LE/EECS 3213 Fall 2014

L8: Physical Media Properties

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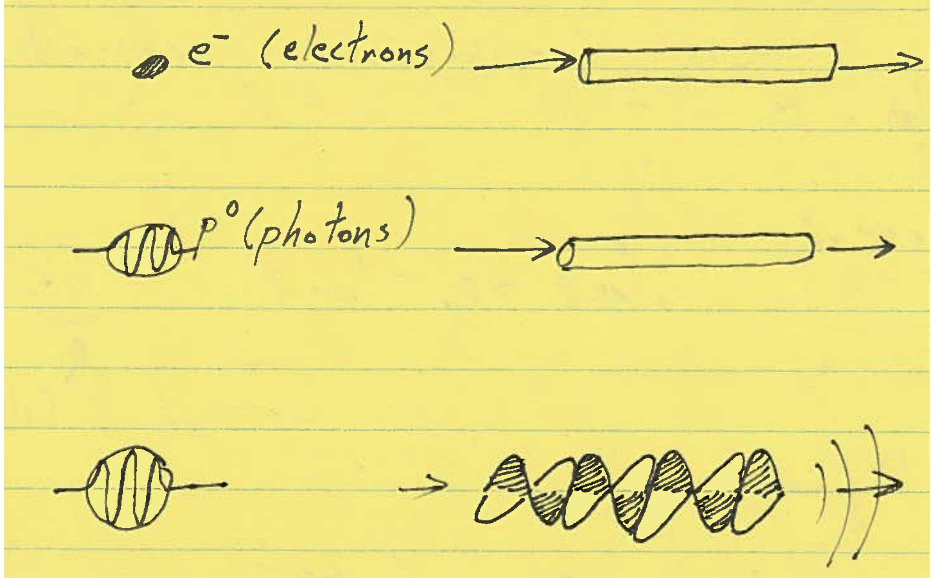
Outline

- Key characteristics of physical media
  - What signals in media are made out of
  - Delay through media
  - Attenuation through media
  - Frequency response of media
- Twisted Pair
- Coax
- Optical
- Wireless

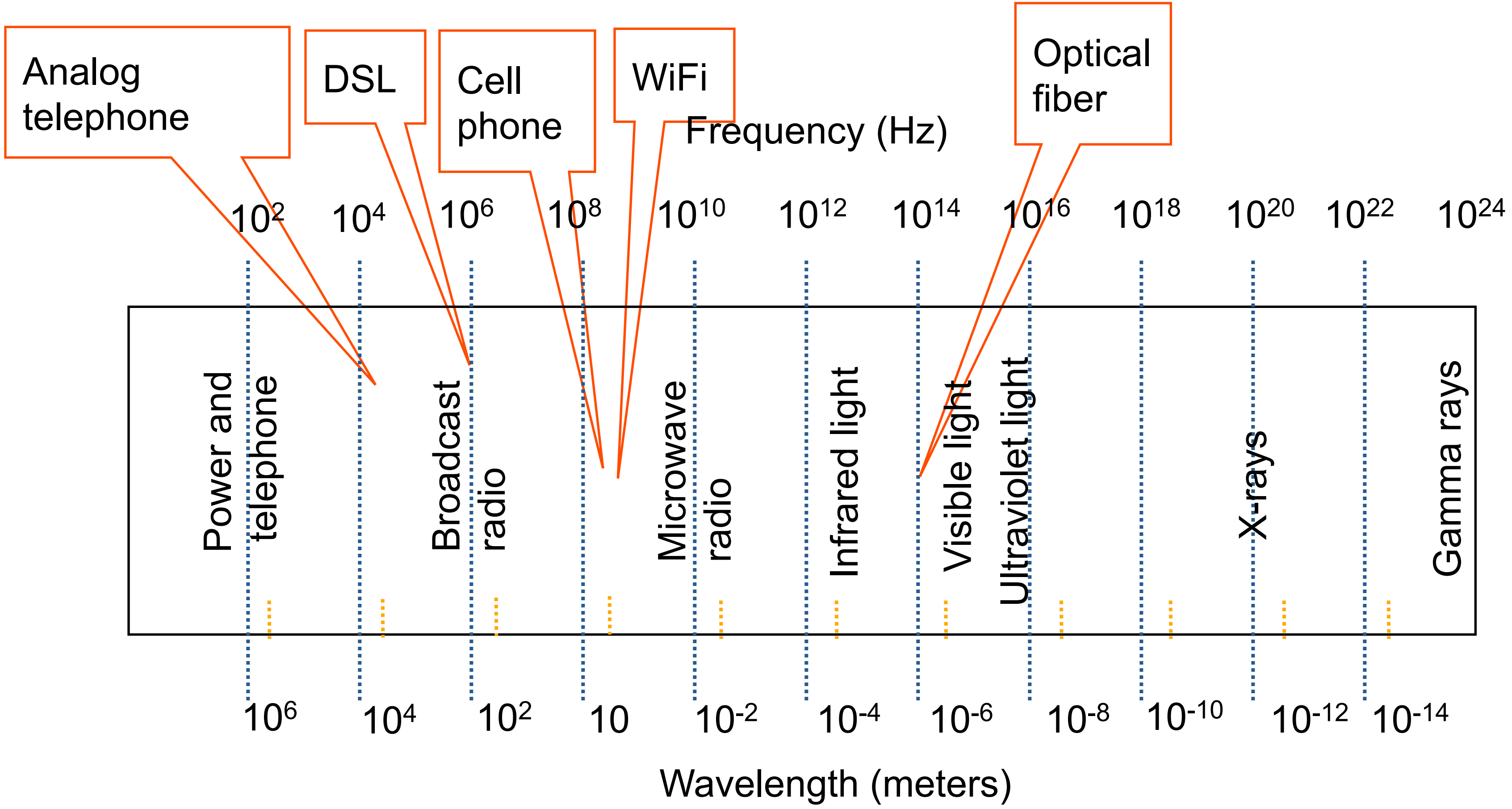
8.1 Signal Particles

- Electrons through metal
- Photons through glass and air

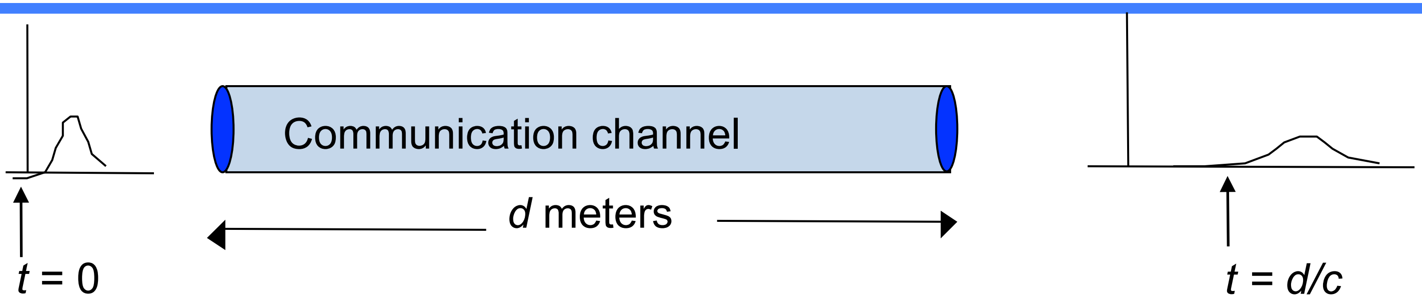


Communications Systems & EM Spectrum

- Frequency of communications signals



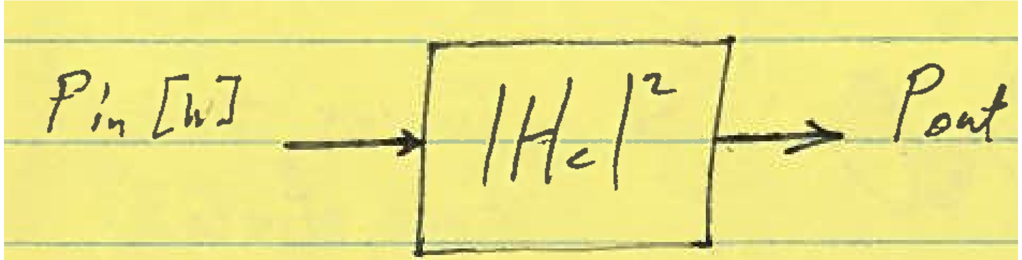
8.2 Delay



- Propagation speed of signal
  - $c = 3 \times 10^8$ meters/second in vacuum
  - $v = c/\sqrt{\varepsilon}$ speed of light in medium
    - $\varepsilon > 1$ is the dielectric constant of the medium
    - $v = 2.3 \times 10^8$ m/sec in copper wire
    - $v = 2.0 \times 10^8$ m/sec in optical fiber

8.2 Attenuation

- Usually the signal power that comes out your channel is less than the signal power that comes in your channel
  - Attenuation = $|A_c|^2 = P_{in}/P_{out}$
- Can also think of it in terms of the channel's frequency response (aka transfer function)
  - $|H_c|^2 = P_{out}/P_{in}$

