ECE 363
Communication Networks

Physical Layer

Physical Layer

- The purpose of the physical layer is to transport data from one machine to another
- Various physical media are used each with their own characteristics such as
  - Bandwidth
  - Delay
  - Cost
- Can be guided (wired) or unguided (wireless)

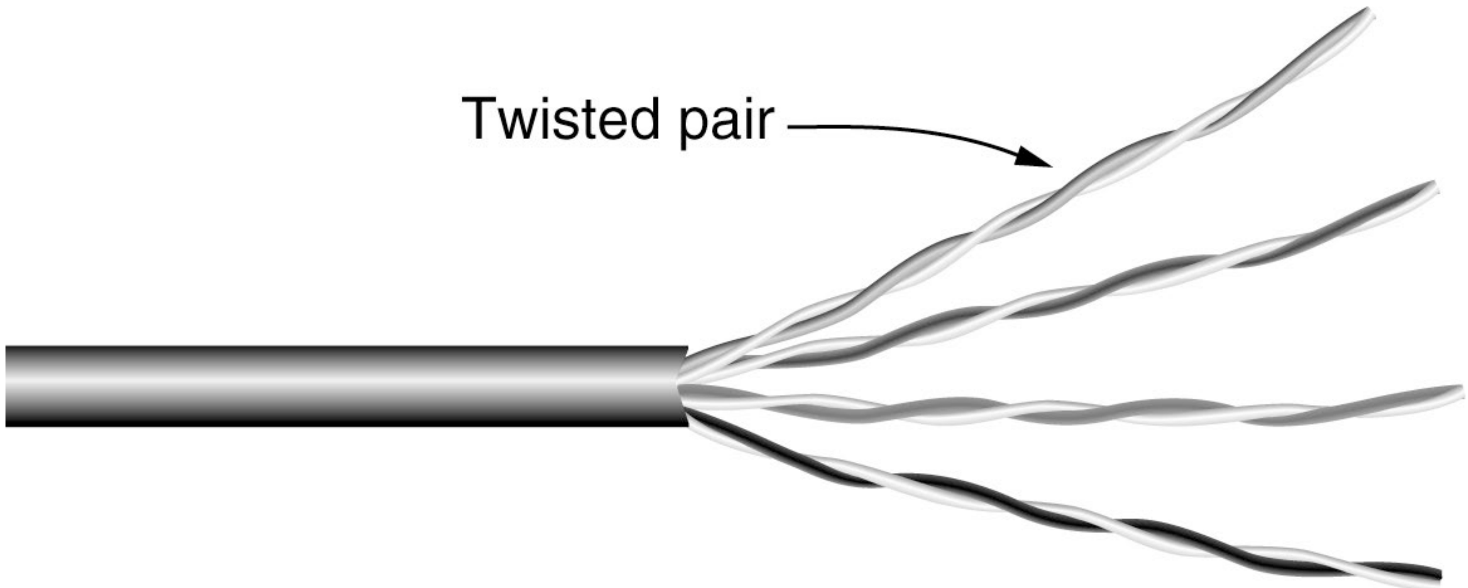
Guided Transmission Media

- Persistent storage
- Twisted pairs
- Coaxial cable
- Power lines
- Fiber optics

Persistent Storage

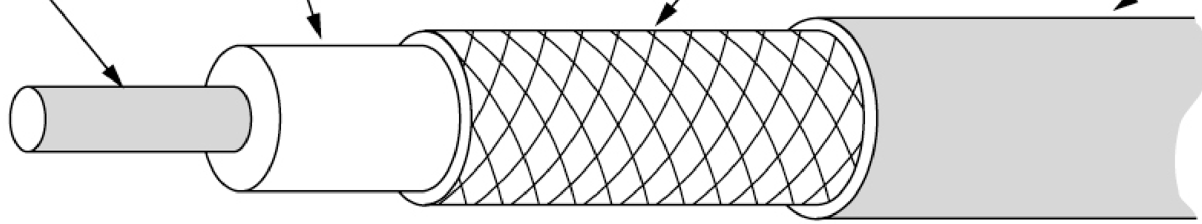
- Magnetic or solid-state storage
- Common and simple way to transport data
  - Write data to persistent storage
  - Physically transport the disks or tapes to the destination machine
  - Read data on the machine
- Cost effective when a high data rate or cost per bit transported is the key factor

Twisted Pairs



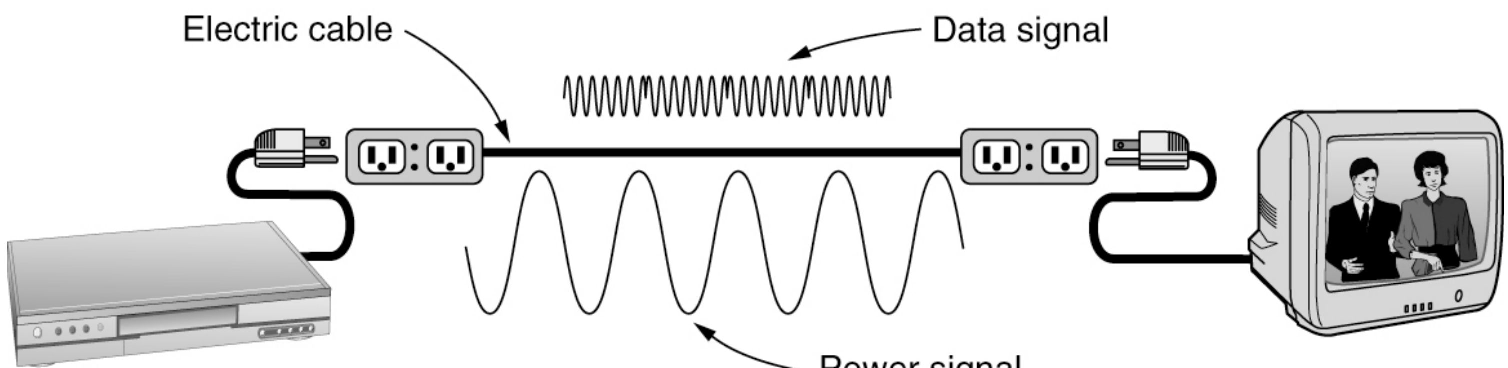
A category 5e twisted pair consists of two insulated wires gently twisted together. Four such pairs are typically grouped in a plastic sheath to protect the wires and keep them together.

Coaxial Cable



A coaxial cable consists of a stiff copper wire as the core, surrounded by an insulating material. The insulation is encased by a cylindrical conductor, often a closely woven braided mesh. The outer conductor is covered in a protective plastic sheath.

Power Lines



Using power lines for networking is simple. In this case, a TV and a receiver are plugged into the wall, which must be done anyway because they need power. Then they can send and receive data such as video over the electrical wiring.

Fiber Optics

- Has very large bandwidth
- Must consider costs
  - For installation over the last mile and to move bits
- Uses
  - Long-haul transmission in network backbones
  - High-speed LANs
  - High-speed Internet access
- Key components
  - Light source, transmission medium, and detector

Fiber Optics

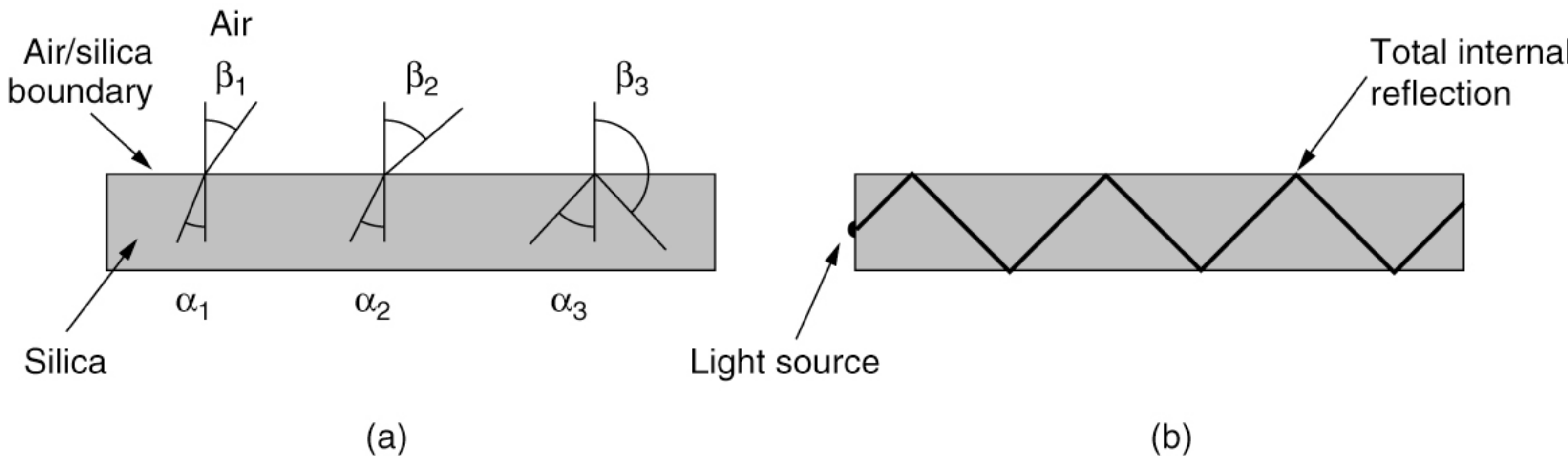


Figure (a) illustrates a light ray inside a silica fiber impinging on the air/silica boundary at different angles. Figure (b) illustrates light trapped by total internal reflection.

