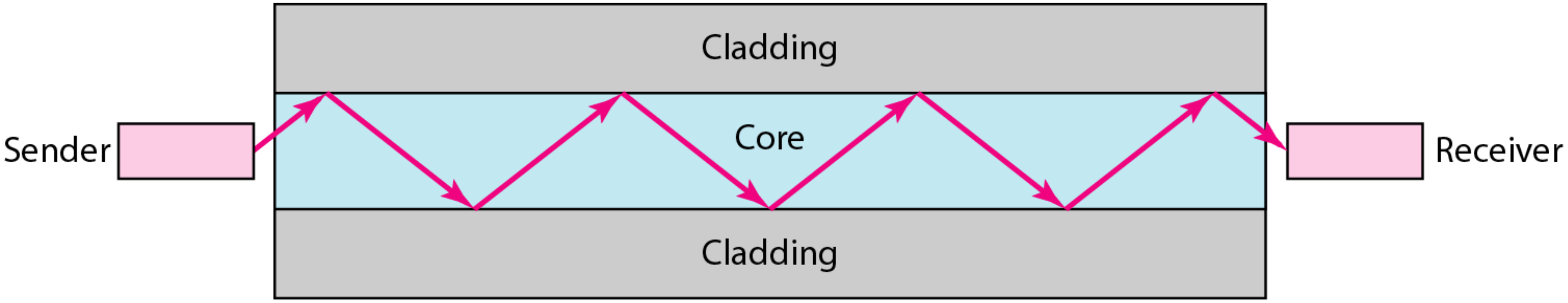


Optical Fiber – Summary

- Light propagating between two materials with different refraction index is partially reflected, partially refracted
- Light going from high refraction index material to low index material refracts with higher angle
- Beyond "critical" angle, light is totally reflected



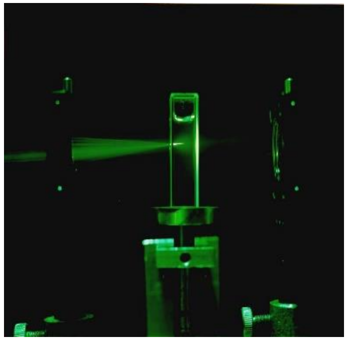
Optical Fiber



Optical Fiber - Light Sources

- **Light Emitting Diode (LED)**
  - Cheaper
  - Wider operating temp range
  - Last longer
  - Typical wavelength 850 nm

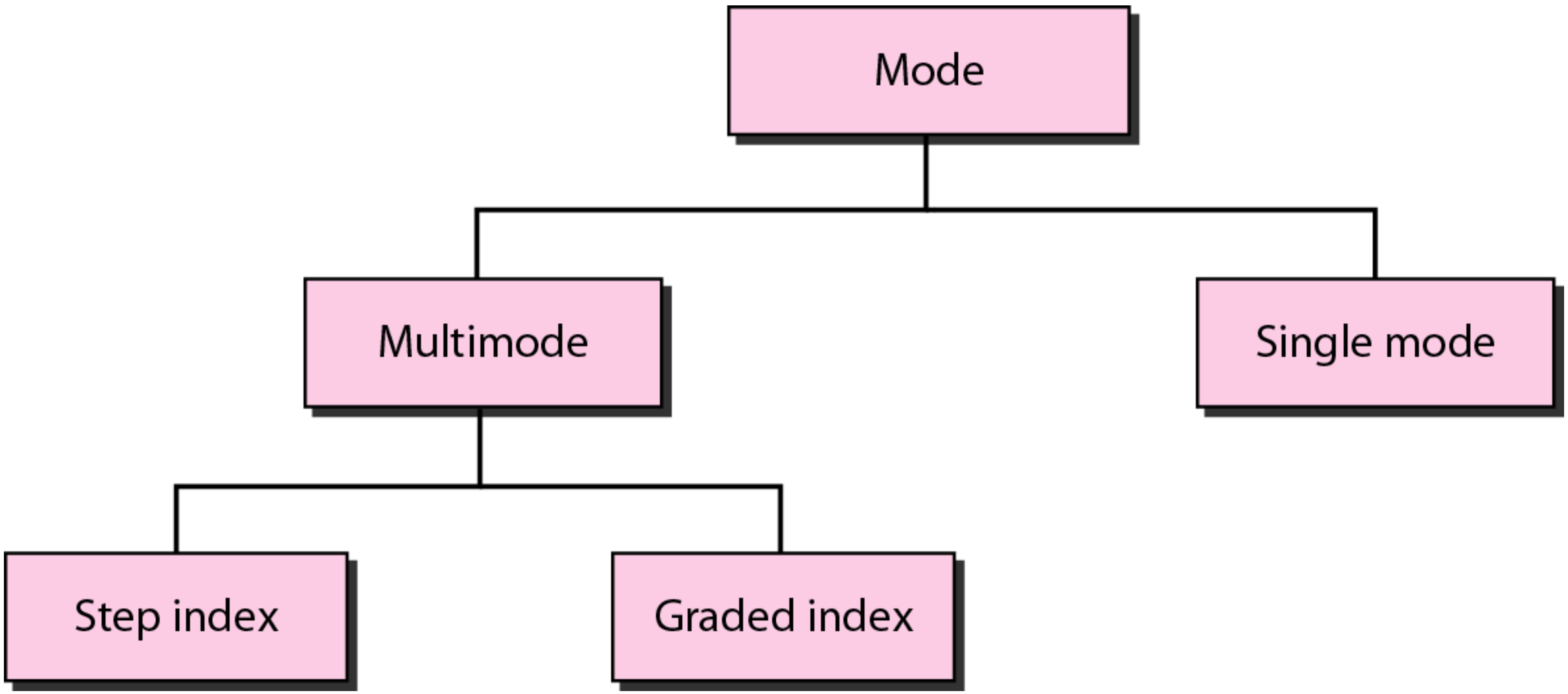
- **Injection Laser Diode (ILD)**
  - More efficient
  - Greater data rate
  - Typical wavelength 1300 - 1500 nm



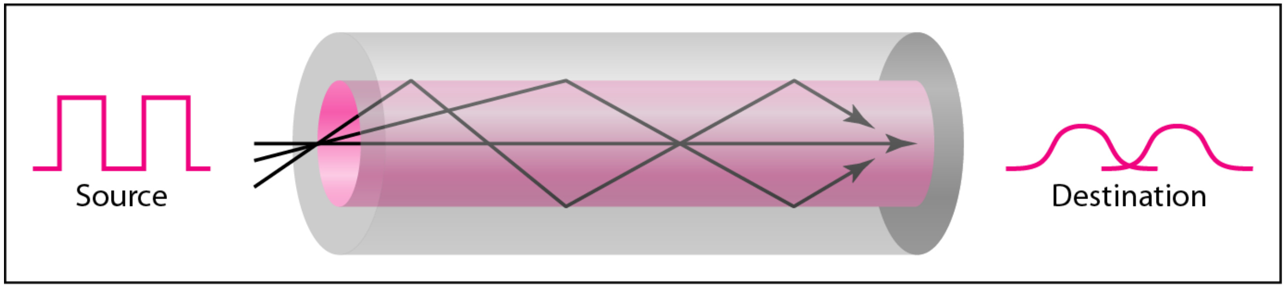
Optical Fiber – Light Sources

- Modulate electrical signals into **optical signals**
- Mostly modulate at **850nm**, **1300nm** and **1550 nm**
- **Lasers** give high intensity, high frequency light
- **LEDs** are economical