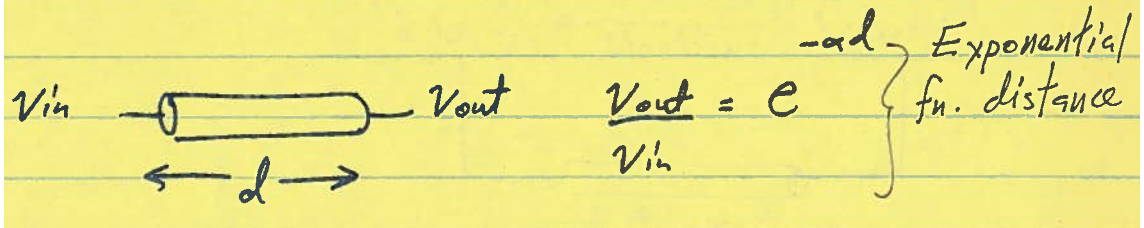


Summary: Attenuation in Wired and Wireless

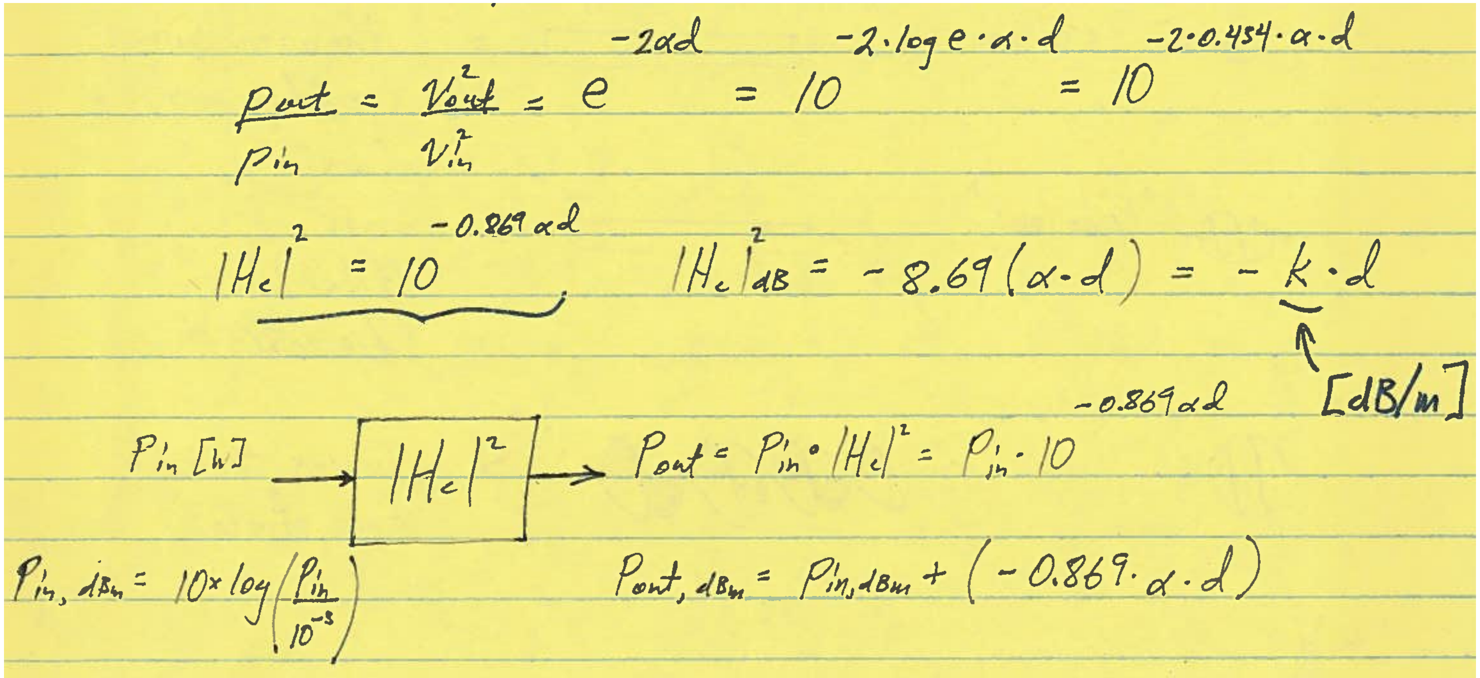
- Attenuation varies with media
  - Dependence on distance of central importance
- Wired media attn. has *exponential function of distance*
  - Received power at *d* meters proportional to 10^{-kd}
  - Attenuation in dB is $k \bullet d$, where *k* is dB/meter
- Wireless media attn. has *power function of distance*
  - Received power at *d* meters proportional to d^{-n}
  - Attenuation in dB is $n \log d$, where *n* is path loss exponent
    - $n=2$ in free space
  - Signal level maintained for much longer distances
  - Space communications possible

Wired Channel Transfer Characteristics

- Exponential characteristics



$$\frac{V_{out}}{V_{in}} = e^{-\alpha d} \Big\} \text{ Exponential fn. distance}$$



$$\frac{P_{out}}{P_{in}} = \frac{V_{out}^2}{V_{in}^2} = e^{-2\alpha d} = 10^{-2\cdot\log e\cdot\alpha\cdot d} = 10^{-2\cdot 0.454\cdot\alpha\cdot d}$$

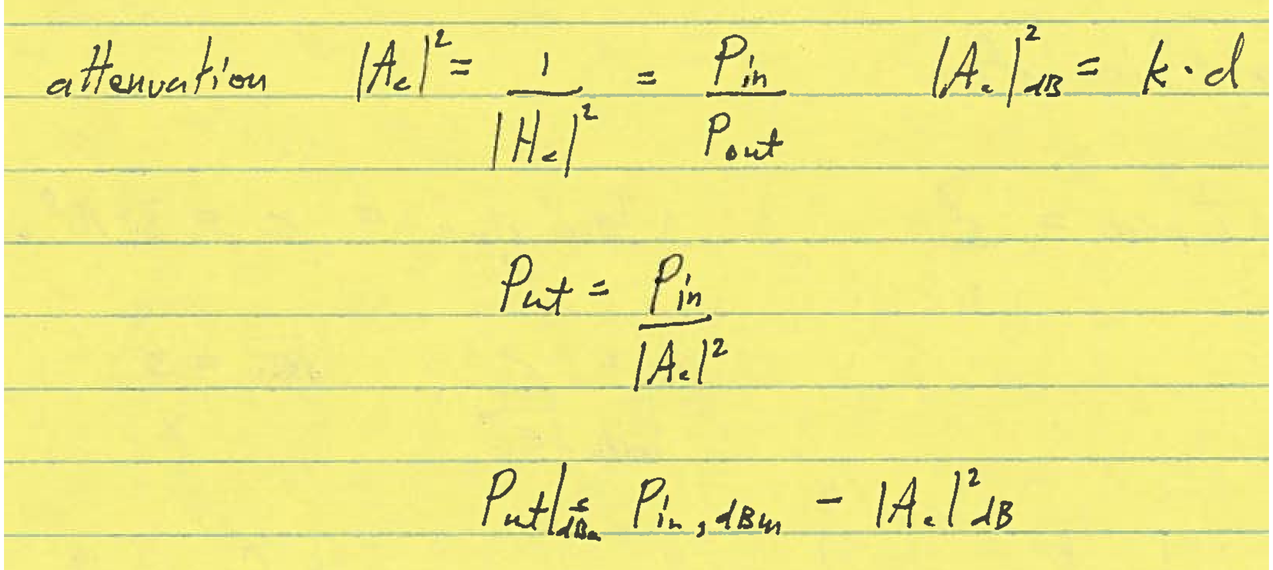
$$\underbrace{|H_c|^2 = 10^{-0.869\alpha d}} \qquad |H_c|^2_{dB} = -8.69(\alpha\cdot d) = -\underset{\uparrow\,[dB/m]}{\underbrace{k}}\cdot d$$

$$P_{out} = P_{in}\cdot|H_c|^2 = P_{in}\cdot 10^{-0.869\alpha d}$$

$$P_{in,dBm} = 10\times\log\left(\frac{P_{in}}{10^{-3}}\right) \qquad P_{out,dBm} = P_{in,dBm} + (-0.869\cdot\alpha\cdot d)$$

Channel Transfer Function and Attenuation

- H_c and A_c relationships



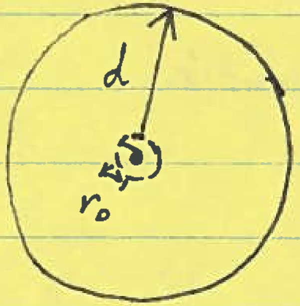
attenuation $|A_c|^2 = \frac{1}{|H_c|^2} = \frac{P_{in}}{P_{out}}$ $|A_c|^2_{dB} = k \cdot d$

$$P_{ut} = \frac{P_{in}}{|A_c|^2}$$

$$P_{ut}|_{dBm} = P_{in,dBm} - |A_c|^2_{dB}$$

Wireless Channel Transfer Characteristics

- As your signal leaves the antenna it spreads out over a broader and broader surface



$$|H_c|^2 = \frac{P_{out}}{P_{in}} = \left(\frac{r_0}{d}\right)^2 = \left(\frac{r_0}{d}\right)^n \Bigg\} \text{Power fn. of distance}$$

$$|H_c|^2_{dB} = \left|\frac{P_{out}}{P_{in}}\right|_{dB} = n \cdot 10 \cdot \log\left(\frac{r_0}{d}\right)$$

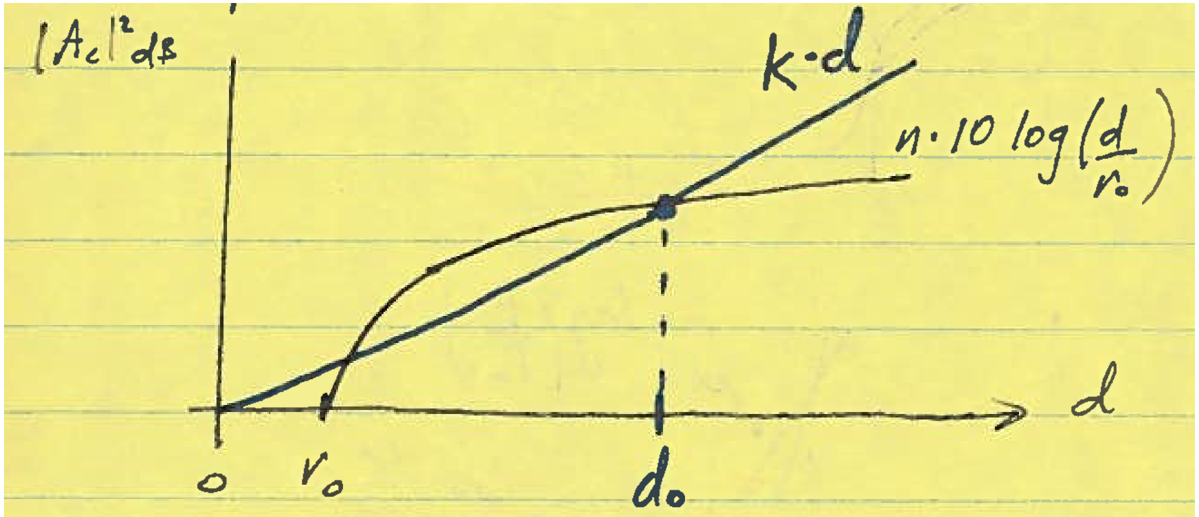
$$r_0 = \frac{\lambda}{4\pi} \qquad \lambda = \frac{c}{f} \qquad \therefore f = 3\times10^9,\ c = 3\times10^8$$

$$\lambda = 10\,cm$$

$$|A_c|^2 = \left(\frac{d}{r_0}\right)^n \qquad |A_c|^2_{dB} = n \cdot 10 \cdot \log\left(\frac{d}{r_0}\right)$$