Fiber Optics

- Transmission of light through fiber
  - Attenuation of light through glass
    - Dependent on the wavelength of the light
    - Defined as the ratio of input to output signal power
- Fiber cables
  - Similar to coax, except without the braid
- Two kinds of signaling light sources
  - LEDs (Light Emitting Diodes)
  - Semiconductor lasers

Views of a Fiber Cable

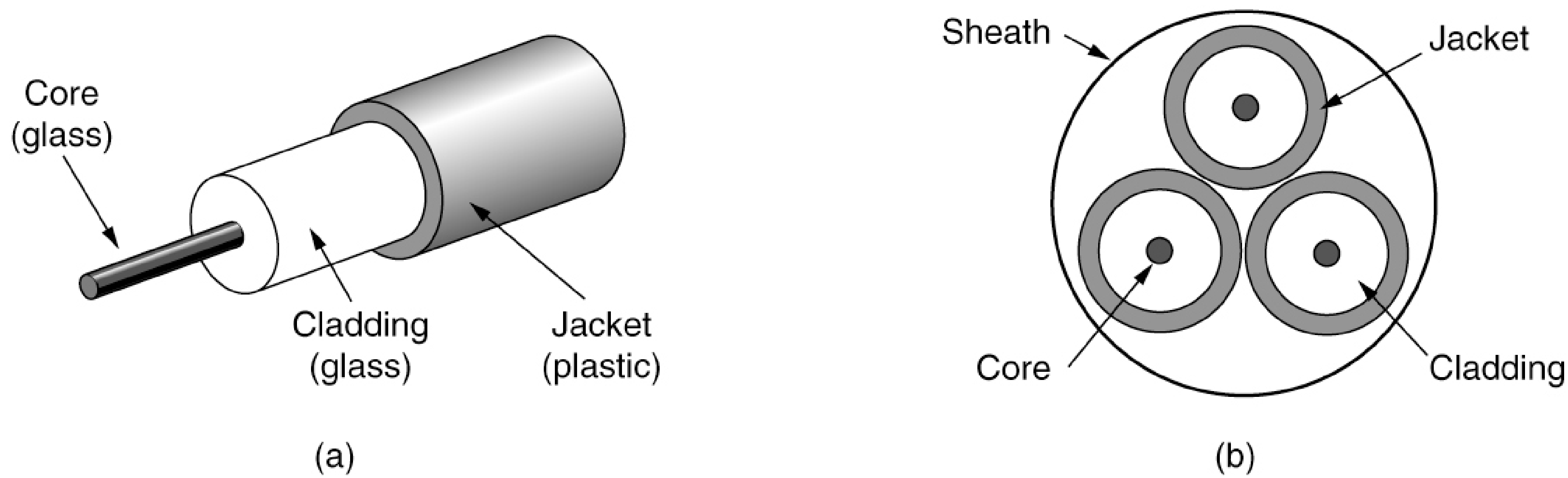
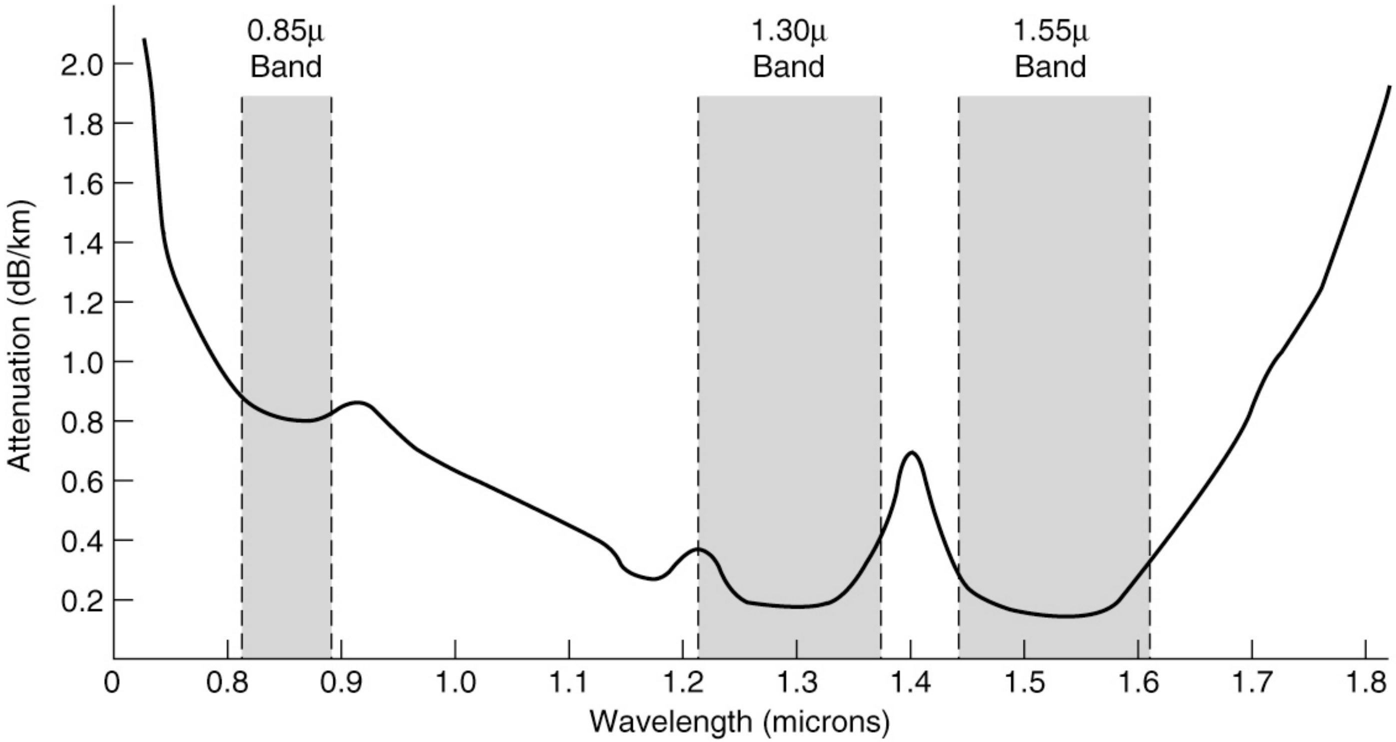


Figure (a) side view of a single fiber. Figure (b) End view of a sheath with three fibers.

Fiber Optic Attenuation



Attenuation of light through fiber in the infrared region is measured in units of decibels (dB) per kilometer of fiber.

Fiber Optics

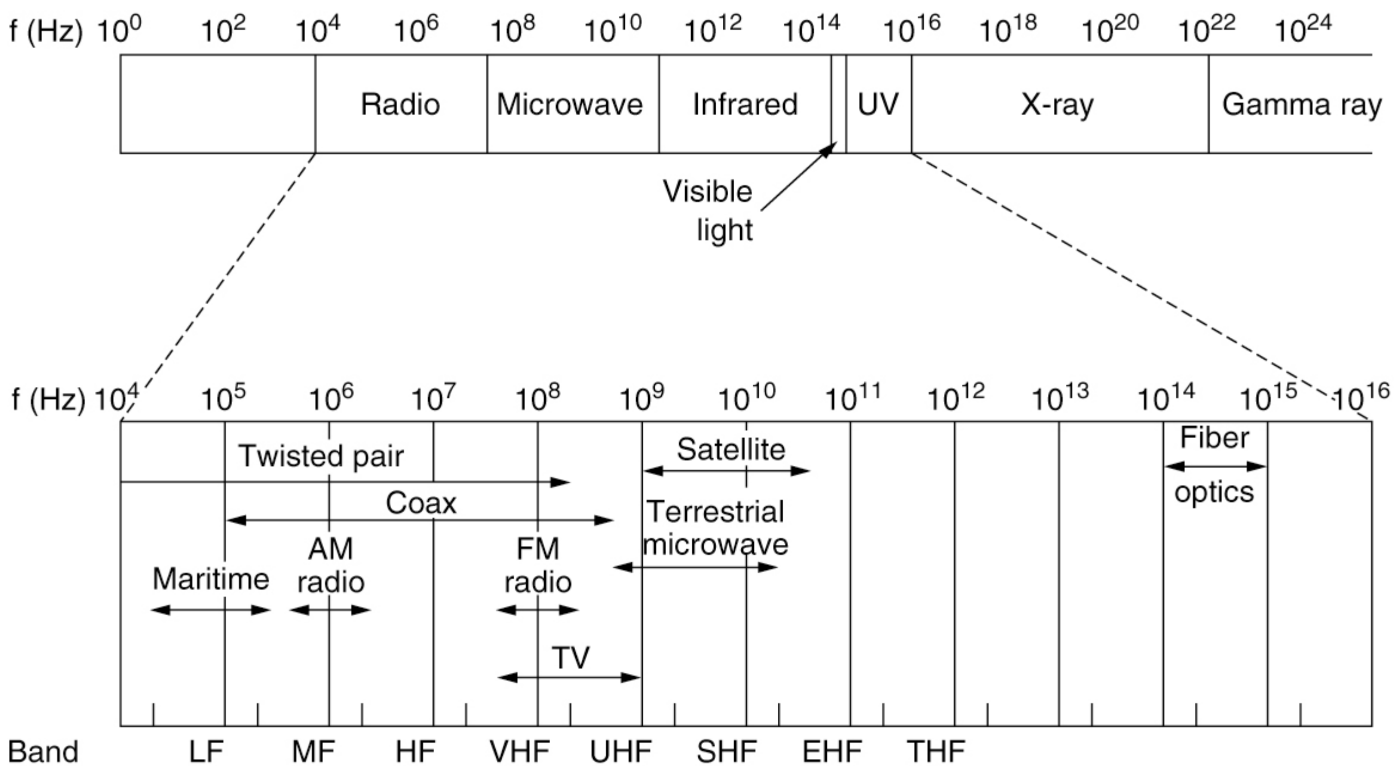
Item	LED	Semiconductor laser
Data rate	Low	High
Fiber type	Multi-mode	Multi-mode or single-mode
Distance	Short	Long
Lifetime	Long life	Short life
Temperature sensitivity	Minor	Substantial
Cost	Low cost	Expensive

A comparison of semiconductor diodes and LEDs as light sources.