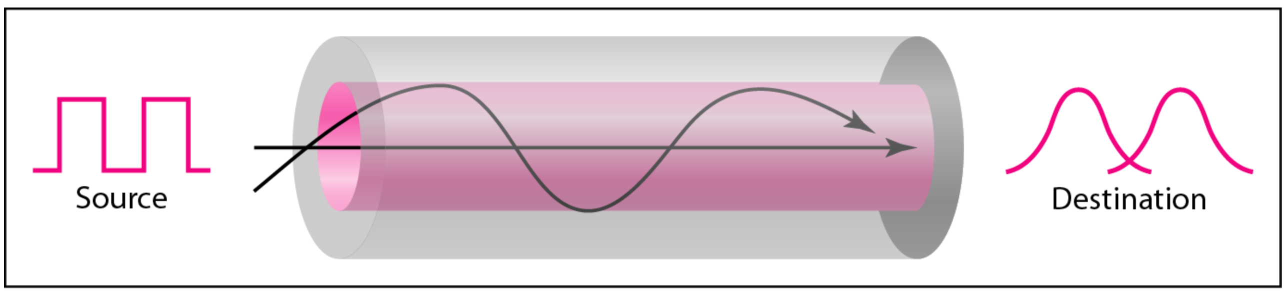
Optical Fiber - Transmission Modes



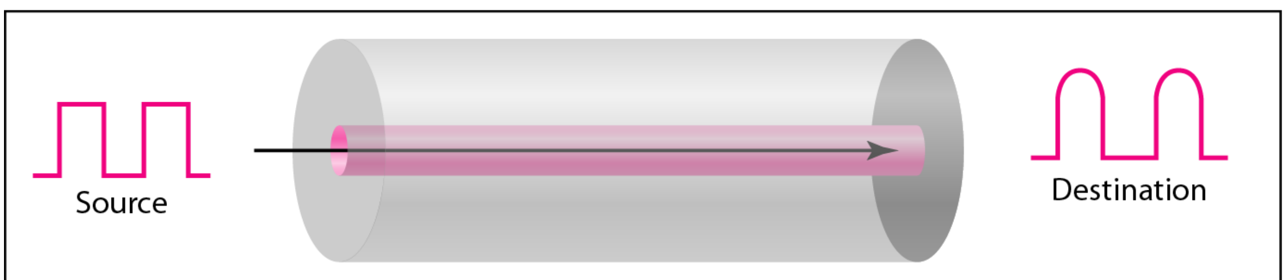
Optical Fiber - Transmission Modes



a. Multimode, step index

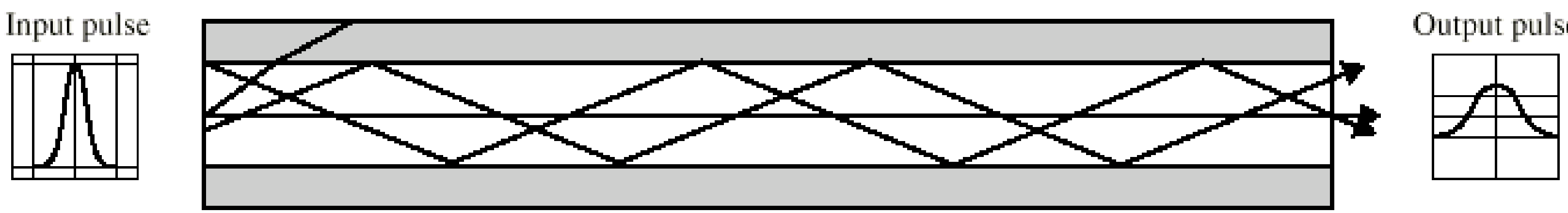


b. Multimode, graded index

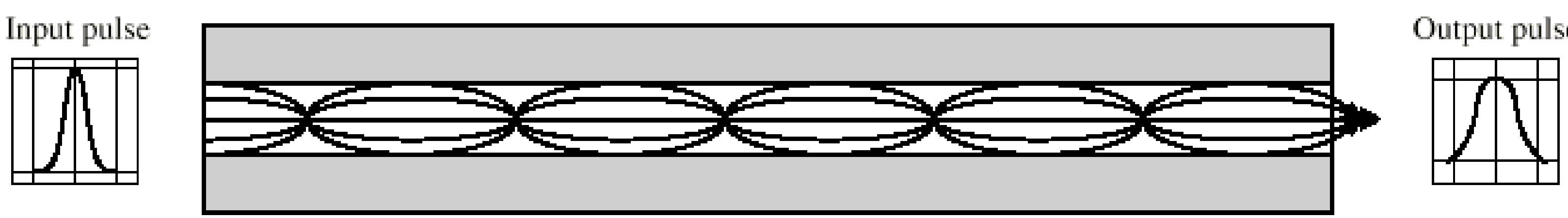


c. Single mode

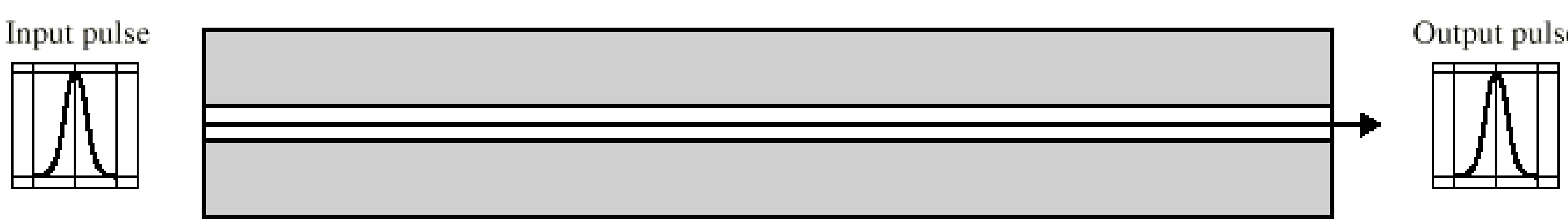
Optical Fiber - Transmission Modes



(a) Step-index multimode



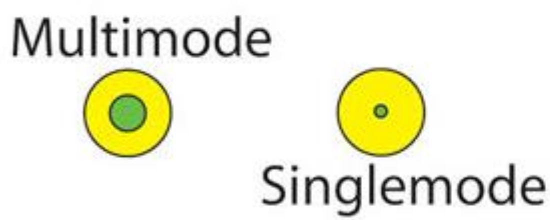
(b) Graded-index multimode



(c) Single mode

Fiber Types

- Step-index multimode
- Graded-index multimode
- Single mode



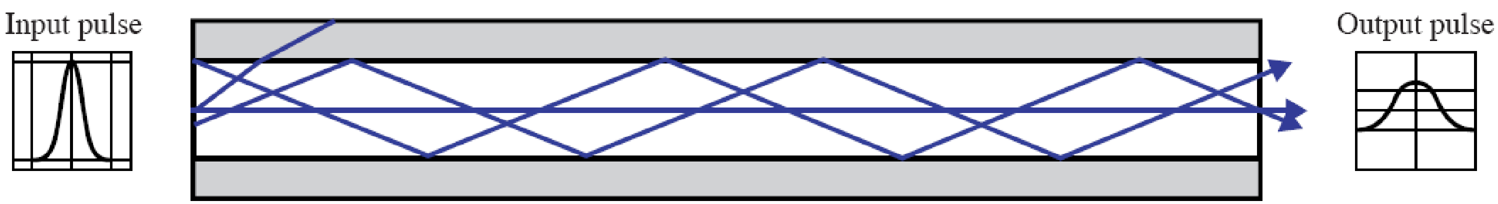
Relative sizes of all fibers

Comparison of core/cladding sizes

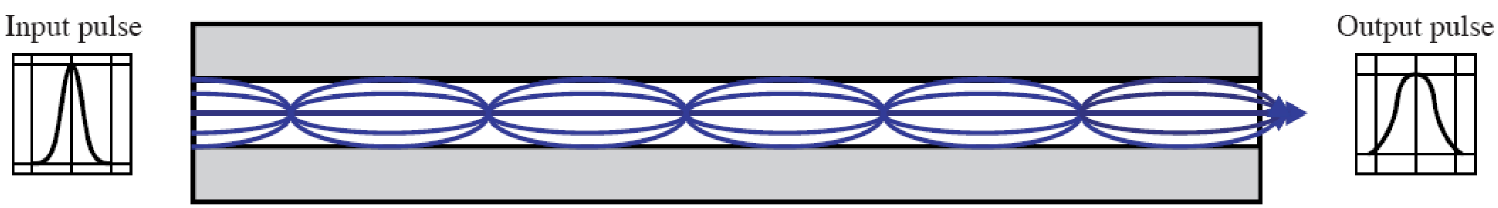
Fiber Types

Type	*Core (μm)*	*Cladding (μm)*	*Mode*
50/125	50.0	125	Multimode, graded index
62.5/125	62.5	125	Multimode, graded index
100/125	100.0	125	Multimode, graded index
7/125	7.0	125	Single mode