Comparison: Wired & Wireless Attenuation

- Compare the attenuation as a function of distance



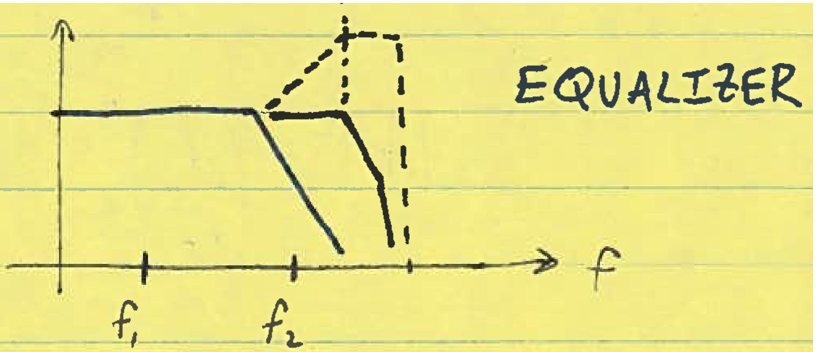
- Compare basic telephone line (k = 0.005 dB/m) to 3-GHz wireless

8.4 Frequency Response

- Typically the attenuation (and channel transfer function) is not flat with frequency

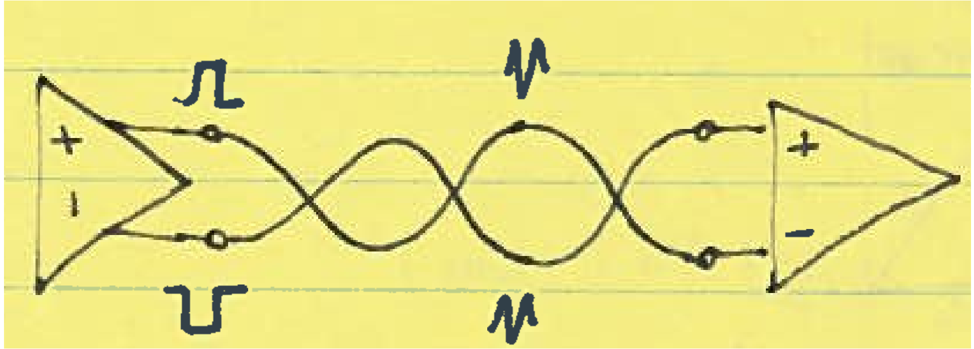
$$|H_c(f_1)|^2 \neq |H_c(f_2)|^2$$

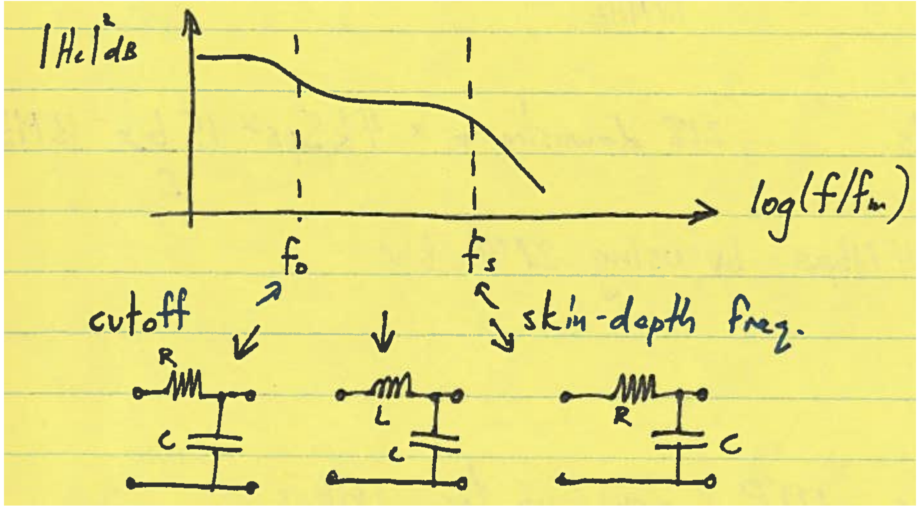
a cause for distortion



8.5 Twisted Pair

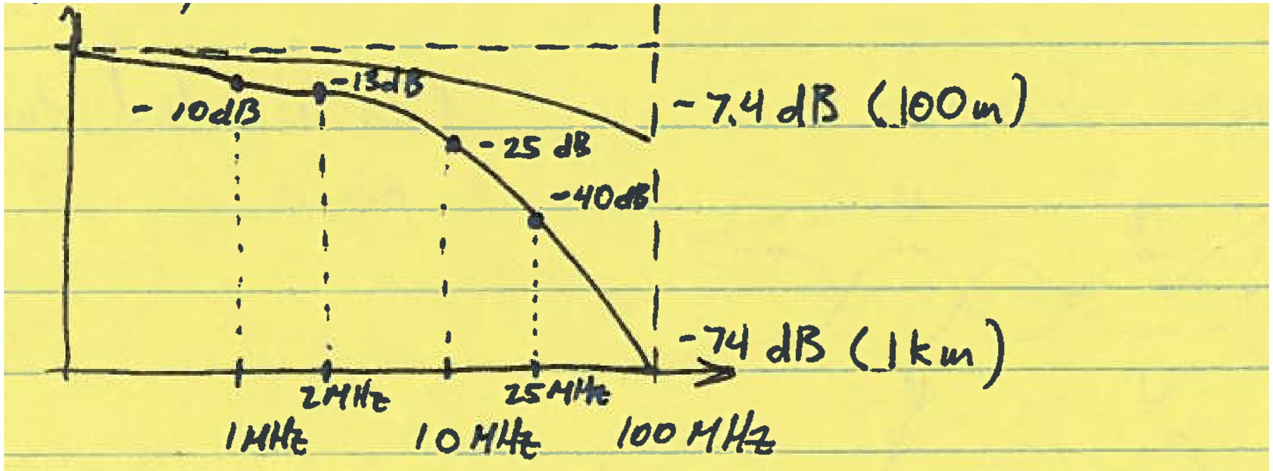
- Wires wound around each other (UTP: unshielded twisted pair)
  - Differential signals
  - Common-mode interference





AWG24 (Telephone/Ethernet) Freq. Response

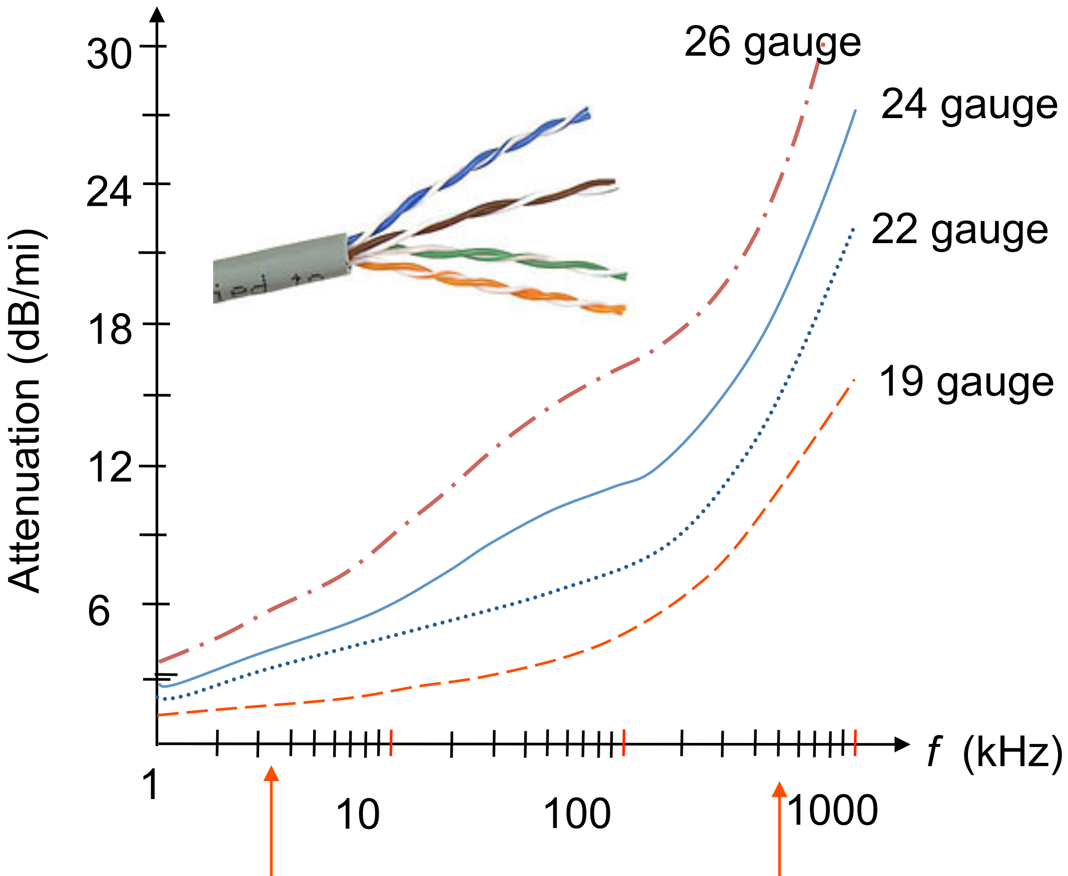
- $|H_c|^2$ (dB)
  - 0.511 mm diameter



for $0 < f < 3\text{kHz}$ $|H_c|^2 \geq -1.5\text{dB}$ @ 1km

Twisted Pair

- Two insulated copper wires arranged in a spiral pattern to minimize interference
- Various thicknesses, e.g. 0.016 inch (24 gauge)
- Low cost
- Telephone subscriber loop from customer to CO
- Intra-building telephone from wiring closet to desktop
- In old installations, loading coils added to improve quality in 3 kHz band, but more attenuation at higher frequencies