Fiber Optics

- Fiber advantages over copper
  - Higher bandwidth
  - Not affected by power surges, electromagnetic interference, power failures, corrosive chemicals
  - Thin and lightweight
  - Does not leak light
  - Difficult to tap
- Fiber disadvantages
  - Technology that requires specific engineering skills
  - Fibers damaged easily by being bent too much

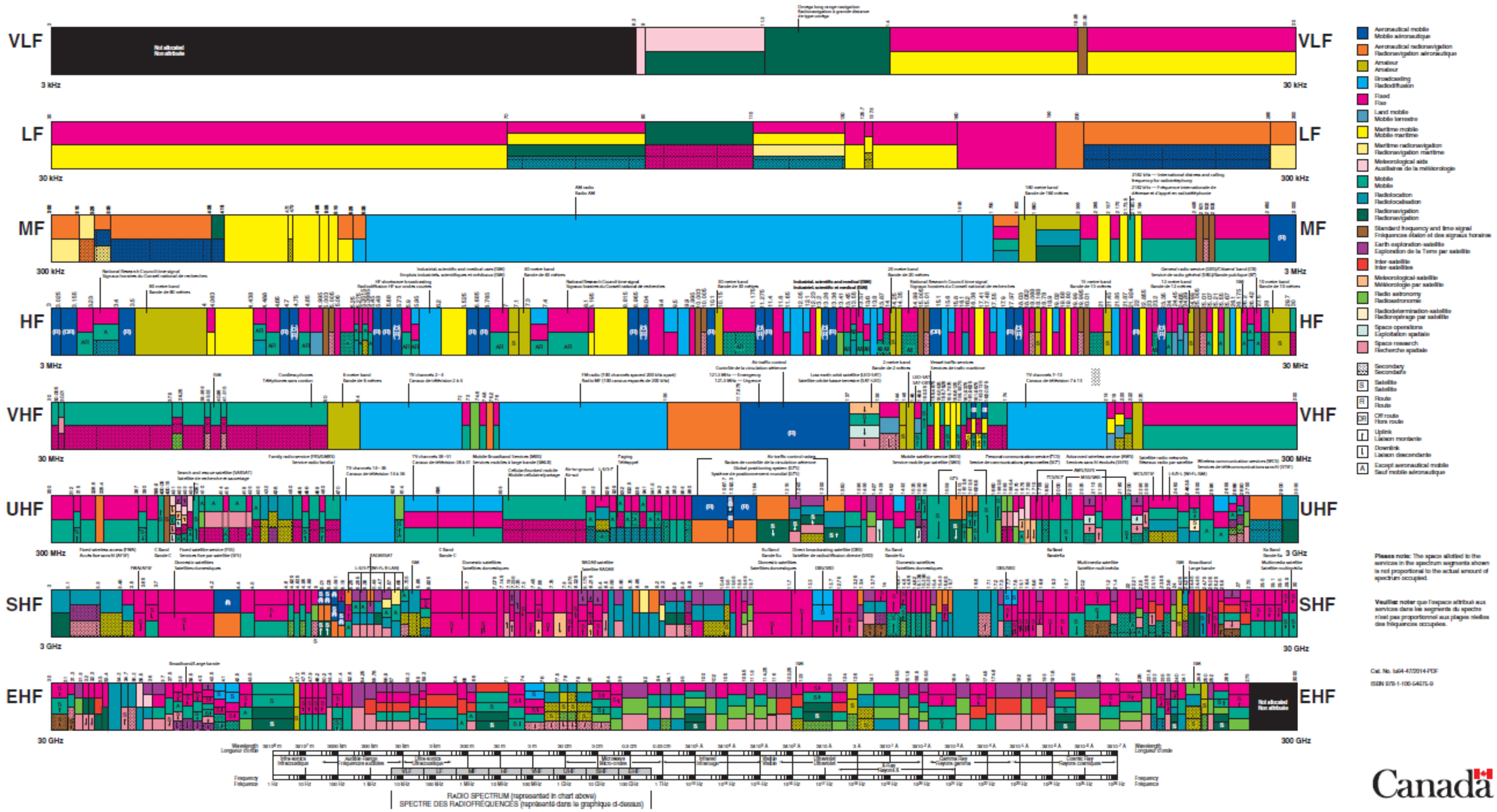
The Electromagnetic Spectrum



Wireless Radio Spectrum

- Radio spectrum is a national asset owned by the nation
- National governments determine how spectrum is used
- Two types of spectrum use
- licensed: dedicated use, typically by one owner (e.g., cellular carrier such as Telus, Bell)
  - often allocated by spectrum auction
- unlicensed: open (free) for anyone to use, conforming to rules (e.g., power transmission levels)
  - 2.4GHz and 5 Ghz WiFi

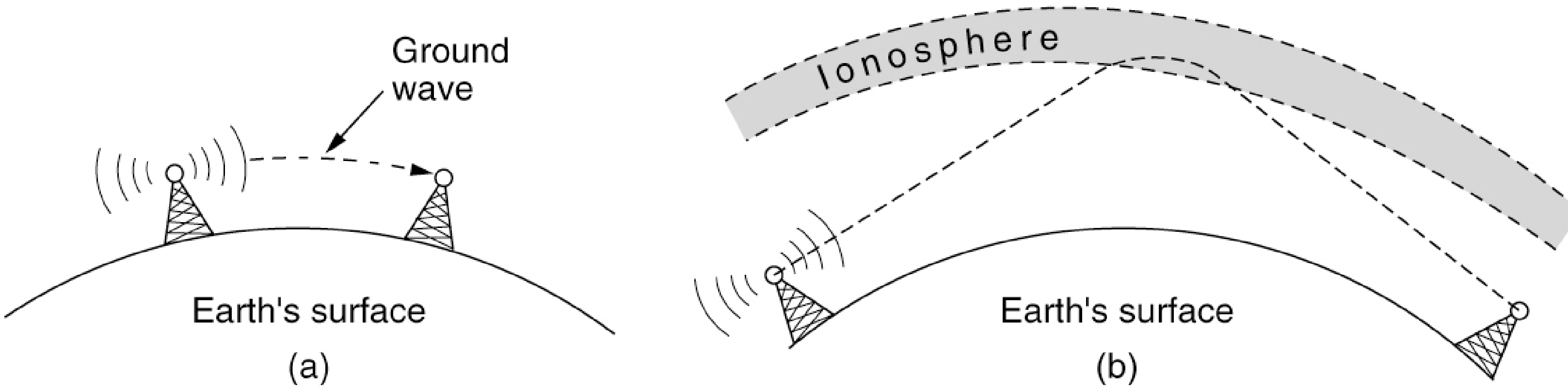
Radio Spectrum Allocation in Canada



Using the Spectrum for Transmission

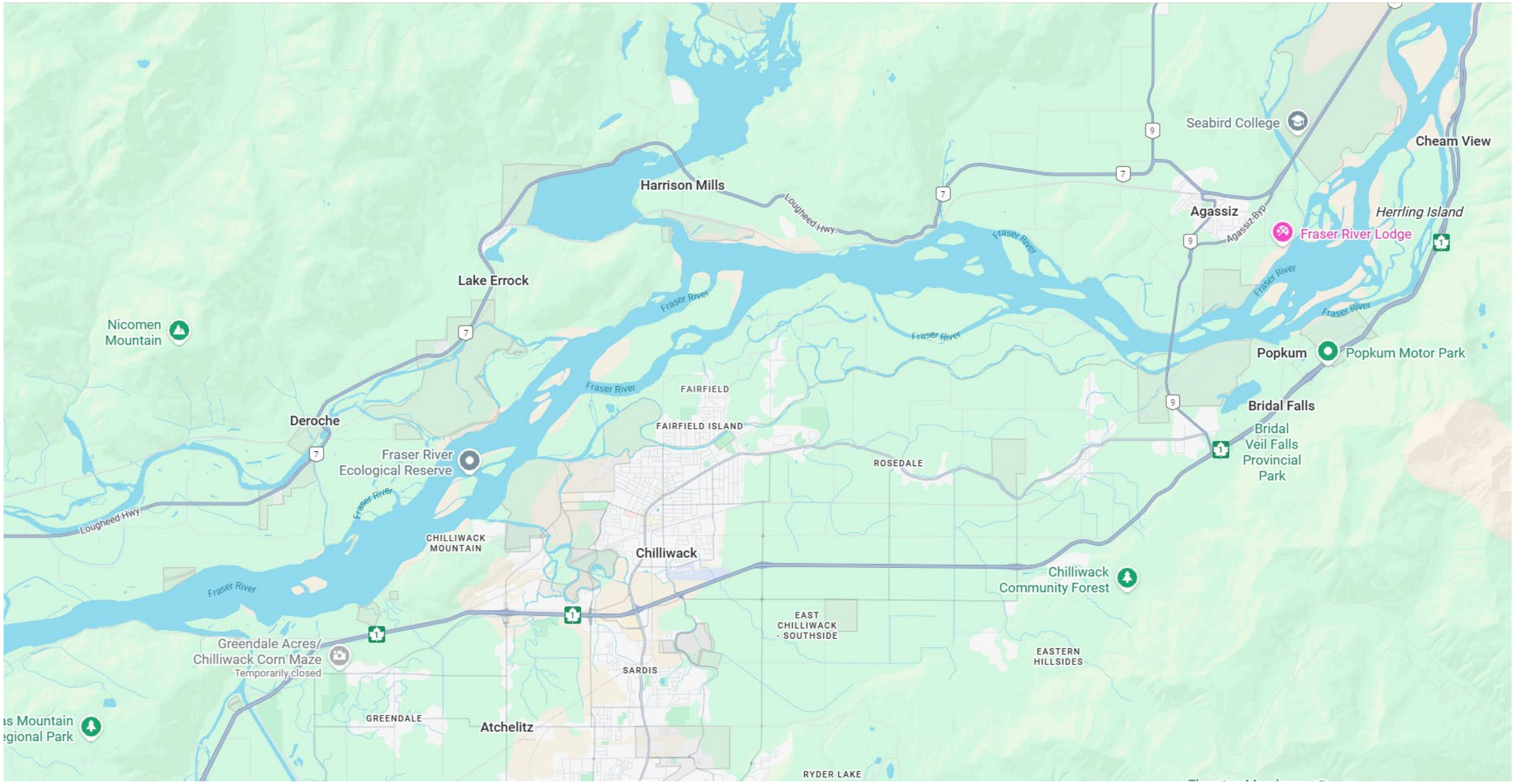
- Radio transmission
  - Omnidirectional waves, easy to generate, travel long distances, penetrate buildings
- Microwave transmission
  - Directional waves requiring repeaters, do not penetrate buildings
- Infrared transmission
  - Unguided waves used for short-range communication, relatively directional, cheap, easy to build, do not penetrate solid walls
- Light transmission
  - Unguided optical communication