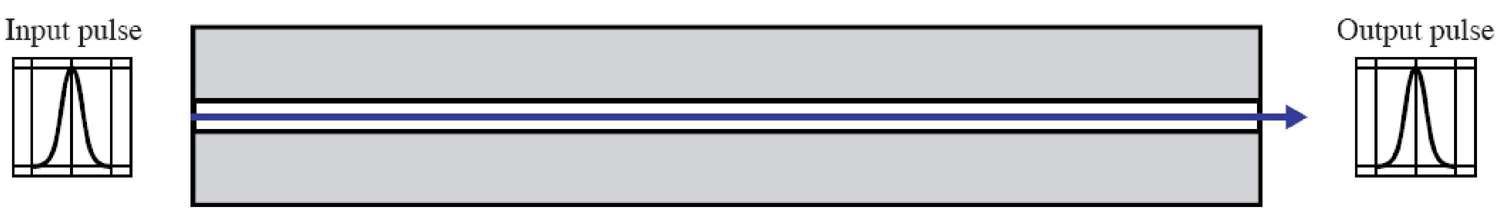
Fiber Types



(a) Step-index multimode

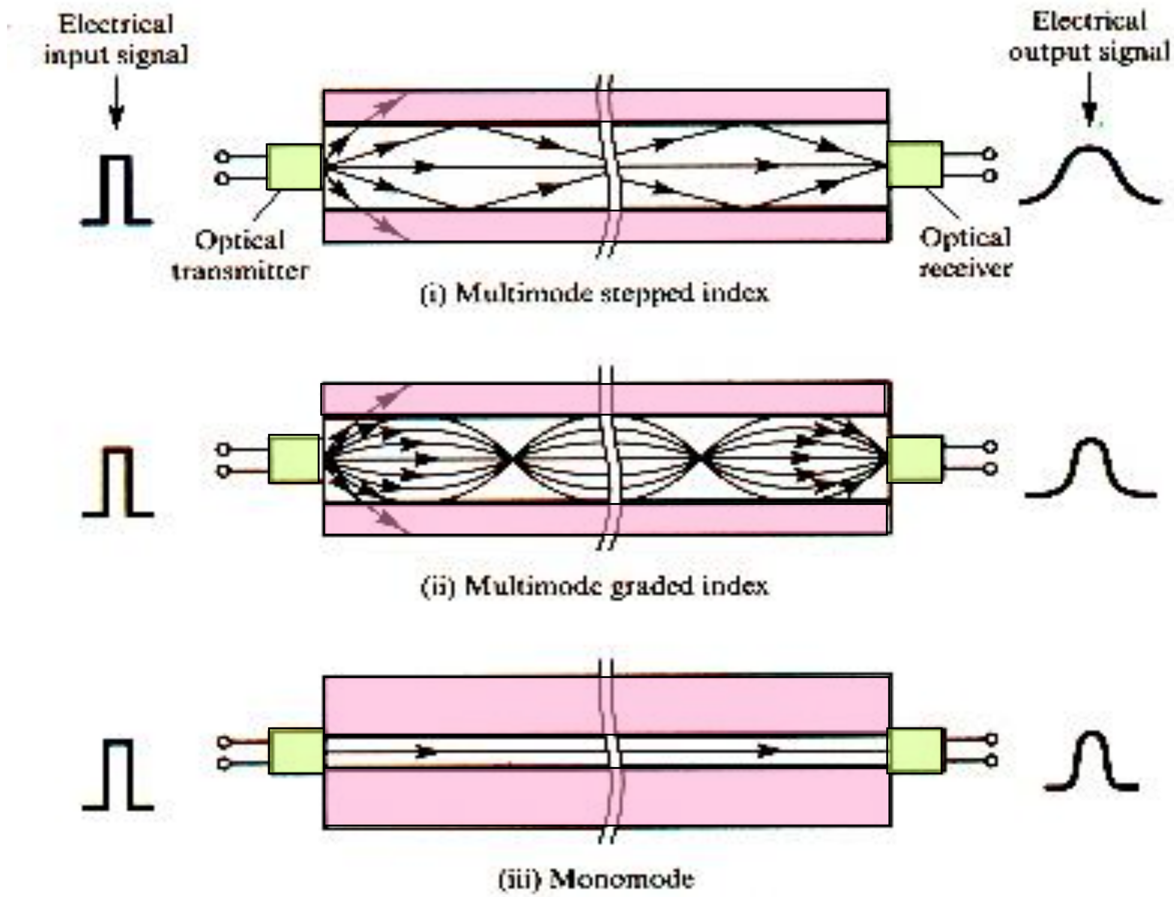


(b) Graded-index multimode



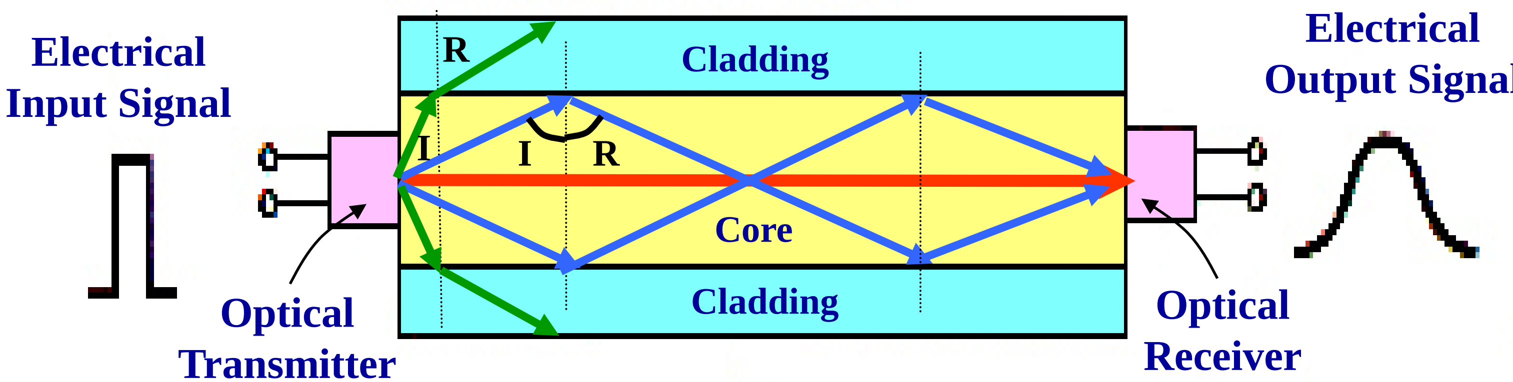
(c) Single mode

Fiber Types



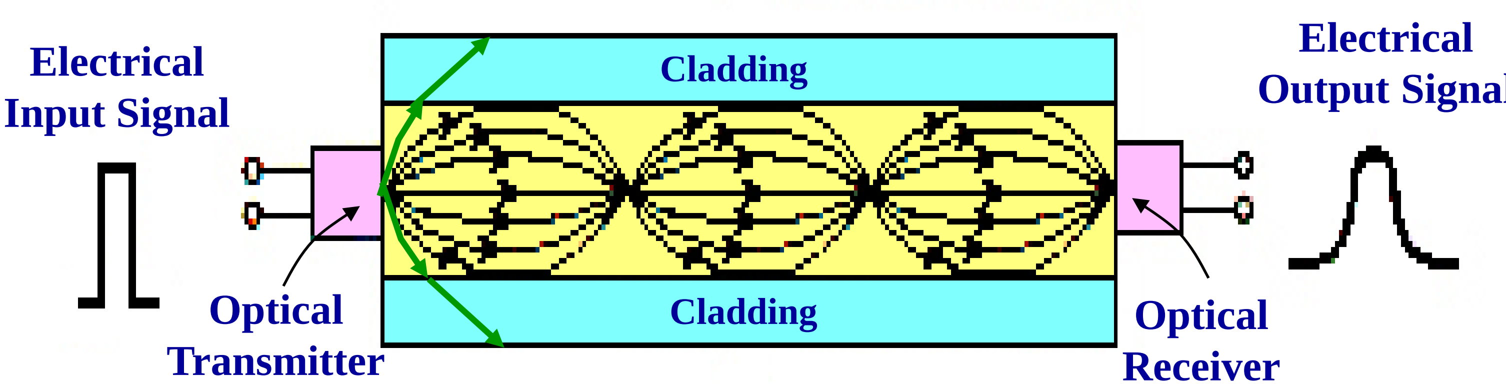
Electrical input signal
Electrical output signal
Optical transmitter
Optical receiver
(i) Multimode stepped index
(ii) Multimode graded index
(iii) Monomode

Multimode Step-Index Fiber



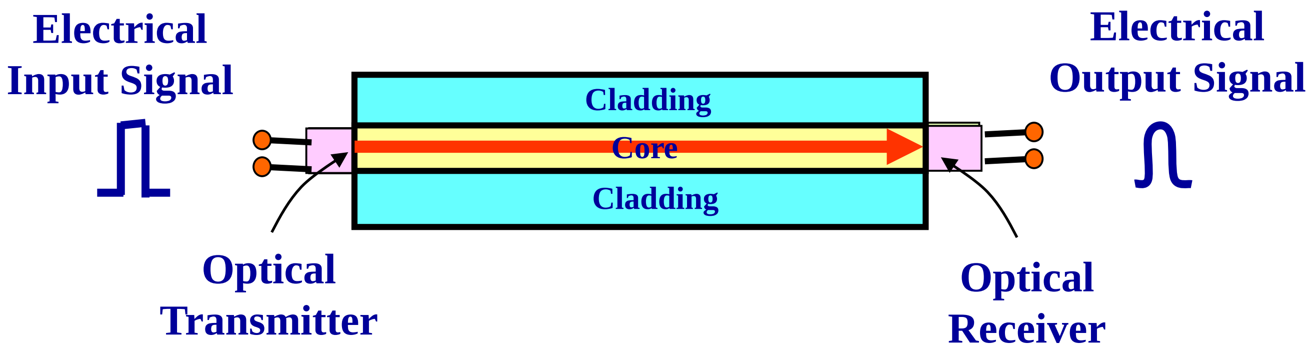
Multimode Step-Index Fiber

Multimode Graded-Index Fiber



Multimode Graded-Index Fiber

Single-Mode Fiber

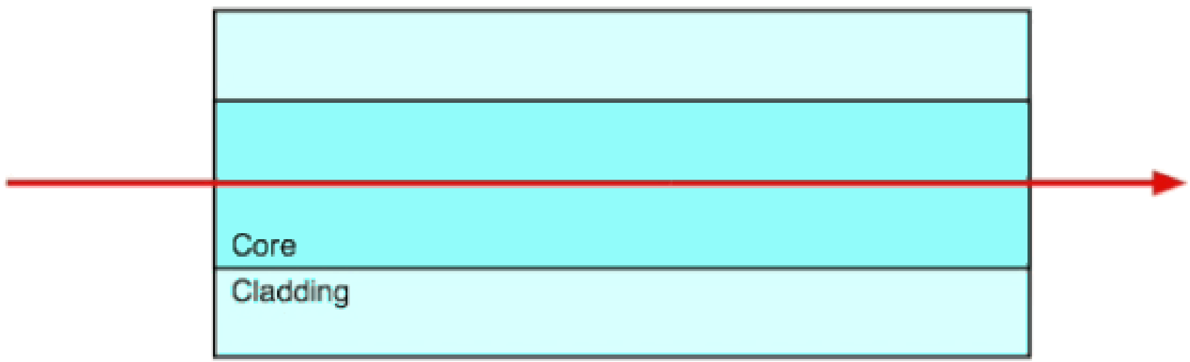


Single-Mode Fiber

Step-Index Multimode

- Multiple reflection angles (modes)
- Multiple propagation paths: **modal dispersion**
  - A pulse of light transmitted through a fiber optic cable is composed of several modes, or rays, of light instead of only one single beam, therefore, it is called **modal dispersion**
  - Each mode of light travels a different path, some short and some long. As a result, the modes will not be received at the same time, and the signal will be distorted**.**
- Signal elements (light pulses) spread out in time
- The need to leave spacing between the light pulses
- i.e. **Limit data rate**
- Core diameter 50 µm, cladding 125 µm
- Suitable for **short distances**