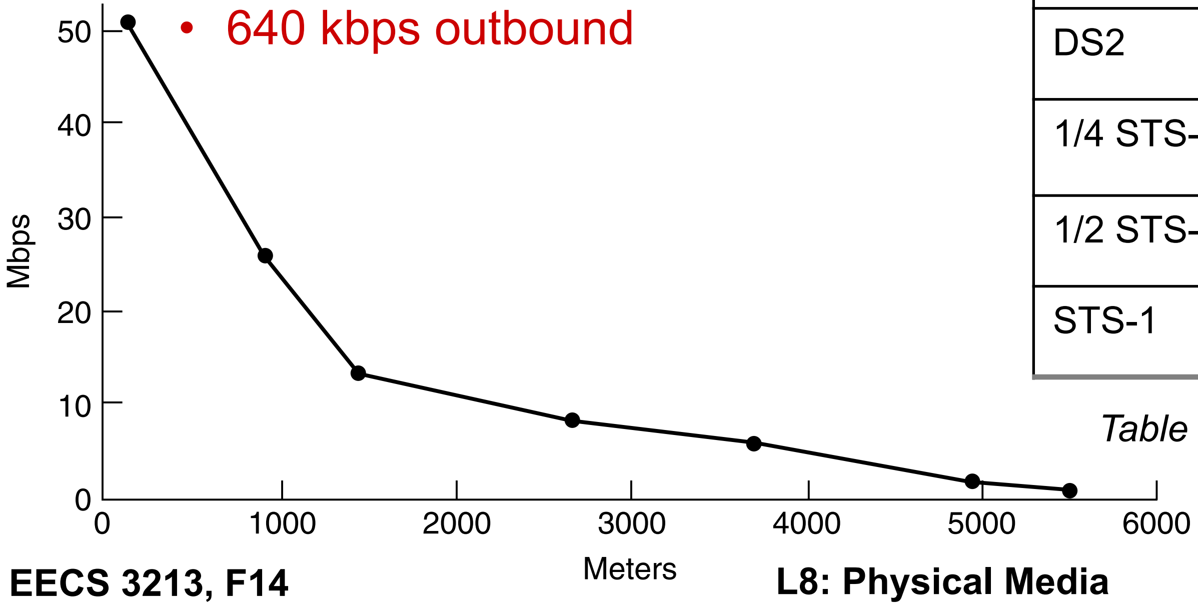


Lower attenuation rate analog telephone

Higher attenuation rate for DSL

Twisted Pair Bit Rates

- Twisted pairs provide high bit rates at short distances
- Asymmetric Digital Subscriber Loop (ADSL)
  - High-speed Internet Access
  - Lower 3 kHz for voice
  - Upper band for data
    - 64 kbps inbound
    - 640 kbps outbound



- Much higher rates possible at shorter distances
  - Strategy is to bring fiber close to home & then twisted pair
  - Higher-speed access + video

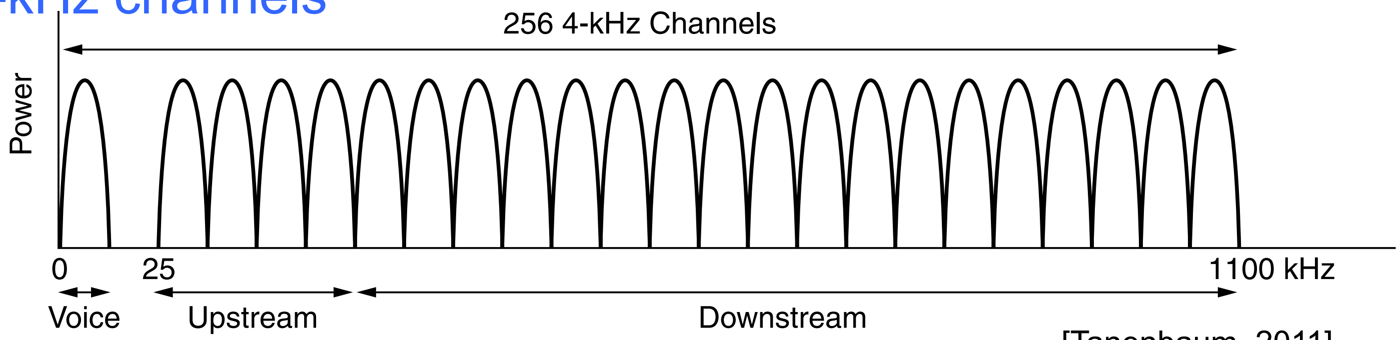
Standard	R (Mbps)	Distance
T-1	1.544	18,000 feet, 5.5 km
DS2	6.312	12,000 feet, 3.7 km
1/4 STS-1	12.960	4500 feet, 1.4 km
1/2 STS-1	25.920	3000 feet, 0.9 km
STS-1	51.840	1000 feet, 300 m

Table 3.5 Data rates of 24-gauge twisted pair

[Tanenbaum, 2011]

8.6 ADSL Signals

- Telephone wire has ~1-MHz reasonable bandwidth
  - 3-kHz voice bandwidth created by load coils
- ADSL divides into channels
  - 256, 4.3125-kHz channels
  - OFDM (4G)

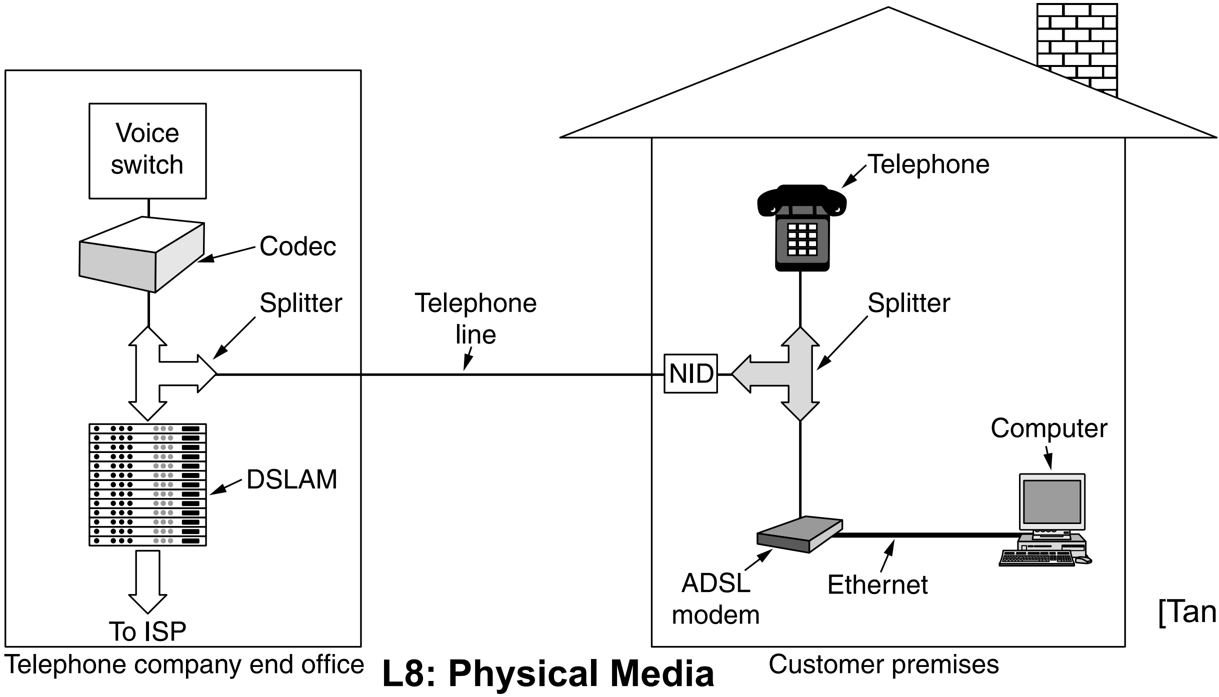


[Tanenbaum, 2011]

  - Typically 32 for upstream and 218 for downstream
    - ADSL2: 1 Mbps upstream and 12 Mbps downstream
    - 4000 symbols/s per channel
    - 1-15 bits per symbol depending on SNR

ADSL Arrangement

- Splitter combines voice and data
  - NID: Network Interface Device
  - Applies necessary filtering to isolate them
- At company office voice and data split
  - DSLAM aggregates customer data and sends to ISP
    - Digital Subscriber Line Access Multiplexer

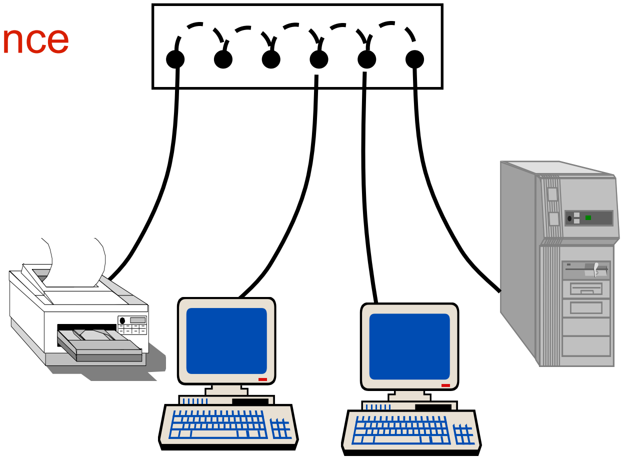


[Tanenbaum, 2011]

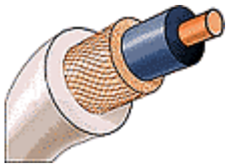
8.7 Ethernet LANs

- Office building telephone wires a great candidate for LANs
- Several categories have been defined…
  - Cat3 UTP: ordinary telephone wires
  - Cat5 UTP: tighter twisting to improve signal quality
  - STP: metallic braid around each pair
    - to minimize interference
    - costly
    - Cat7