Radio Transmission

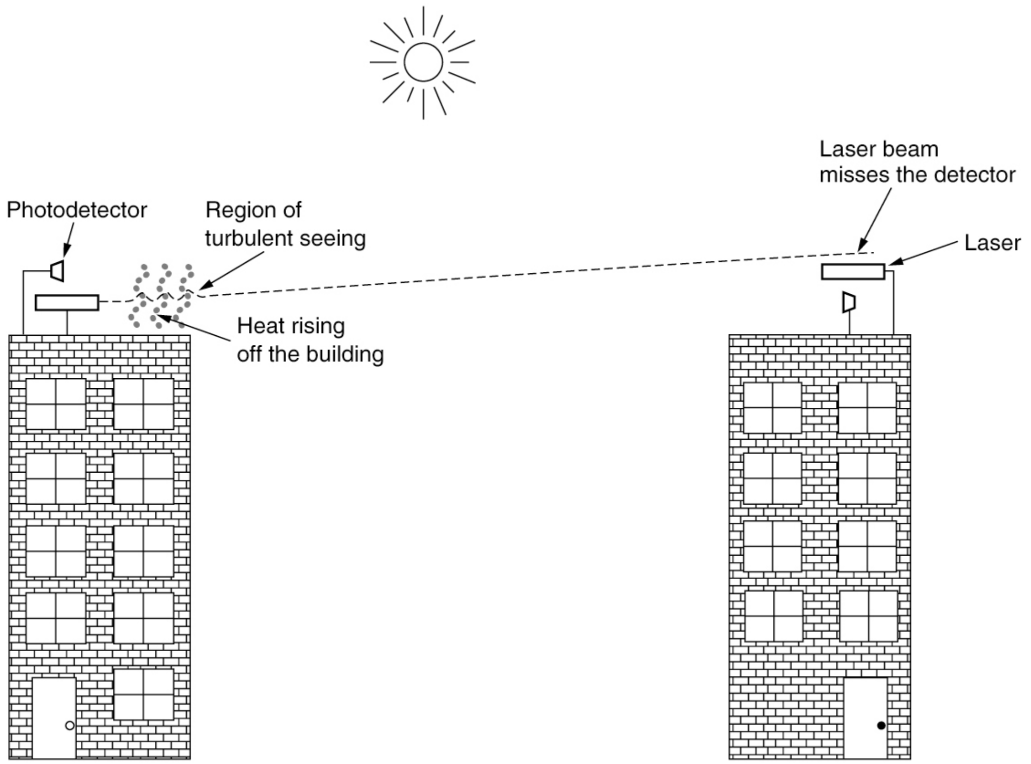


In the VLF, LF, and MF bands, radio waves follow the curvature of the earth. In the HF band, they bounce off the ionosphere.

Microwave Transmission



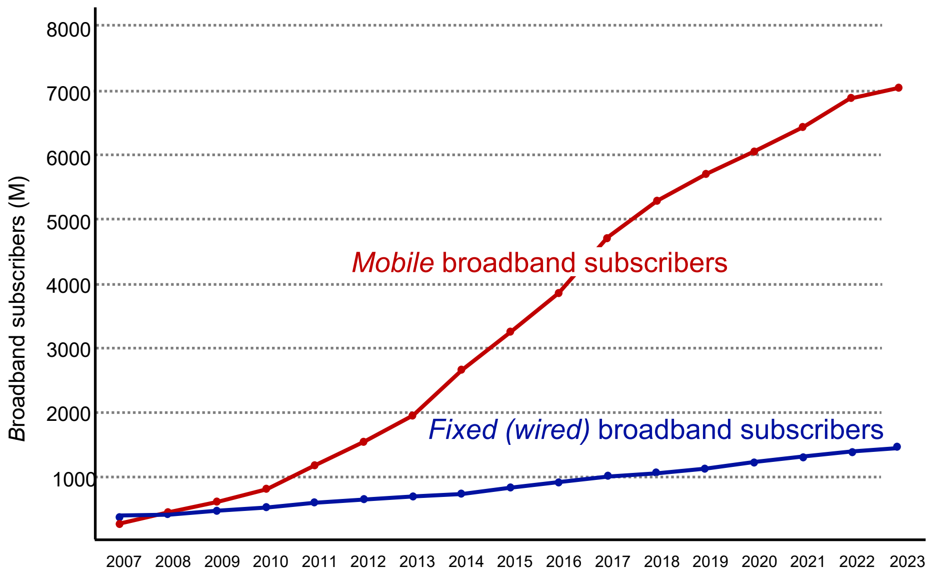
Light Transmission



A bidirectional system with two lasers. Convection currents can interfere with laser communication systems.

Wireless Transmission

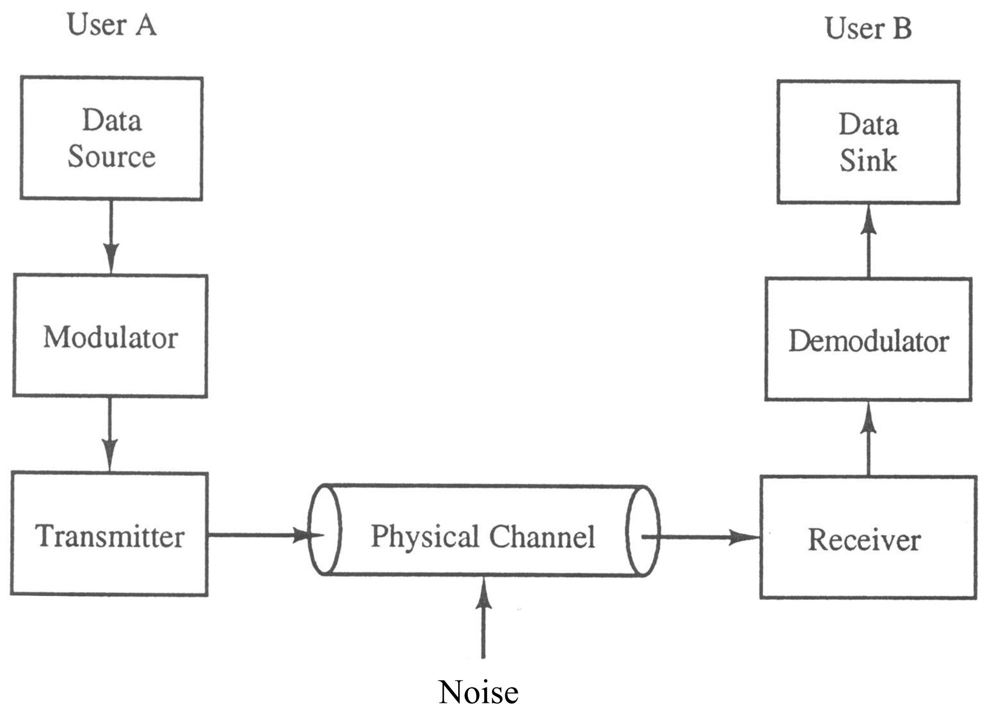
- There are more mobile-broadband-connected (cellular) devices than fixed-broadband-connected devices
- Wireless connectivity is even greater when WiFi users are considered (80% of broadband homes use WiFi)
- 60% of Internet traffic from major websites is destined for mobile devices



Digital Modulation

- Digital modulation is the process of converting bits to analog signals (waveforms) for transmission
- Baseband transmission
  - The signal occupies frequencies from 0 Hz up to a maximum depending on the data rate
  - Commonly used with wired transmission
- Passband transmission
  - The signal occupies a band of frequencies around the carrier frequency f_c
  - Commonly used for wireless transmission
- Channels are often shared by multiple signals
  - Called multiplexing

Digital Communication System



Modulator/Transmitter

- Matches the data to the channel
- Modulation maps the data bits to waveforms
- These waveforms are transmitted through the channel

Receiver/Demodulator

- The receiver amplifies and filters the signal
- The demodulator extracts the data from the receiver output
  - Converts the receiver output to bits

Channel

- Physical medium which signals are transmitted through
- Examples: air, coaxial cables, fiber optic cables, space, water
- Every channel introduces some amount of distortion, noise, and/or interference
  - Creates errors in the data

Maximum Data Rate of a Channel

Nyquist proved that for a channel (noiseless) of bandwidth *B*, the maximum data rate is