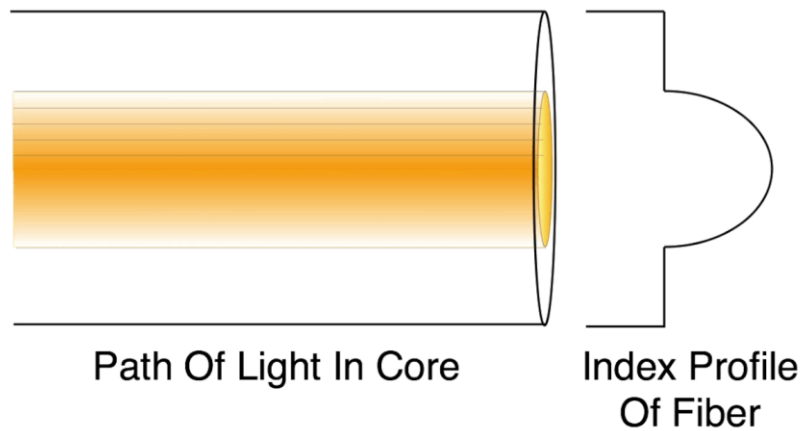
Step-Index Multimode



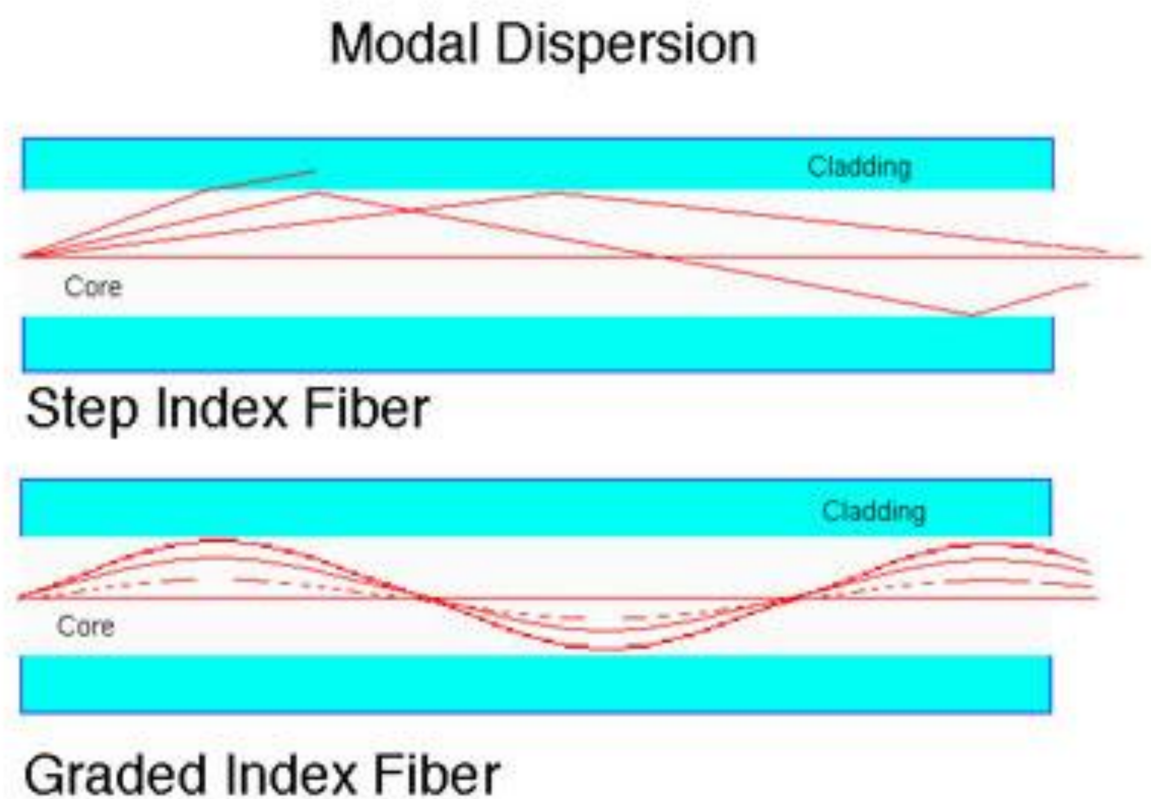
Graded-Index Multimode

- Refractive index of core center is higher than near cladding
- Light at center travel slower than those near to cladding.
- Rather than zig-zagging of the cladding, light in the core curves because of the graded index, reducing the travel distance.
- The **shortened path** and **higher speed** **allows light at the edge to arrive at the receiver at about the same time as the straight rays in the core axis.**
- Modal dispersion is reduced

Graded-Index Multimode



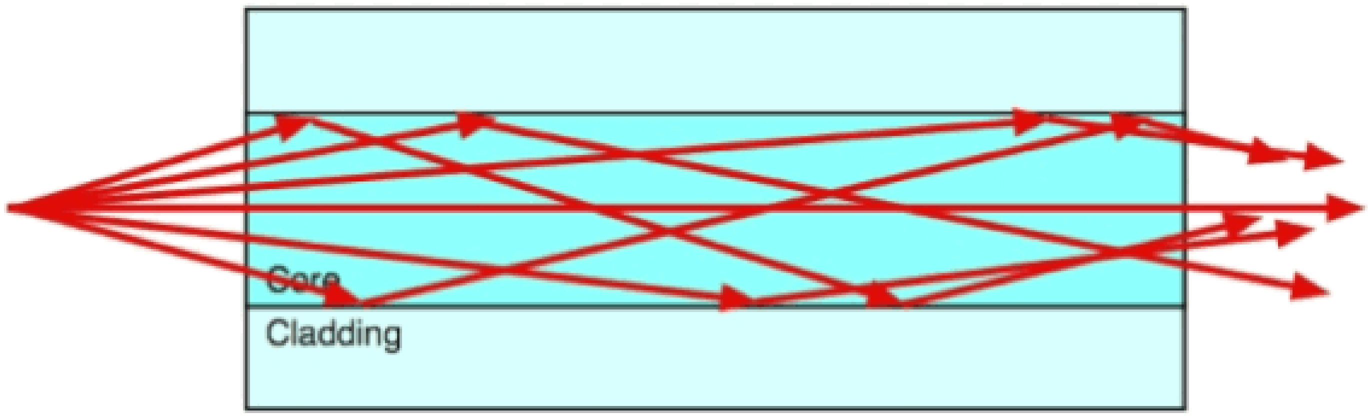
Model Dispersion



Single Mode

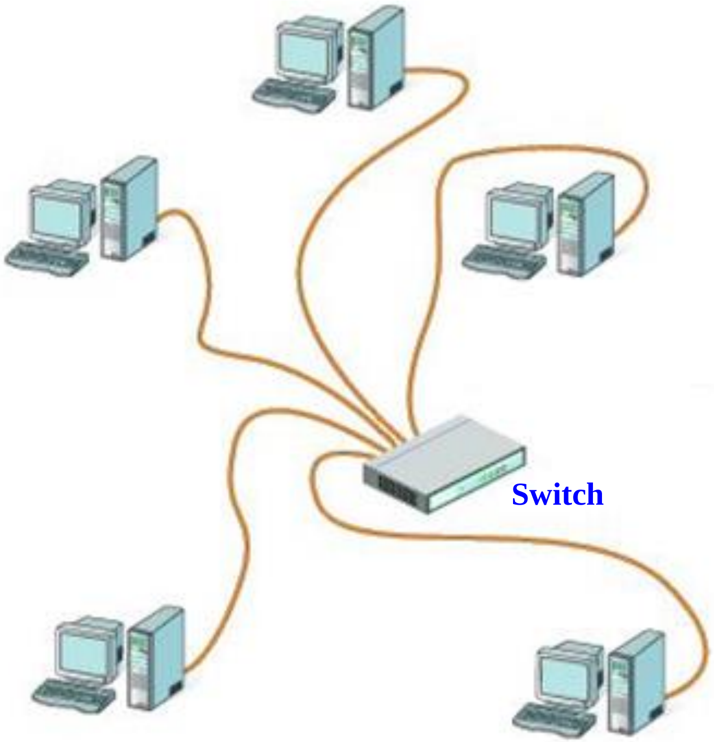
- **Core radius in the order of a wavelength**
- Diameter 8-10 μm, cladding 125 μm
- Only single angle can pass (axial path)
- Used for **long distance transmission**