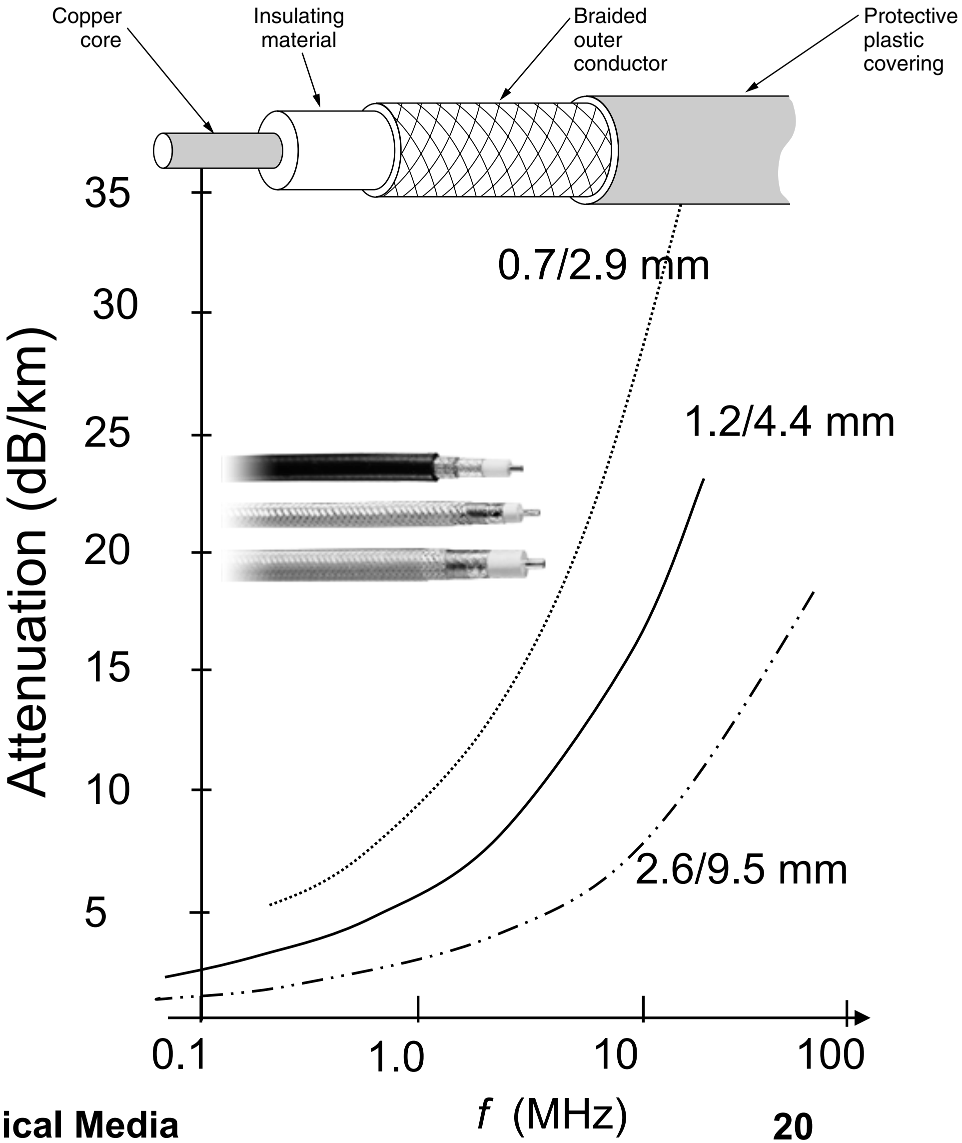
- 10BASE-T Ethernet
  - 10 Mbps
    - Two Cat3 pairs
    - Manchester coding, 100 meters
- 100BASE-T4 Fast Ethernet
  - 100 Mbps
    - Four Cat3 pairs
    - Three pairs for one direction at-a-time
    - 100/3 Mbps per pair;
    - 8B10B line code, 100 meters



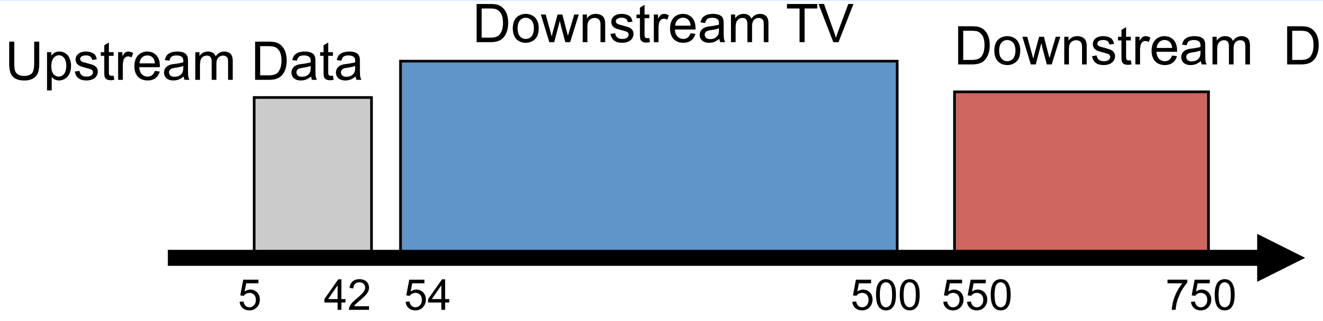
8.8 Coaxial Cable



- Cylindrical braided outer conductor surrounds insulated inner wire
- High interference immunity
- Higher bandwidth than twisted pair
- Hundreds of MHz
- Cable TV distribution
- Long distance telephone transmission
- Original Ethernet LAN medium



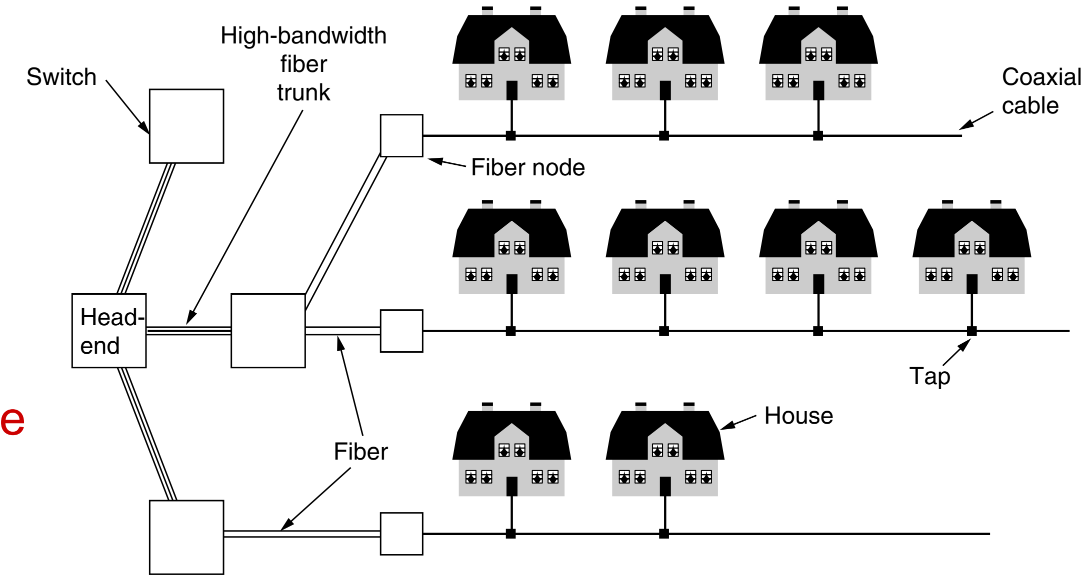
8.9 Cable Modem & TV Spectrum

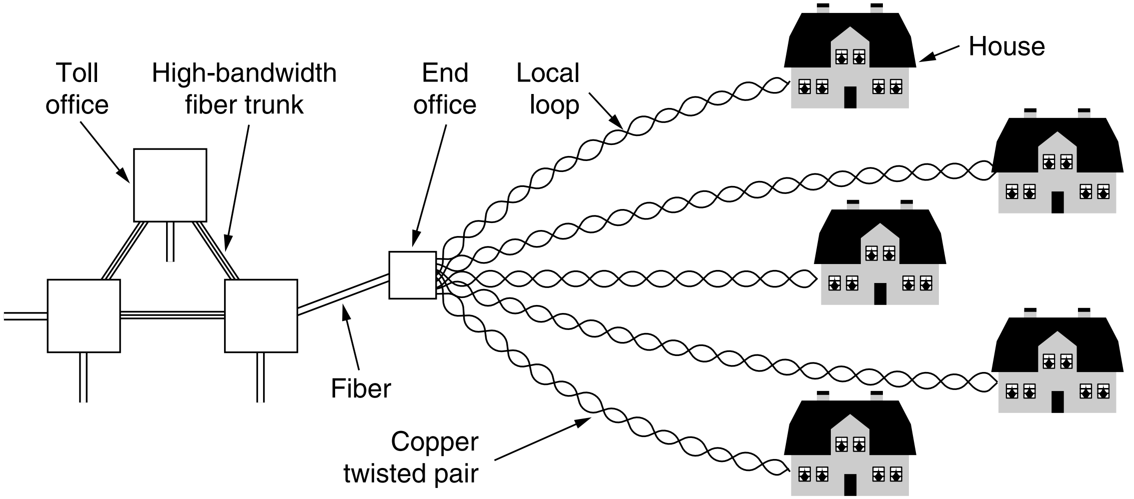


- Cable TV network originally unidirectional
  - 54-500 MHz TV service
    - 6 MHz = 1 analog TV channel or several digital TV channels
- Cable Modem: shared upstream & downstream
  - Open DOCSIS standard
  - 5 – 42 MHz upstream into network
    - 2 MHz channels
    - 500 kbps to 4 Mbps
  - > 550 MHz downstream from network
    - 6 MHz channels
    - 36 Mbps

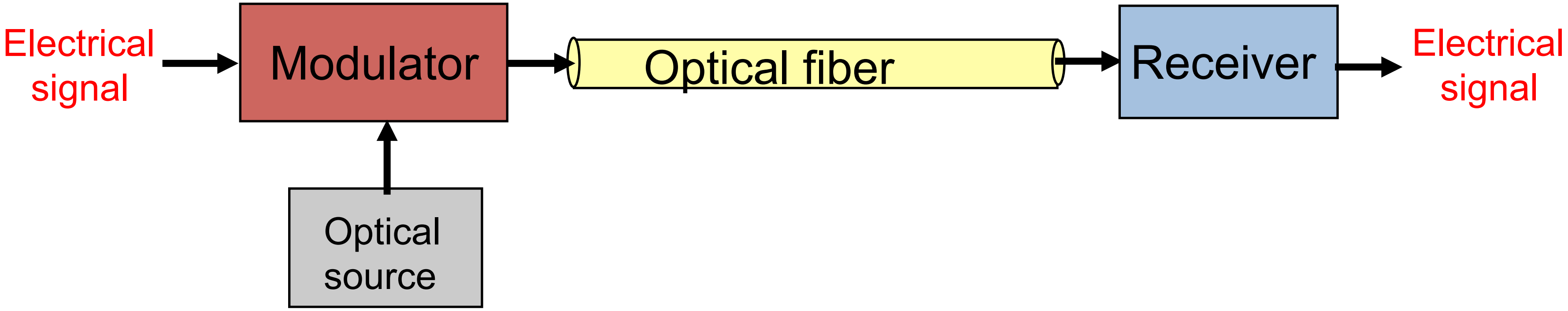
Cable/DSL Network Topology

- Cable
  - Users share medium
    - Managed by “Head-end”
    - FDMA: 6-MHz channels
    - TDMA: Users get minislots
    - CDMA/ALOHA: Users share minislots
    - 500-2000 users per cable
  - Data aggregated on fiber
- DSL
  - No sharing
    - But lower quality link
  - Data aggregated on fiber