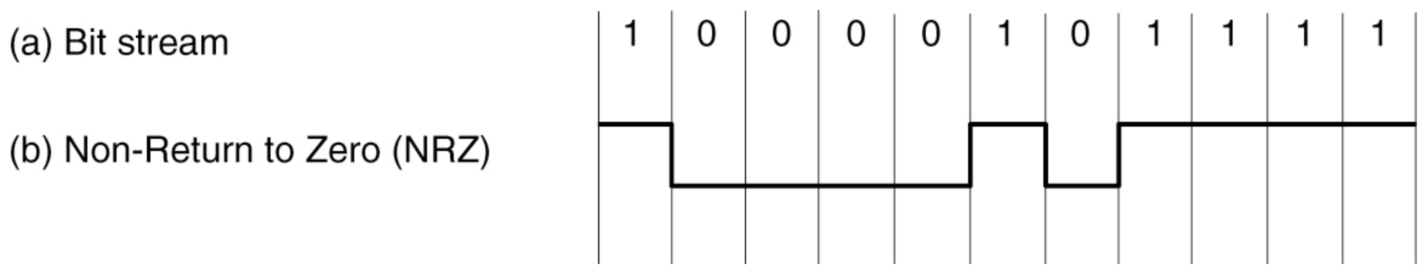
$$R = 2B\log_2 V \text{ bits/sec}$$

where *V* is the number of signal levels

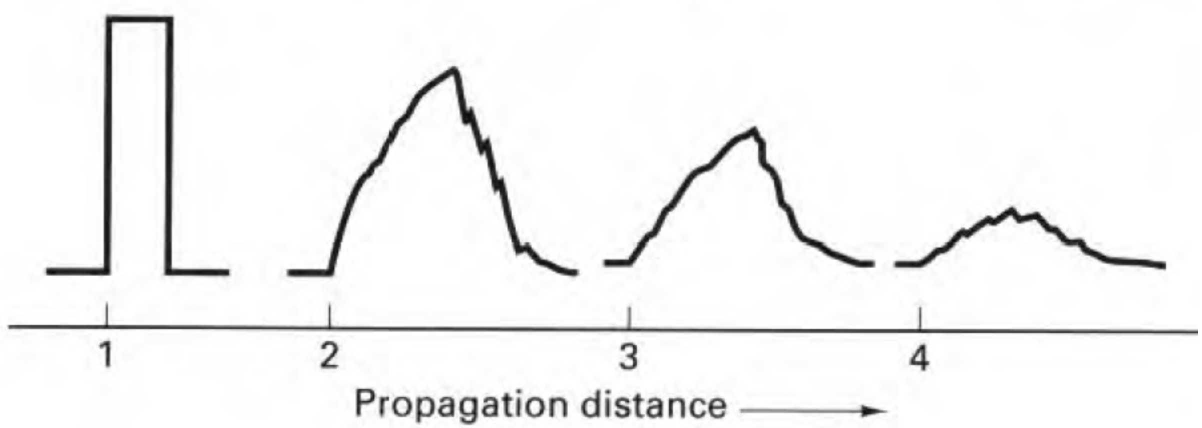
Harry T. Nyquist (1889-1976)

Baseband (Wired) Transmission

- The simplest form of digital modulation is to use a positive voltage for 1 and a negative voltage for 0
  - Non-Return-to-Zero (NRZ)



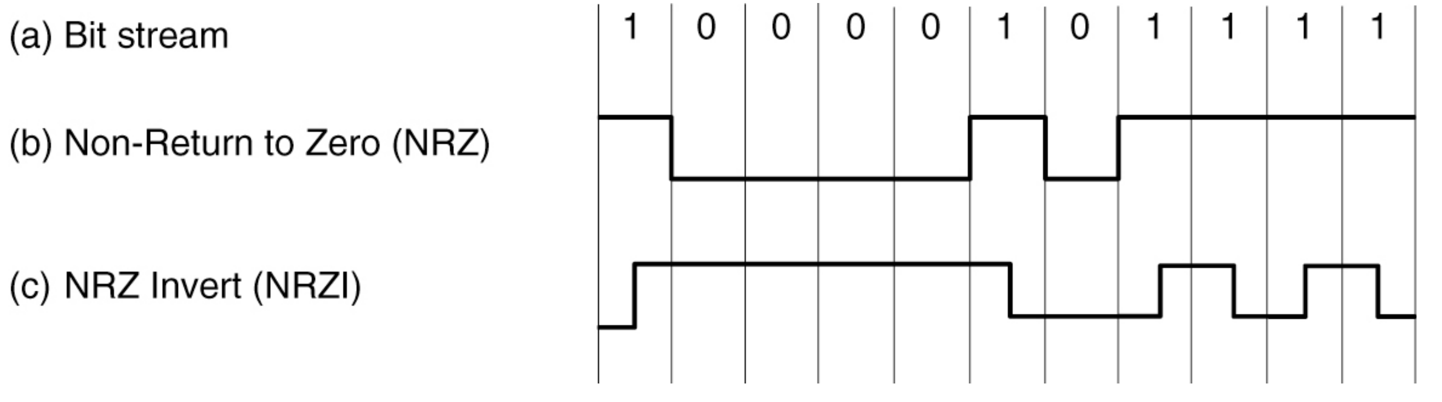
Baseband Transmission



The transmitted pulse becomes distorted as it travels through the wire

Baseband (Wired) Transmission

- The simplest form of digital modulation is to use a positive voltage for 1 and a negative voltage for 0
  - Non-Return-to-Zero (NRZ)
- Encode a 1 as a transition and a 0 as no transition
  - Non-Return-to-Zero-Inverted (NRZI)



Synchronization

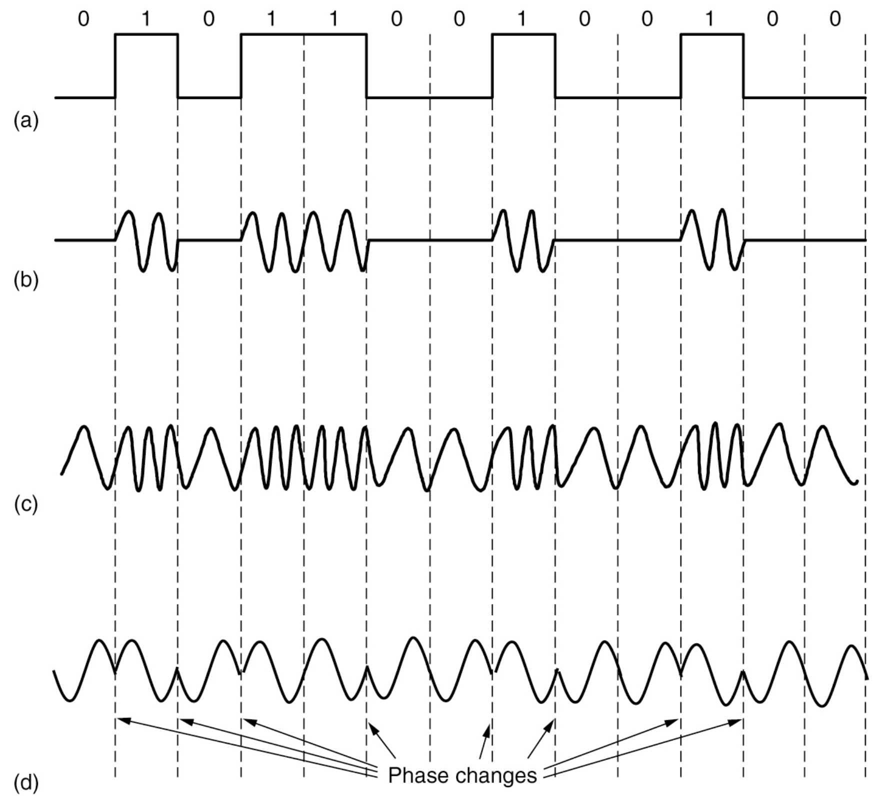
Data (4B)	Codeword (5B)	Data (4B)	Codeword (5B)
0000	11110	1000	10010
0001	01001	1001	10011
0010	10100	1010	10110
0011	10101	1011	10111
0100	01010	1100	11010
0101	01011	1101	11011
0110	01110	1110	11100
0111	01111	1111	11101

4B/5B mapping

Passband (Wireless) Transmission

- Modulate the amplitude, frequency, or phase of the signal using the data
- Amplitude Shift Keying (ASK)
- Frequency Shift Keying (FSK)
- Phase Shift Keying (PSK)

Binary Modulation



(a) Binary signal (b) Amplitude shift keying
(c) Frequency shift keying (d) Phase shift keying

Binary Modulation

- BPSK

$$\text{data } 0 \leftrightarrow s_0(t) = -\sqrt{2S}\cos(2\pi f_c t) \qquad 0 \le t \le T_b$$

$$\text{or} \quad \sqrt{2S}\cos(2\pi f_c t + \pi)$$

$$\text{data } 1 \leftrightarrow s_1(t) = \sqrt{2S}\cos(2\pi f_c t) \qquad 0 \le t \le T_b$$

- BFSK

$$\text{data } 0 \leftrightarrow s_0(t) = \sqrt{2S}\cos(2\pi f_0 t) \qquad 0 \le t \le T_b$$

$$\text{data } 1 \leftrightarrow s_1(t) = \sqrt{2S}\cos(2\pi f_1 t) \qquad 0 \le t \le T_b$$

Binary Modulation

- Energy = Power × Time
- $S = E_b/T_b = E_b R_b$
- $R_b = 1/T_b$ bits/sec

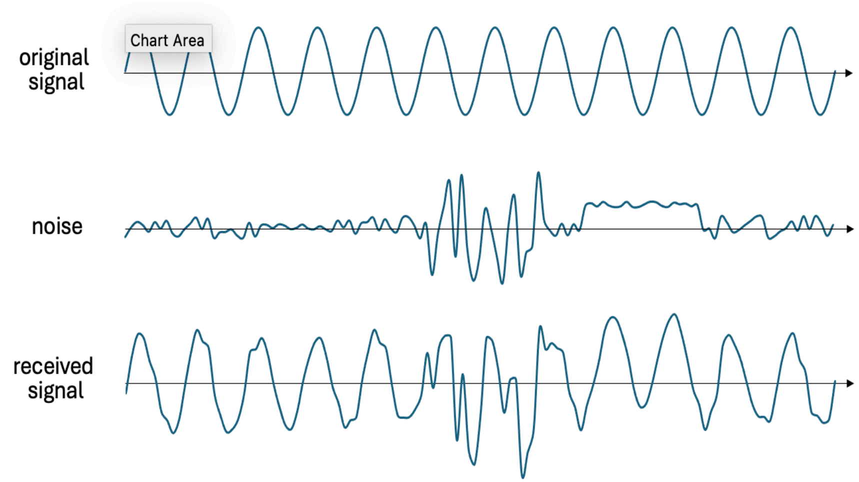
- Power levels are typically expressed in decibels (dB)
  - $S_{dB} = 10\log_{10} S_{watts}$