Single Mode



Optical Fiber

Fiber Standards



SC Duplex Patch Cord

ST Duplex Patch Cord

Fiber Standards

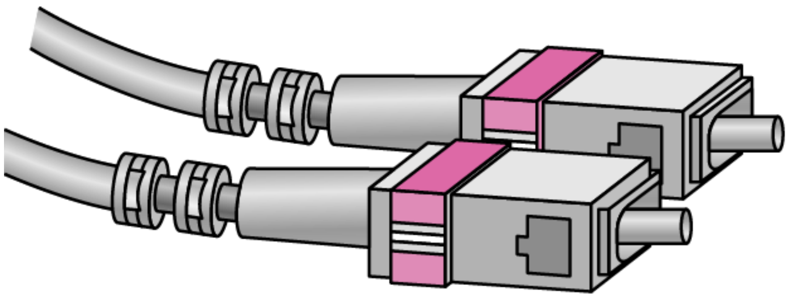
IEEE Designation	Description	Cabling	Maximum Distance
1000BASE-T (IEEE 802.3ab)	Long Distance Copper Physical Layer	UTP CAT5 and CAT5e	100m
1000BASE-CX (IEEE 802.3z)	Short Distance Copper Physical Layer	Shielded Copper	25m
1000BASE-LX (IEEE 802.3z)	Long Distance Fiber Physical Layer	9 micron Single-mode Fiber	up to 5km
1000BASE-SX (IEEE 802.3z)	Short Distance Fiber Physical Layer	62.5 micron Multi-mode Fiber or 50 micron Multi-mode Fiber	Up to 275m or 550m respectively.

IEEE 802.3z Summary

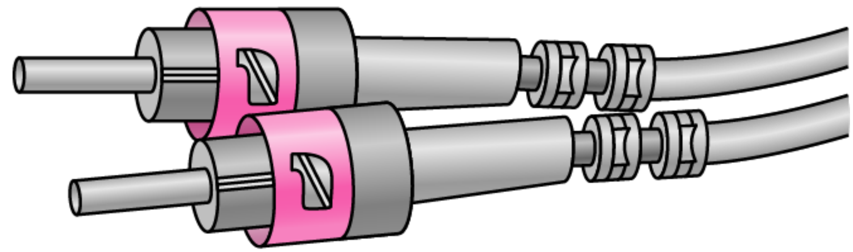
The IEEE 802.3z standard addresses the overall requirements for 1000 Mbps operation, plus three of the four physical layer interfaces using existing Fibre Channel technology.

- **1000BASE-CX:** (Copper-based media, short haul) supporting distances up to 25 meters.
- **1000BASE-LX:** (1300nm LWL - long wavelength) single-mode fiber (SMF) supporting distances up to 5km.
- **1000BASE-SX:** (850nm SWL - short wavelength) 62.5 micron or 50 micron multimode fibre (MMF) supporting distances up to 275 meters or 550 meters respectively.