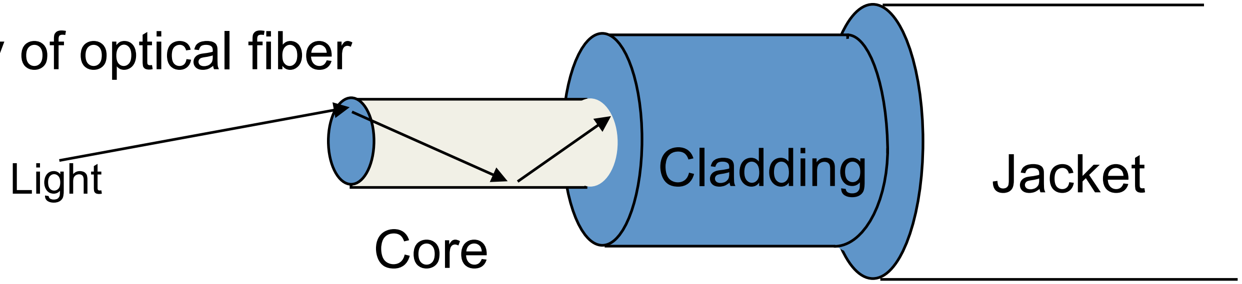
8.10 Optical Fiber



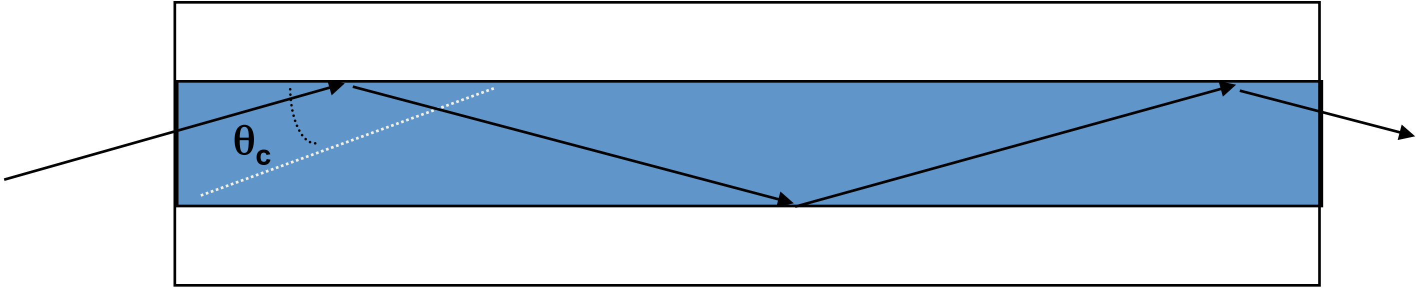
- Light sources (lasers, LEDs) generate pulses of light that are transmitted on optical fiber
  - Very long distances (>1000 km)
  - Very high speeds (>40 Gbps/wavelength)
  - Nearly error-free (BER of 10^{-15})
- Profound influence on network architecture
  - Dominates long distance transmission
  - Distance less of a cost factor in communications
  - Plentiful bandwidth for new services

Transmission in Optical Fiber

Geometry of optical fiber



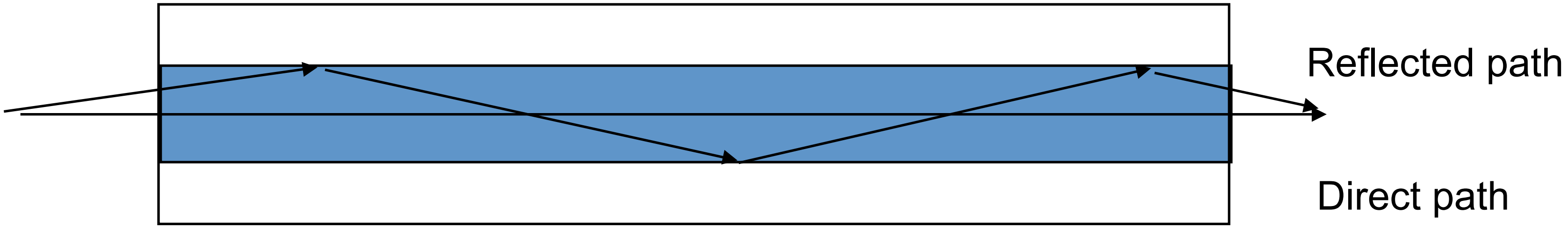
Total Internal Reflection in optical fiber



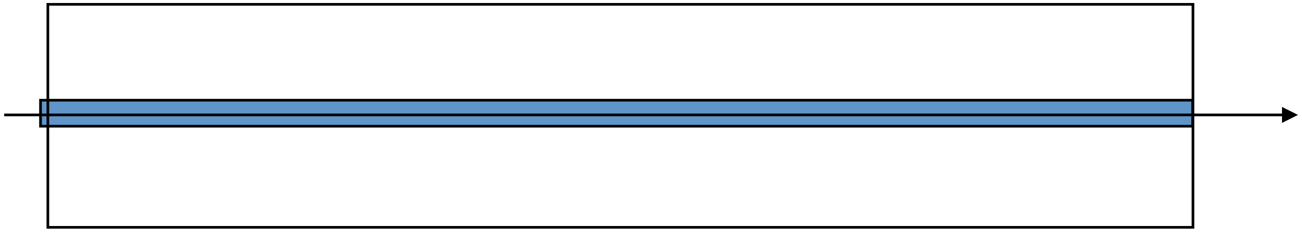
- Very fine glass cylindrical core surrounded by concentric layer of glass (cladding)
- Core has higher index of refraction than cladding
- Light rays incident at less than critical angle θ_c is completely reflected back into the core

Multimode & Single-Mode Fiber

Multimode fiber: multiple rays follow different paths (50-100 um diameter)



Single-mode fiber: only direct path propagates in fiber (8-10 um diameter)



- Multimode: Thicker core, shorter reach
  - Rays on different paths interfere causing dispersion & limiting bit rate
- Single mode: Very thin core supports only one mode (path)
  - More expensive lasers, but achieves very high speeds
    - 100 Gbps for 100 km without amplification

Fiber Connections

- Connectors
  - Fiber sockets

- Mechanical splicing
  - Align two cut pieces closely in a sleeve and clamp together
  - 10% light loss

- Fused (melted) together
  - Fusion splice

Optical Fiber Properties

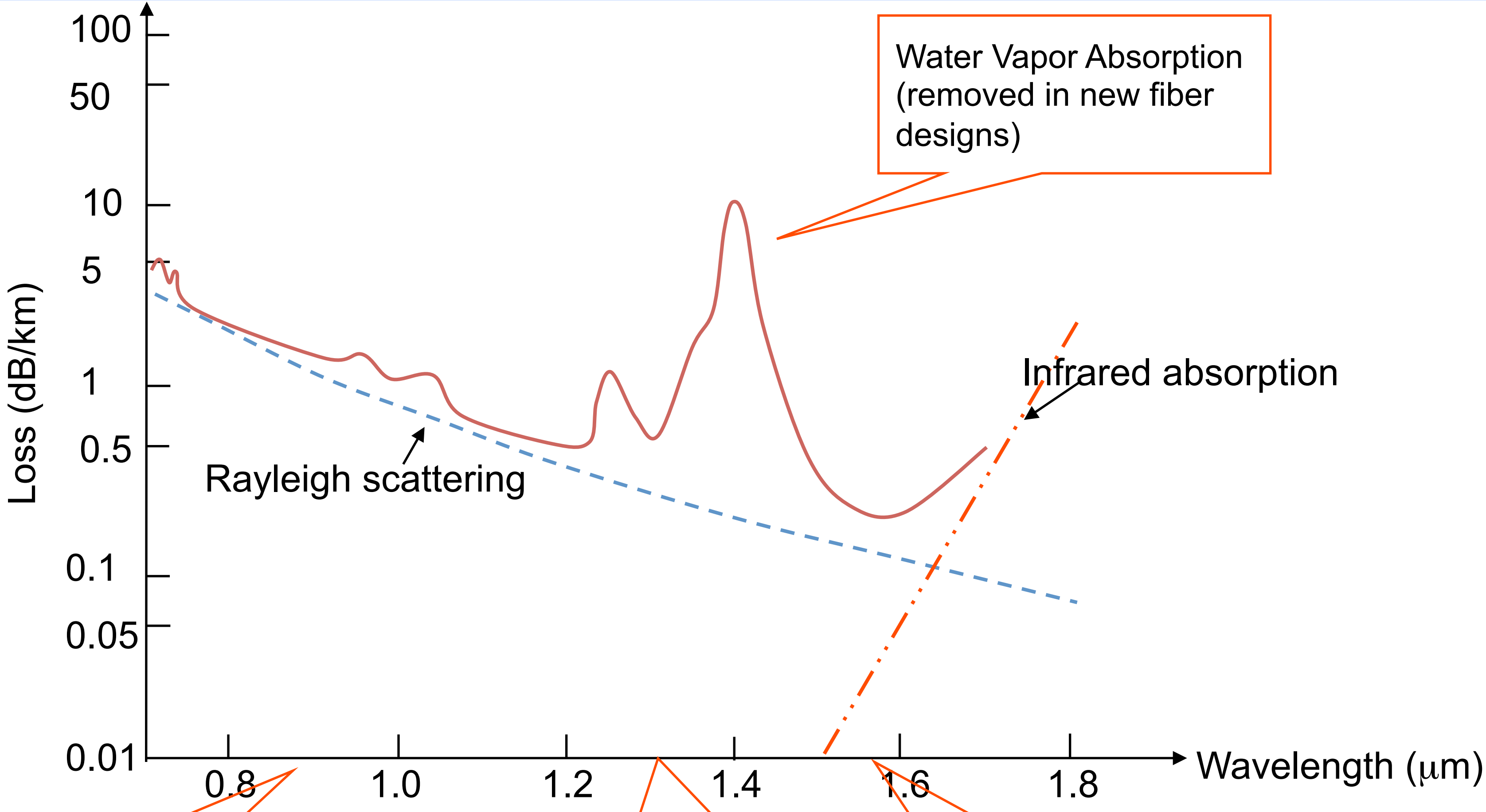
Advantages

- ***Very low attenuation***
- ***Noise immunity***
- ***Extremely high bandwidth***
- Security: Very difficult to tap without breaking
- No corrosion
- More compact & lighter than copper wire