- The most common noise model is

  additive white Gaussian noise (AWGN)
  - Noise power spectral density N_0

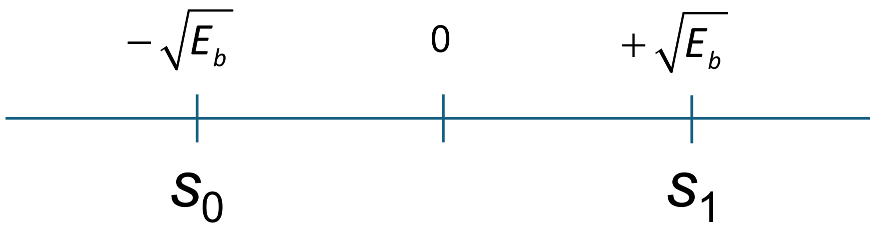
Noise and Interference

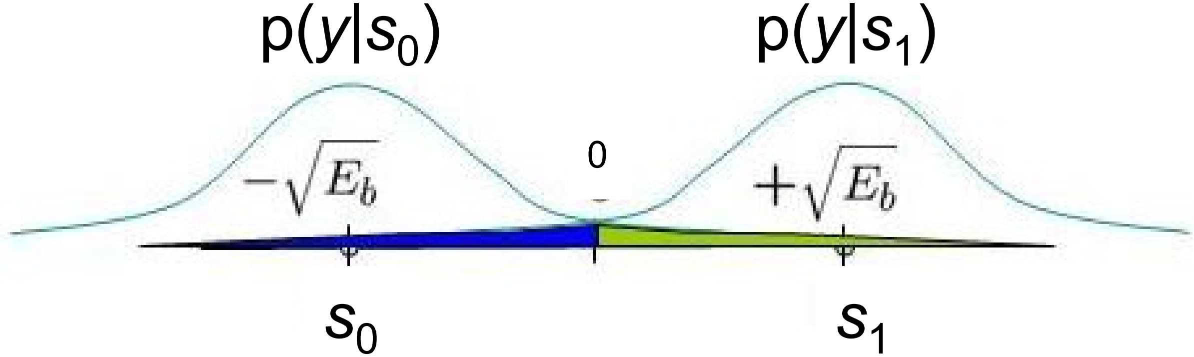
- Interference: other transmitters and EM radiation in the same frequency band
  - hundreds of consumer devices operate in unlicensed bands: WiFi, Bluetooth, Zigbee, satellite TV, microwave ovens, garage-door openers, baby monitors, cordless phones, wireless speakers, radio-controlled drones and toys, amateur radio, ...
- Thermal and electronic noise in receivers
  - natural thermal variations, imperfections in electronics



Original signal, noise, and noisy received signal

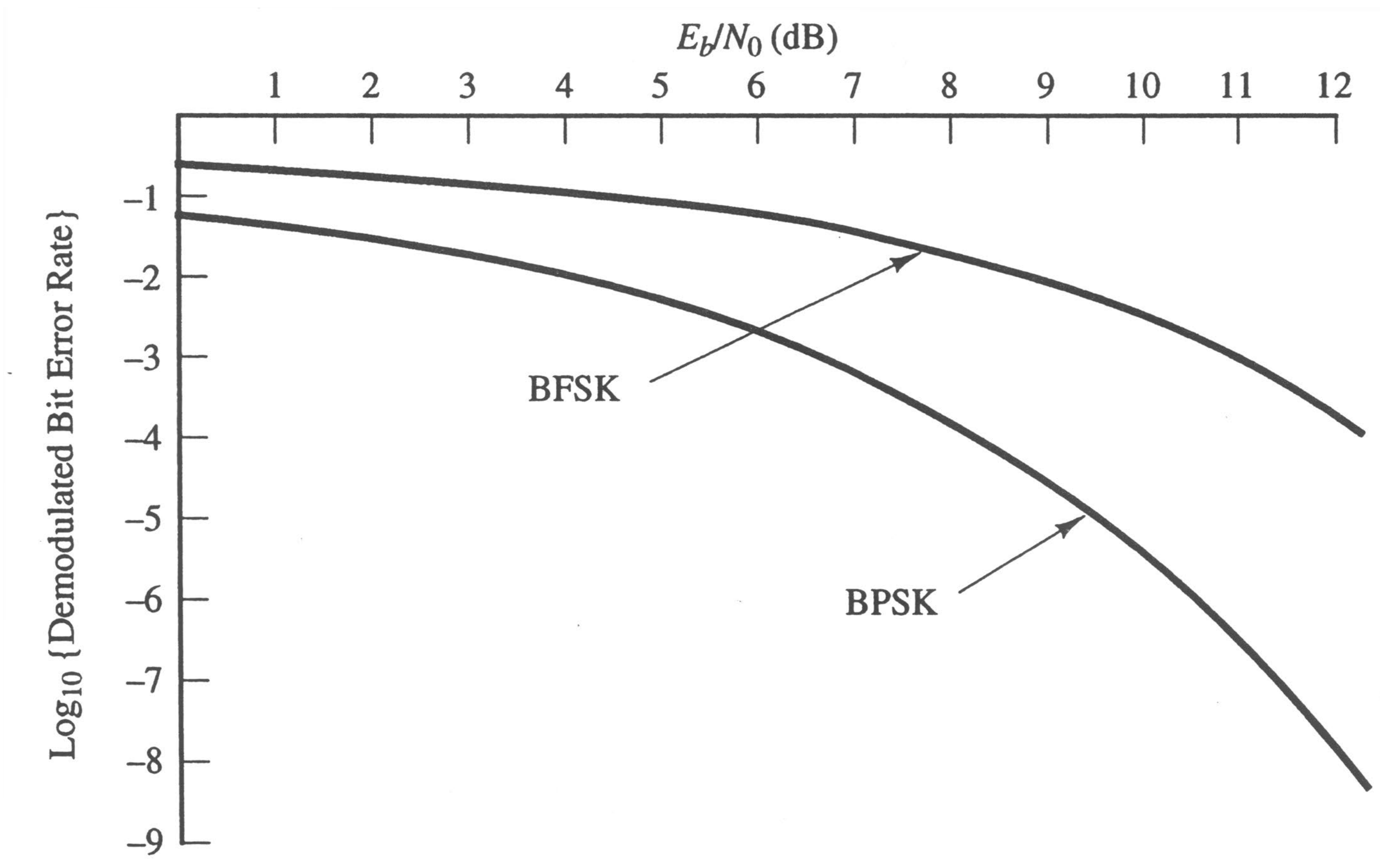
BPSK Demodulation in AWGN





$$f(y \mid s_k) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(y - s_k)^2}{2\sigma^2} \right]$$

Performance of BPSK and BFSK in AWGN



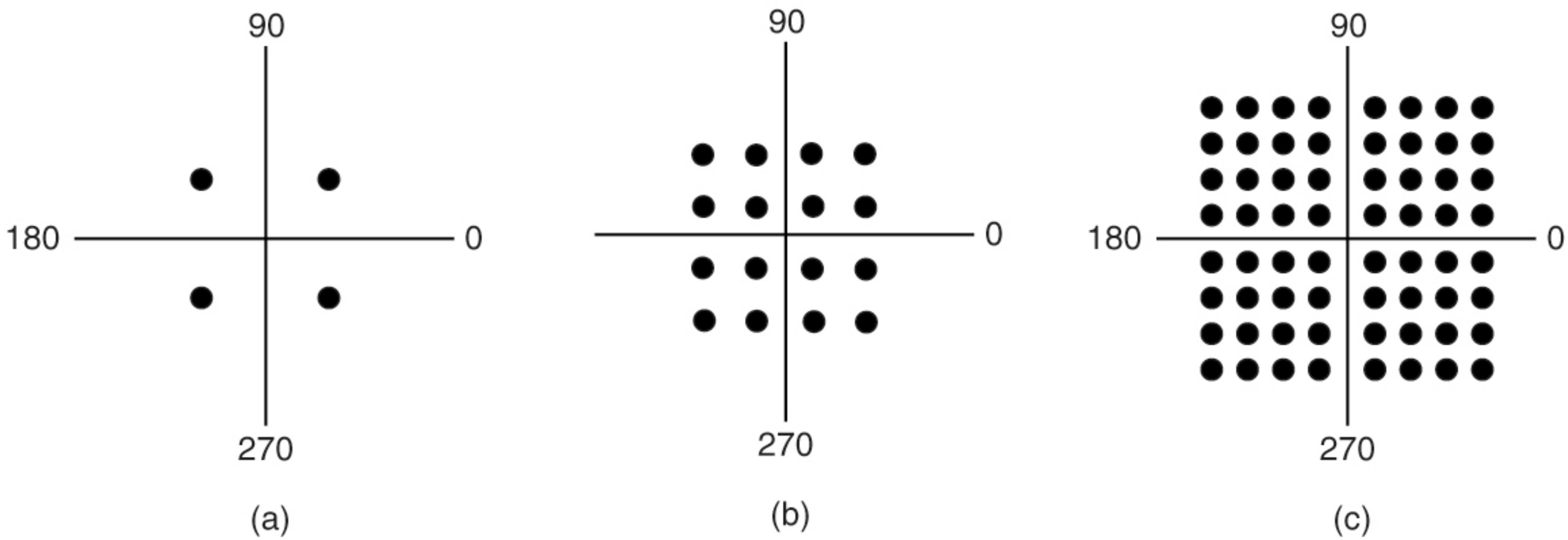
Bandwidth Efficiency

- Bandwidth is a limited resource
- To improve the efficiency
  - Use more than two signaling levels
  - By using four levels we can send 2 bits as a single symbol
  - The signal at the receiver must be sufficiently strong to distinguish the four levels
  - V levels can represent $\log_2 V$ bits
  - Example: 16-PSK symbols represent 4 bits

M-ary Modulation

- In MASK (PAM) a group of n bits is transmitted using $M=2^n$ different amplitudes
- In MPSK a group of n bits is transmitted using $M=2^n$ different phases
- In MFSK a group of n bits is transmitted using $M=2^n$ different frequencies
- Quadrature amplitude modulation (QAM) uses a combination of amplitude and phase modulation to convey information