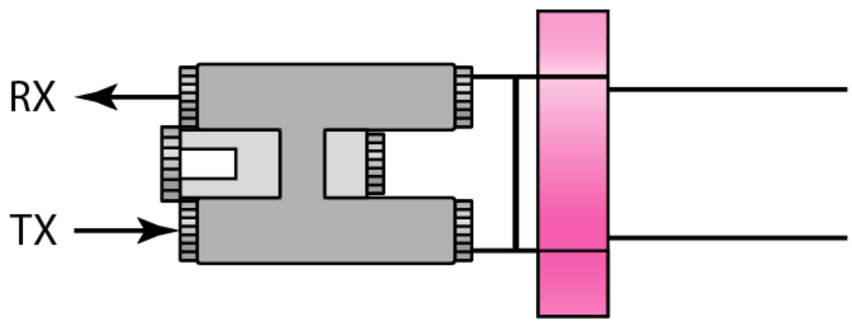
Fiber-Optic Cable Connectors



SC connector

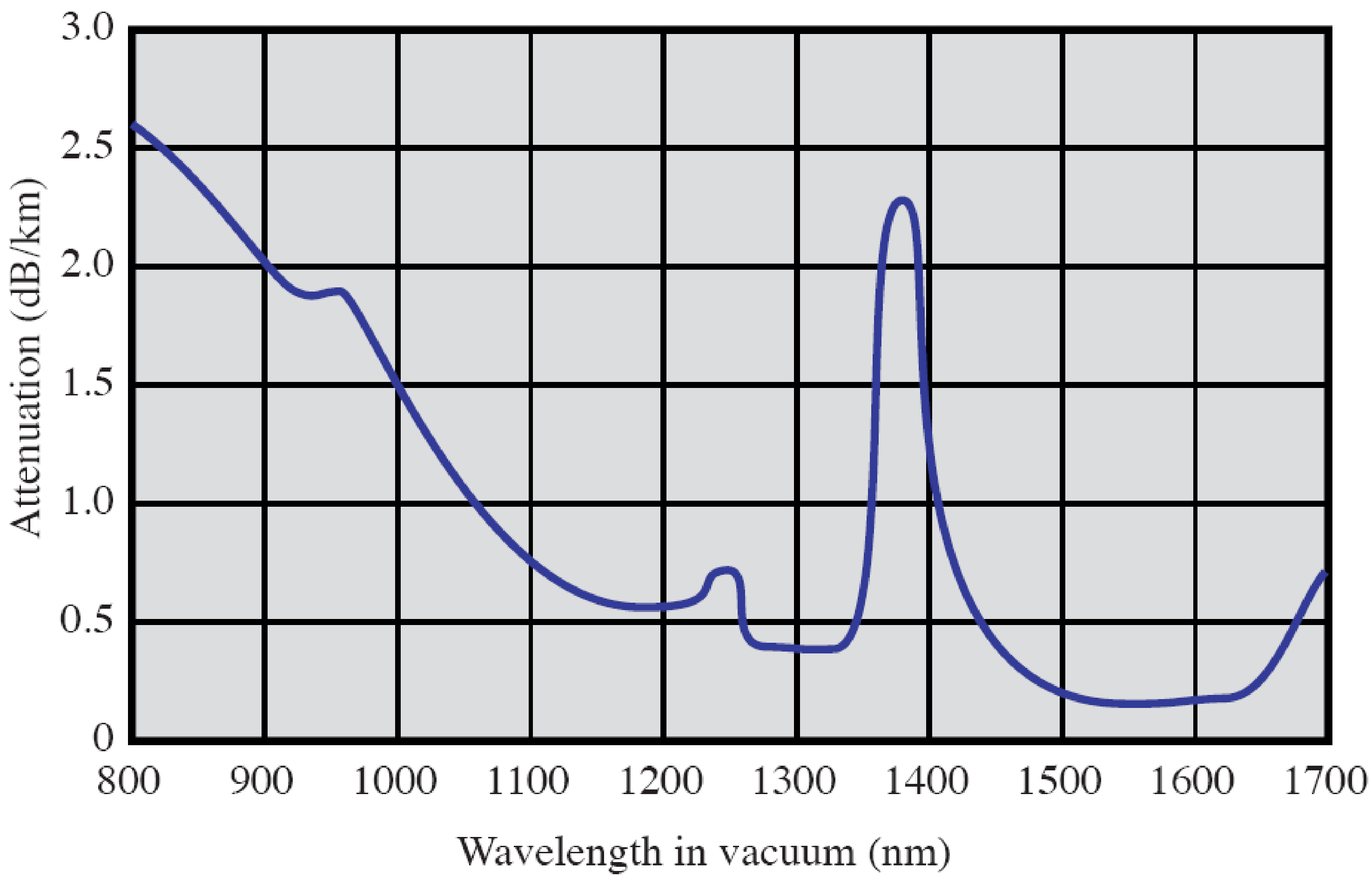


ST connector



MT-RJ connector

Transmission Characteristics



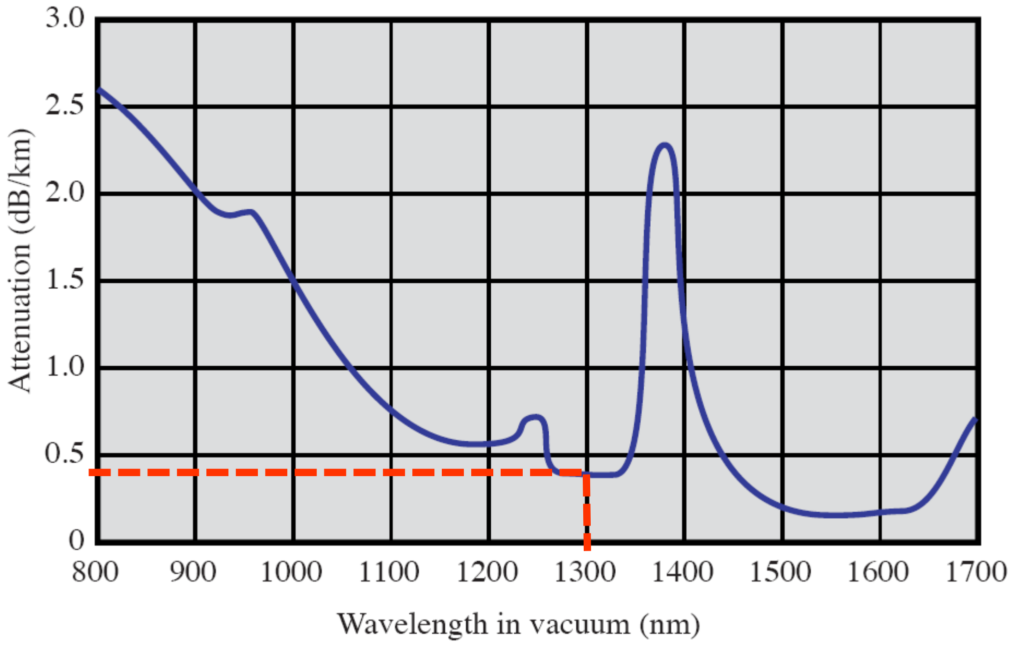
Transmission Characteristics Example:

- ⌘ Assume that the Allowable power loss = 20 dB
- ⌘ Consider Optical fiber operating at wavelength 1300 nm

→ Attenuation = 0.4 dB/km

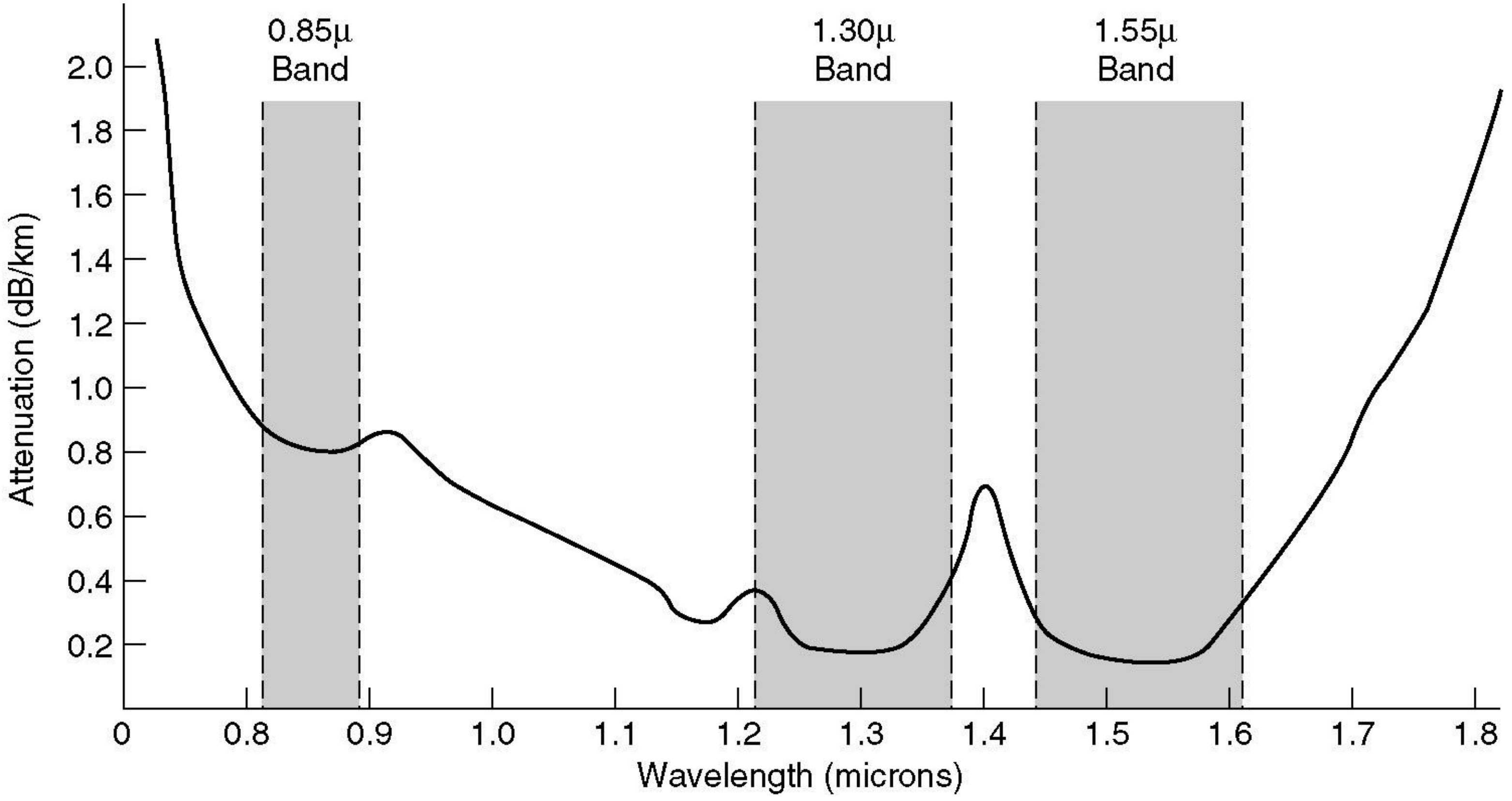
→ Cable length = 20 dB / 0.4 dB/km

→ Cable length = 50 km



Frequency Utilization

850 nm 1300 nm 1550 nm

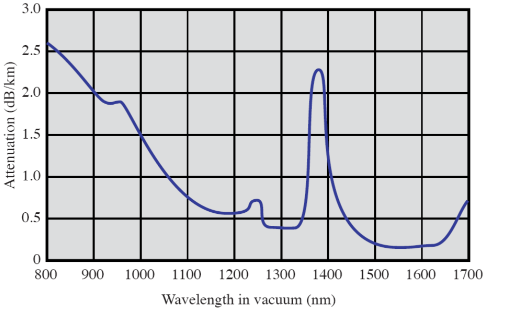


Frequency Utilization

Wavelength (in vacuum) range (nm)	Frequency Range (THz)	Band Label	Fiber Type	Application
820 to 900	366 to 333		Multimode	LAN
1280 to 1350	234 to 222	S	Single mode	Various
1528 to 1561	196 to 192	C	Single mode	WDM
1561 to 1620	192 to 185	L	Single mode	WDM