Disadvantages

- New types of optical signal impairments & dispersion
  - Polarization dependence
  - Wavelength dependence
- Limited bend radius
  - If physical arc of cable too high, light lost or won't reflect
  - Will break
- Difficult to splice
- Mechanical vibration becomes signal noise

8.11 Optical Attenuation



Water Vapor Absorption (removed in new fiber designs)

850 nm
Low-cost LEDs
LANs

1300 nm
Metropolitan Area Networks
“Short Haul”

1550 nm
Long Distance Networks
“Long Haul

8.12 Optical Bandwidth

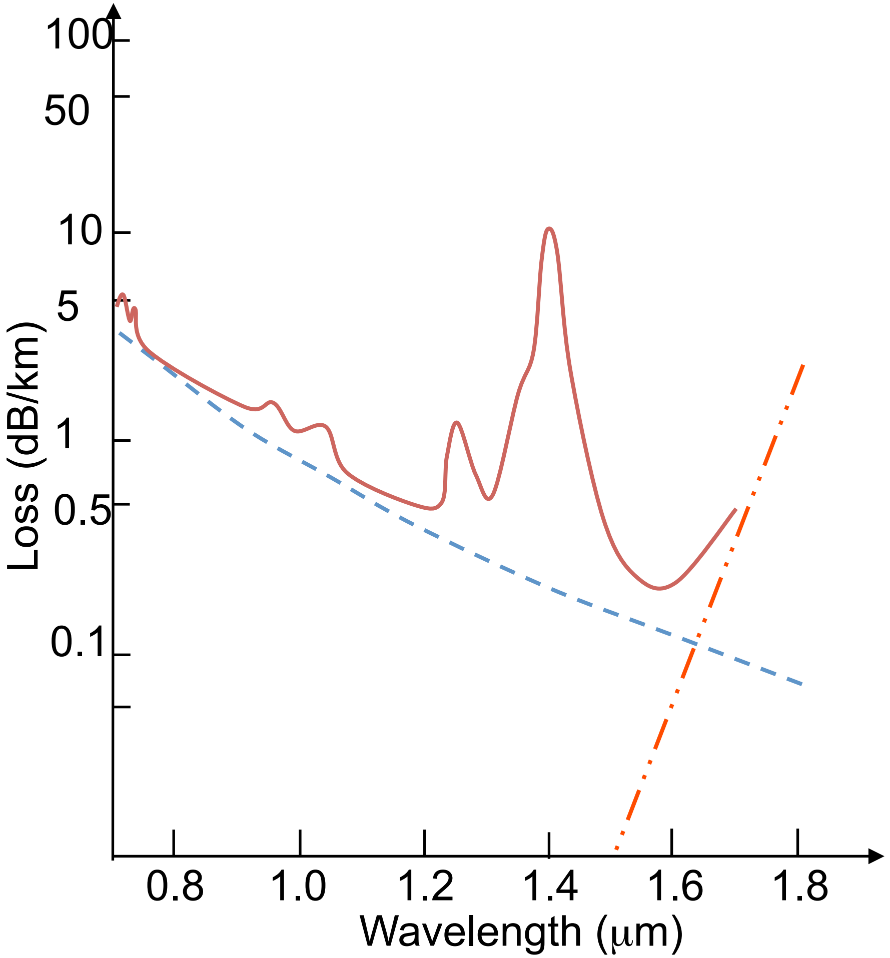
- Optical range from λ_1 to $\lambda_1 + \Delta\lambda$ contains bandwidth

$$B = f_1 - f_2 = \frac{v}{\lambda_1} - \frac{v}{\lambda_1 + \Delta\lambda}$$

$$= \frac{v}{\lambda_1}\left\{\frac{\Delta\lambda / \lambda_1}{1 + \Delta\lambda / \lambda 1}\right\} \approx \frac{v\,\Delta\lambda}{\lambda_1^2}$$

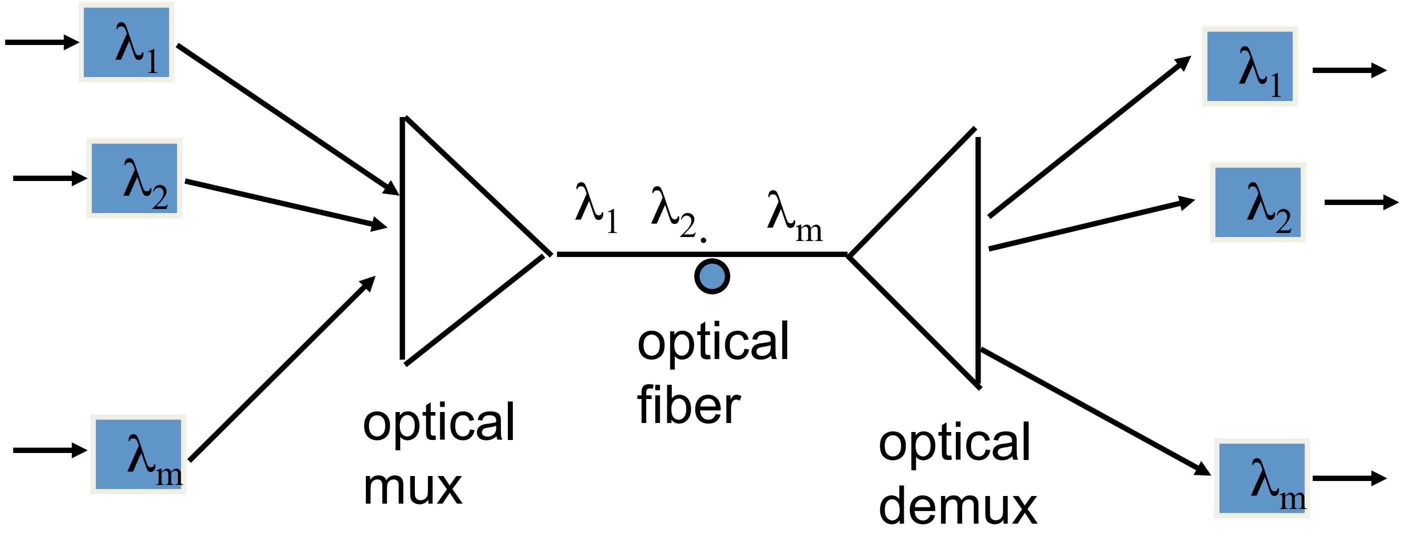
- Example: $\lambda_1 = 1450$ nm $\lambda_1 + \Delta\lambda = 1650$ nm:

$$B = \frac{2(10^8)\text{m/s } 200\text{nm}}{(1450\text{ nm})^2} \approx 19\text{ THz}$$

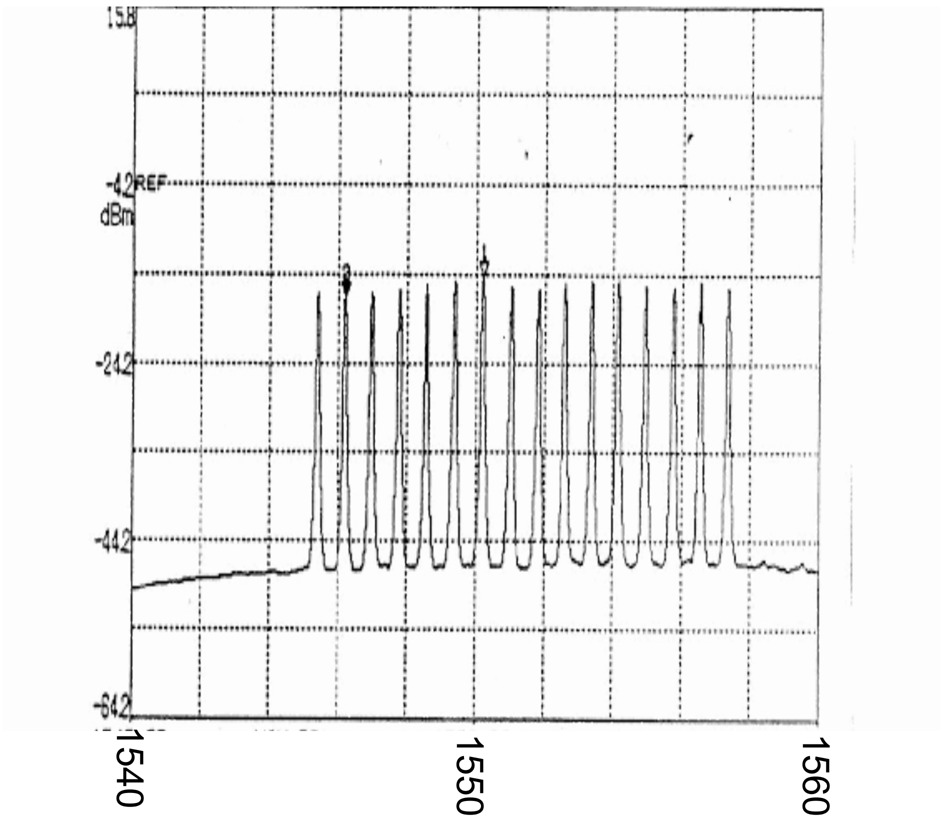


Wavelength-Division Multiplexing

- Different wavelengths carry separate signals
- Multiplex into shared optical fiber
- Each wavelength like a separate circuit
  - 192 channels • 10 Gbps = 1.92 Tbps
  - 64 channels • 40 Gbps = 2.56 Tbps