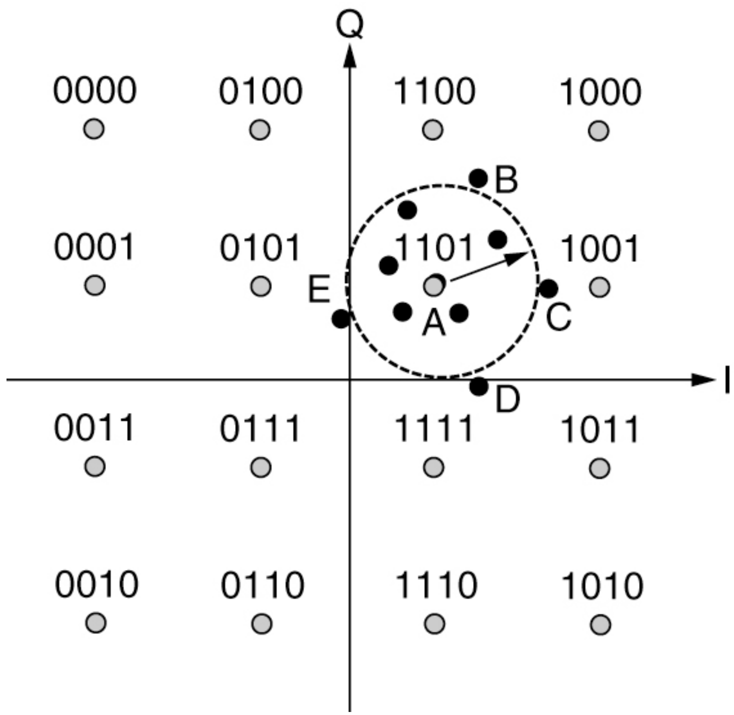
M-ary Modulation



(a) QPSK (b) 16-QAM (c) 64-QAM

M-ary Modulation

Gray-coded 16-QAM



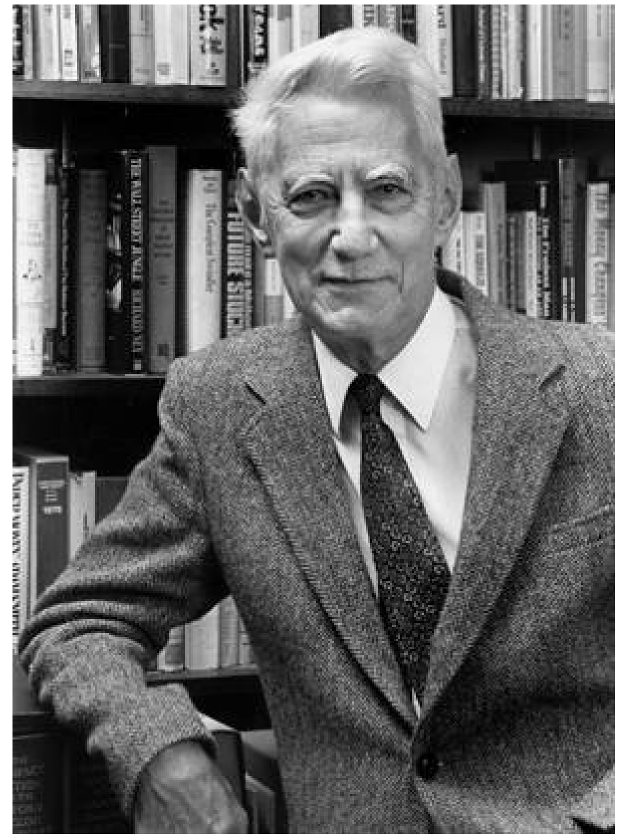
When 1101 is sent:

Point	Decodes as	Bit errors
A	1101	0
B	1100	1
C	1001	1
D	1111	1
E	0101	1

A Mathematical Theory of Communication, BSTJ July 1948

The fundamental problem of communication is that of reproducing at one point exactly or approximately a message selected at another point.

If the channel is noisy, it is not in general possible to reconstruct the original message or the transmitted signal with certainty by any operation on the received signal.



Claude Shannon (1916-2001)

Channel Capacity

Shannon proved that for a channel (noisy) of bandwidth W, the maximum data rate (capacity) is

$$C = W\log_2(1+S/N) \text{ bits/sec}$$

where S/N is the Signal to Noise Ratio (SNR)

Signal to Noise Ratio (SNR)

SNR: ratio of average received signal power to average noise power (often measured in dB)

$$\text{SNR (dB)} = 10 \cdot \log_{10}\left(\frac{\text{received signal power}}{\text{noise power}}\right)$$

- high (low) SNR: easy (hard) to extract the data from the received signal
- lower limit for cellular: -10 to -6 dB
- lower limit for WiFi: 20 dB

AWGN Channel Capacity

$$C = W \log_2 \left(1 + \frac{S}{N} \right)$$

$$S = E_b R \qquad N = N_0 W$$

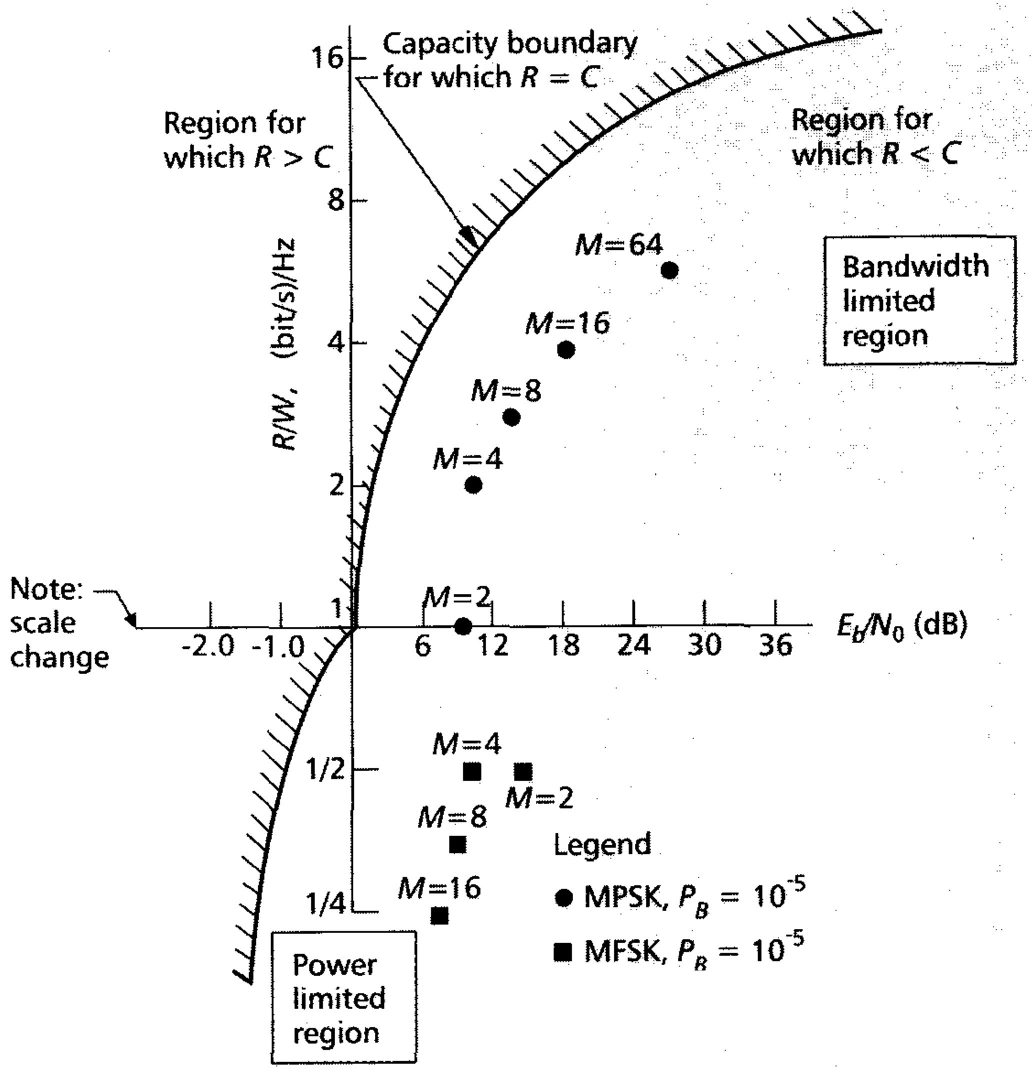
$$C = W \log_2 \left(1 + \frac{E_b R}{N_0 W} \right)$$