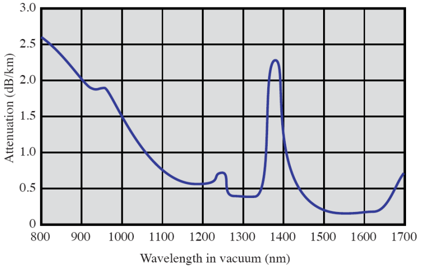
Frequency Utilization

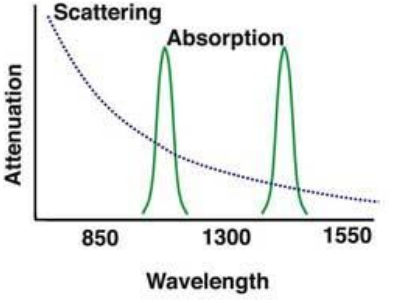
- Four transmission windows are in the infrared portion of the frequency spectrum, below the visible-light portion
- The visible-light portion (400-700 nm)
- Loss is lower at higher wavelengths, allowing greater date rate over longer distances.
- **Many applications use 850 nm light source. To achieve higher data rates and longer distances, a 1300 nm LED or laser source is needed.**
- The highest data rates and longest distances require **1550 nm laser sources**.



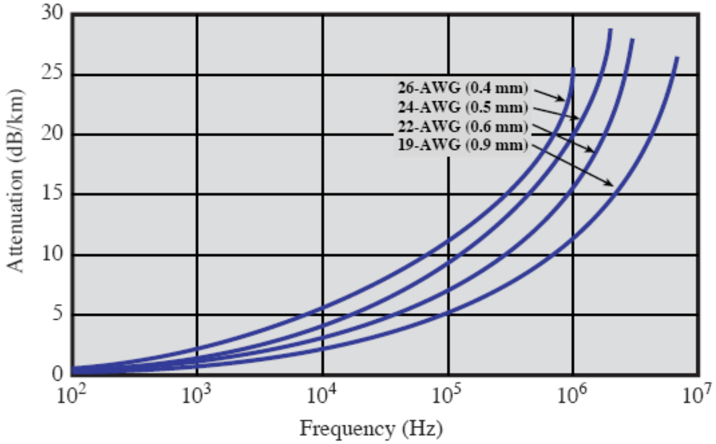
Frequency Utilization

- The unusual shape of the curve is due to absorption and scattering.
  - **Absorption:**
    - The absorption is caused by **the absorption of the light and conversion to heat by molecules in the glass**. This absorption occurs at discrete wavelengths, determined by the elements absorbing the light. It occurs most strongly around **1000 nm, 1400 nm and above 1600 nm**.
      http://www.thefoa.org/tech/ref/basic/fiber.html
  - **scattering:**
    - **The change in direction of light rays after they strike small particles in medium**

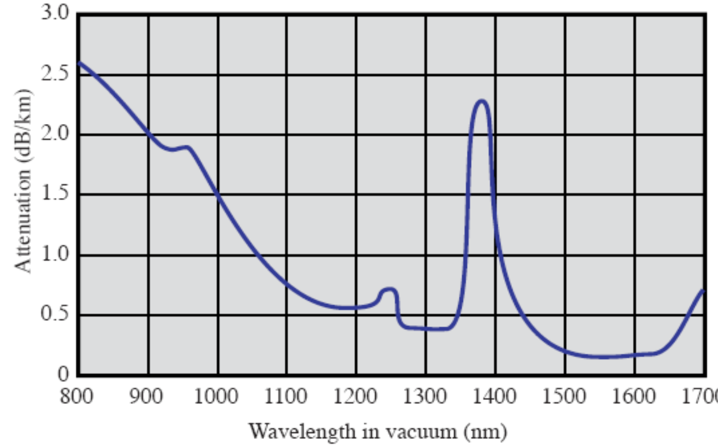




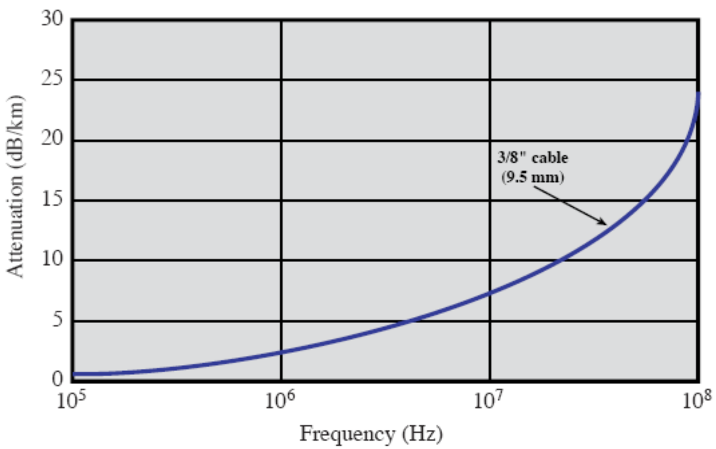
Advantages of Optical Fiber



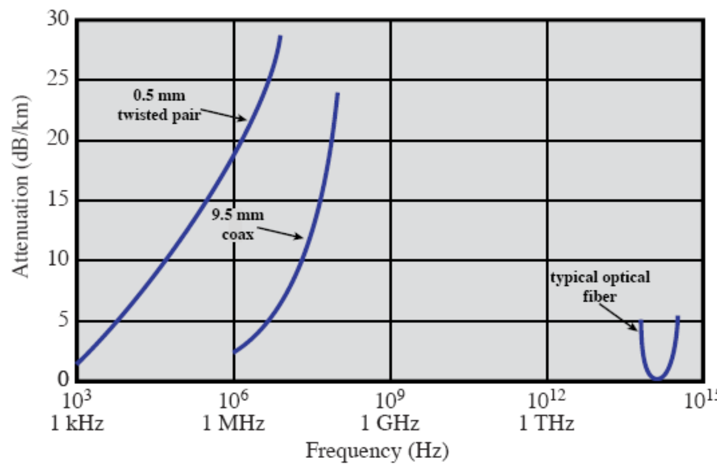
(a) Twisted pair (based on [REEV95])



(c) Optical fiber (based on [FREE02])



(b) Coaxial cable (based on [BELL90])



(d) Composite graph

Standards

Topology	Transmission Medium	Maximum PCs per Switch	Maximum Segment Length (m)	Signal	Data Rate (Mbps)	Standard
BUS	Thick coaxial Cable	100	500	Digital	10	**10Base5**
BUS	Thin coaxial Cable	30	185	Digital	10	**10Base2**
STAR	UTP	1024 (Switch)	100	Digital	10	**10BaseT**
STAR	UTP	1024 (Switch)	100	Digital	100	**100BaseT**
STAR	UTP	1024 (Switch)	100	Digital	100	**100BaseTX**
STAR	UTP	1024 (Switch)	100	Digital	1000	**1000BaseT**
STAR	Shielded Copper	1024 (Switch)	25	Digital	1000	**1000BaseCX**
STAR	9 micron SMF	1024 (Switch)	Up to 5 km	Optical Analog	1000	**1000BaseLX**
STAR	62.5 micron MMF 50 micron MMF	1024 (Switch)	Up to 275 m Up to 550 m	Optical Analog	1000	**1000BaseSX**
						10 Gigabit

Required Reading

- Stallings Chapter 4