Coarse & Dense WDM



Coarse WDM

- Few wavelengths 4-18 with very wide spacing (~20 nm)
- Low-cost, simple

Dense WDM

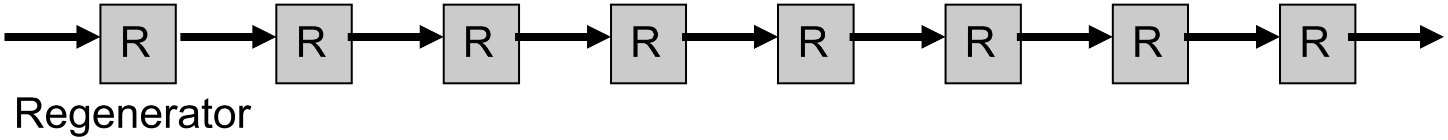
- Many tightly-packed wavelengths
- ITU Grid: 0.8 nm separation for 10 Gbps signals
- 0.4 nm for 2.5 Gbps

Regenerators & Optical Amplifiers

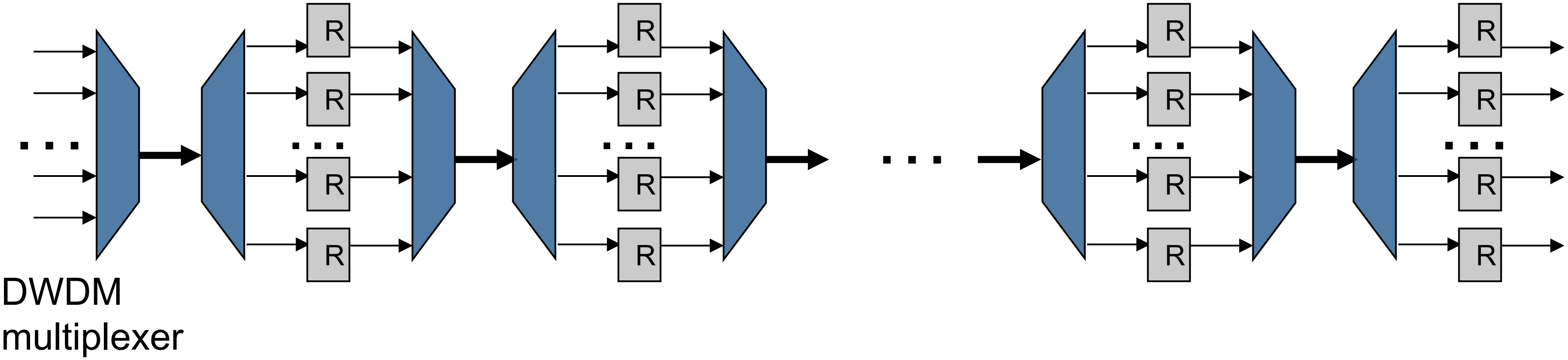
- The maximum span of an optical signal is determined by the available power & the attenuation:
  - Ex. If 30 dB power available,
  - then at 1550 nm, optical signal attenuates at 0.25 dB/km,
  - so max span = 30 dB/0.25 km/dB = 120 km
- Optical amplifiers amplify optical signal (no equalization, no regeneration)
- Impairments in optical amplification limit maximum number of optical amplifiers in a path
- Optical signal must be regenerated when this limit is reached
  - Requires optical-to-electrical (O-to-E) signal conversion, equalization, detection and retransmission (E-to-O)
  - Expensive
- Severe problem with WDM systems

DWDM & Regeneration

- Single signal per fiber requires 1 regenerator per span

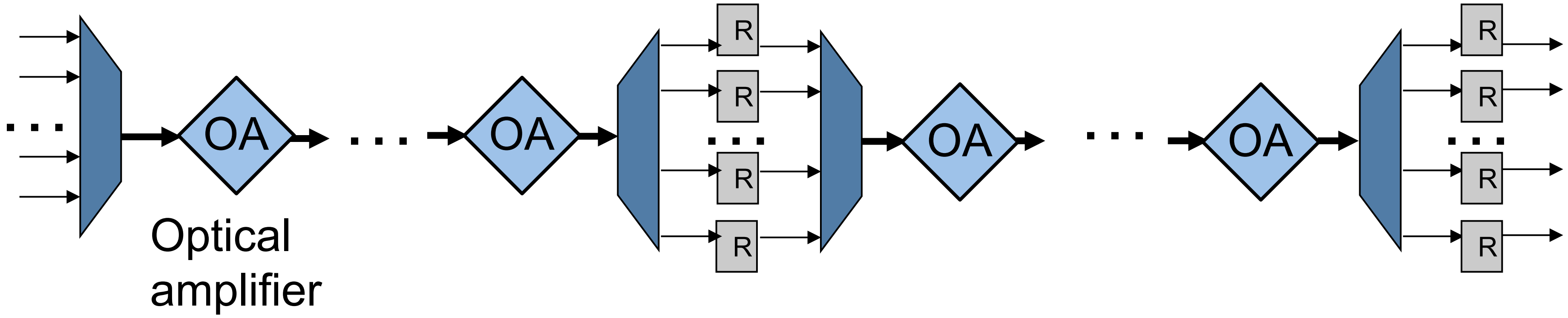


- DWDM system carries many signals in one fiber
- At each span, a separate regenerator required per signal
- Very expensive



Optical Amplifiers

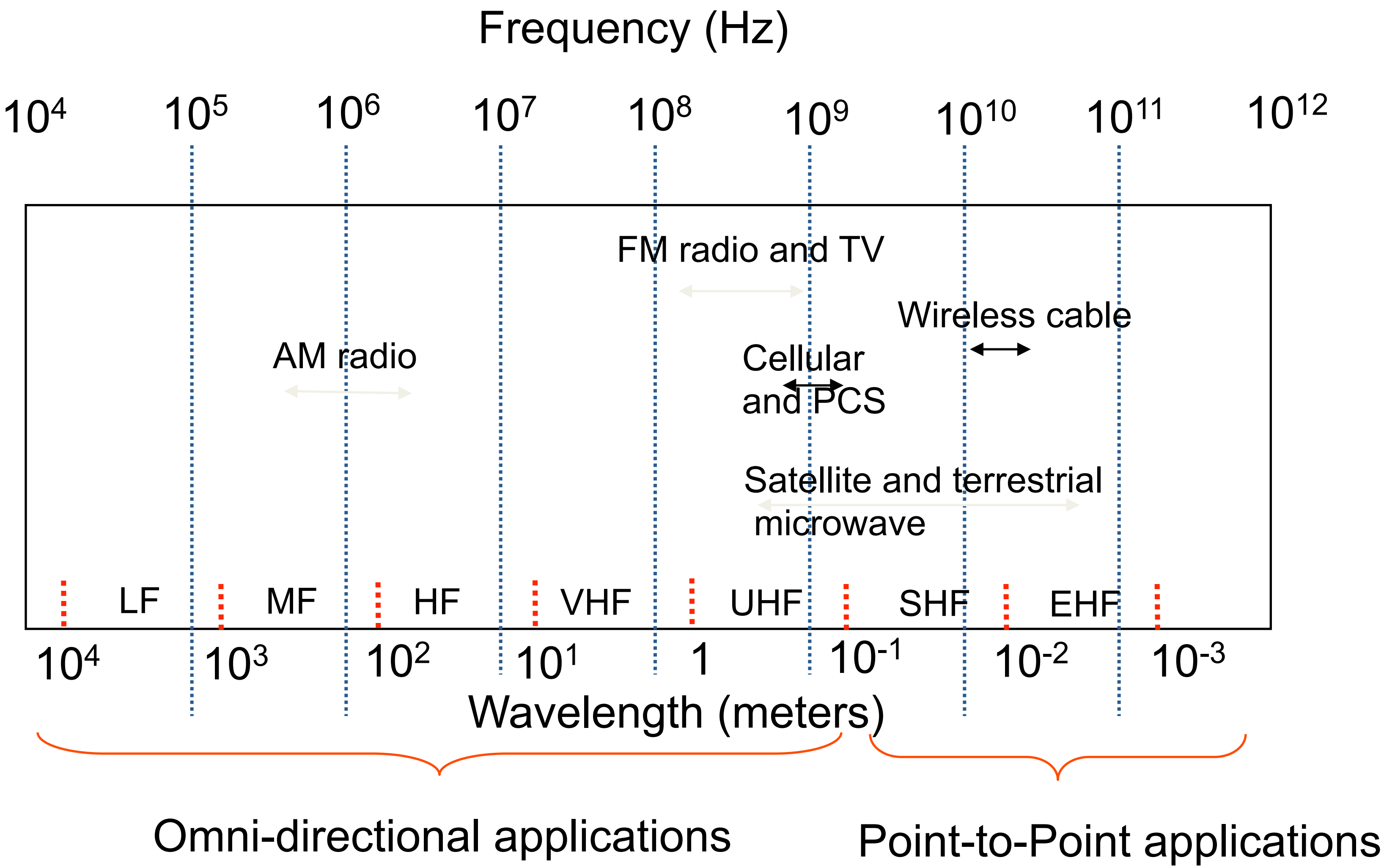
- Optical amplifiers can amplify the composite DWDM signal without demuxing or O-to-E conversion
- Erbium Doped Fiber Amplifiers (EDFAs) boost DWDM signals within 1530 to 1620 range
  - Spans between regeneration points >1000 km
  - Number of regenerators can be reduced dramatically
- Dramatic reduction in cost of long-distance communications



8.13 Radio Transmission

- Radio signals: antenna transmits sinusoidal signal ("carrier") that radiates in air/space
- Information embedded in carrier signal using modulation, e.g. QAM
- Communications without tethering
  - Cellular phones, satellite transmissions, Wireless LANs
- Multipath propagation causes fading
- Interference from other users
- Spectrum regulated by national & international regulatory organizations

Radio Spectrum



Examples

Cellular Phone

- Allocated spectrum
- First generation:
  - 800, 900 MHz
  - Initially analog voice
- Second generation:
  - 1800-1900 MHz
  - Digital voice, messaging

Wireless LAN

- Unlicensed ISM spectrum
  - Industrial, Scientific, Medical
  - 902-928 MHz, 2.400-2.4835 GHz, 5.725-5.850 GHz
- IEEE 802.11 LAN standard
  - 11-54 Mbps

Point-to-Multipoint Systems

- Directional antennas at microwave frequencies
- High-speed digital communications between sites
- High-speed Internet Access Radio backbone links for rural areas

Satellite Communications

- Geostationary satellite @ 36000 km above equator
- Relays microwave signals from uplink frequency to downlink frequency
- Long distance telephone
- Satellite TV broadcast