Let $R = C$

$$\frac{R}{W} = \log_2 \left(1 + \frac{E_b}{N_0} \frac{R}{W} \right)$$

$$\frac{E_b}{N_0} = \frac{2^{R/W} - 1}{R / W}$$

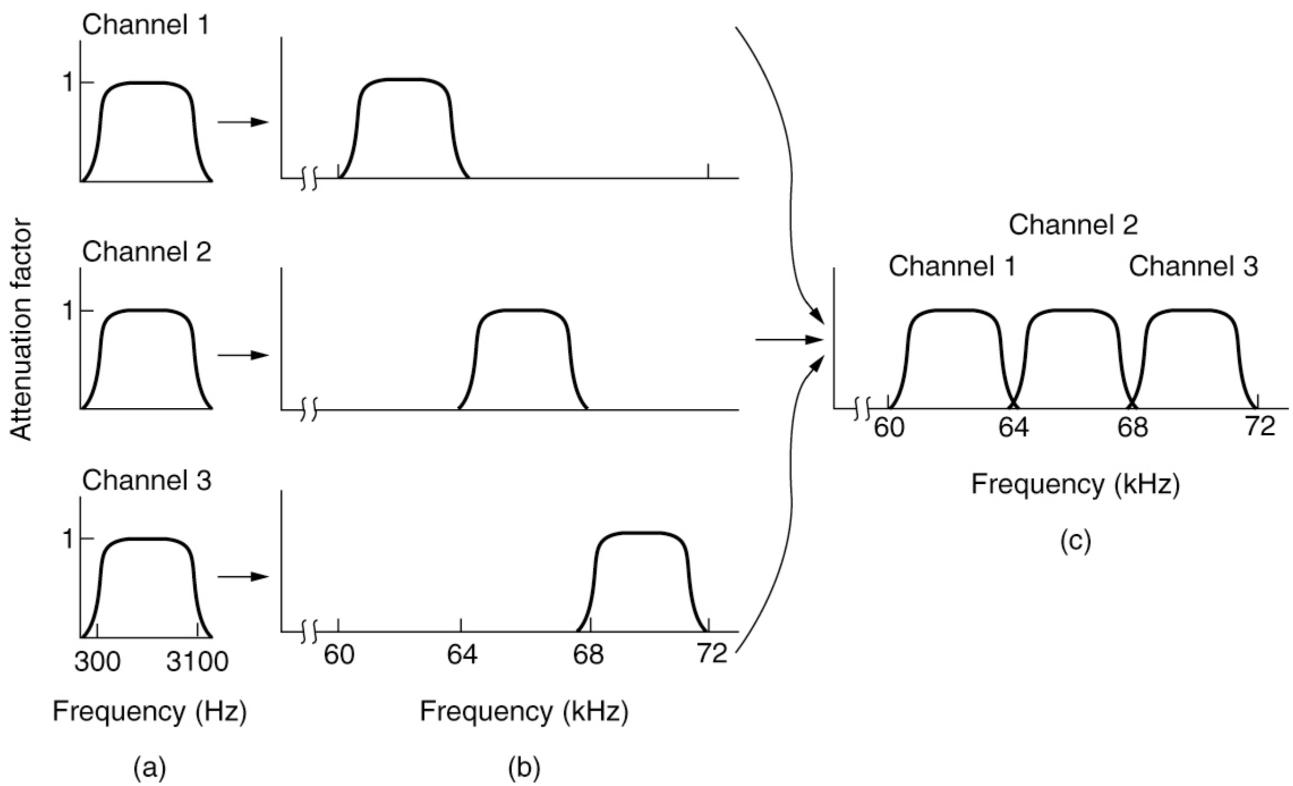
Bandwidth Efficiency (R/W) versus E_b/N_0



Multiplexing

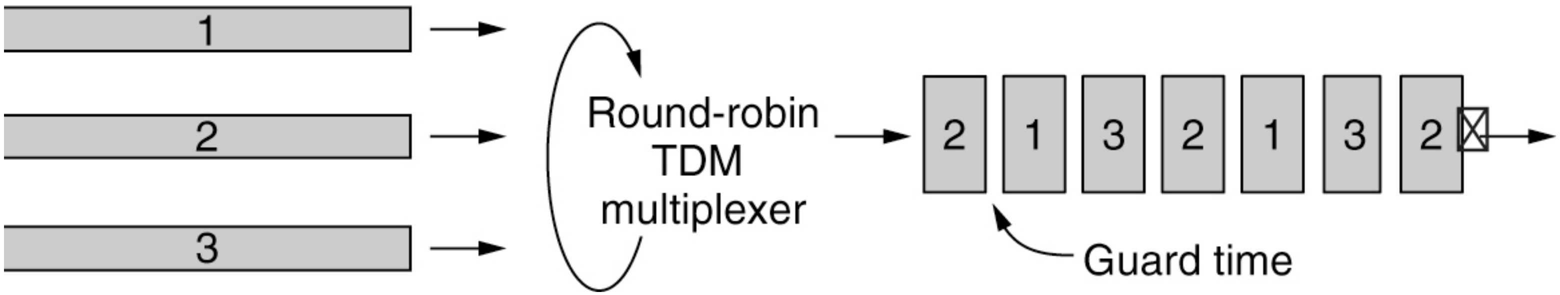
- Frequency Division Multiplexing (FDM)
- Time Division Multiplexing (TDM)
- Code Division Multiplexing (CDM)
- Wavelength Division Multiplexing (WDM)

Frequency Division Multiplexing



(a) original bandwidths (b) bandwidths shifted in frequency
(c) multiplexed channels

Time Division Multiplexing



Code Division Multiplexing

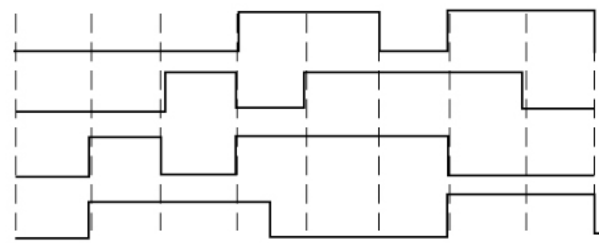
$A = (-1\ -1\ -1\ +1\ +1\ -1\ +1\ +1)$

$B = (-1\ -1\ +1\ -1\ +1\ +1\ +1\ -1)$

$C = (-1\ +1\ -1\ +1\ +1\ +1\ -1\ -1)$

$D = (-1\ +1\ -1\ -1\ -1\ -1\ +1\ -1)$

(a)



(b)

$S_1 = C \qquad\qquad\quad = (-1\ +1\ -1\ +1\ +1\ +1\ -1\ -1)$

$S_2 = B+C \qquad\quad\ = (-2\ \ 0\ \ 0\ \ 0\ +2\ +2\ \ 0\ -2)$

$S_3 = A+\overline{B} \qquad\quad = (\ 0\ \ 0\ -2\ +2\ \ 0\ -2\ \ 0\ +2)$

$S_4 = A+\overline{B}+C \qquad = (-1\ +1\ -3\ +3\ +1\ -1\ -1\ +1)$

$S_5 = A+B+C+D = (-4\ \ 0\ -2\ \ 0\ +2\ \ 0\ +2\ -2)$

$S_6 = A+B+\overline{C}+D = (-2\ -2\ \ 0\ -2\ \ 0\ -2\ +4\ \ 0)$

(c)

$S_1 \bullet C = [1+1+1+1+1+1+1+1]/8 = 1$

$S_2 \bullet C = [2+0+0+0+2+2+0+2]/8 = 1$

$S_3 \bullet C = [0+0+2+2+0-2+0-2]/8 = 0$

$S_4 \bullet C = [1+1+3+3+1-1+1-1]/8 = 1$

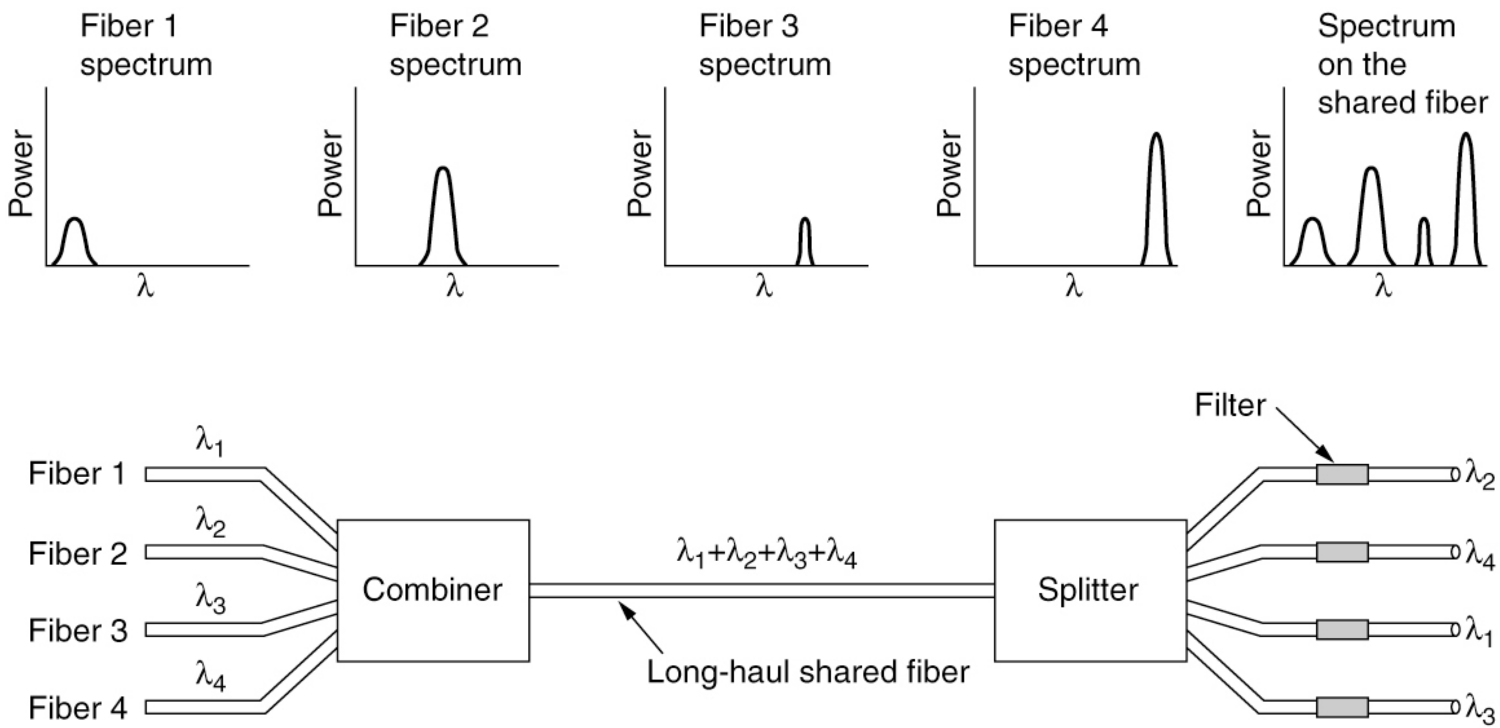
$S_5 \bullet C = [4+0+2+0+2+0-2+2]/8 = 1$

$S_6 \bullet C = [2-2+0-2+0-2-4+0]/8 = -1$

(d)

(a) Chip sequences for four stations (b) Signals the sequences represent. (c) Six examples of transmissions. (d) Recovery of station C signal.

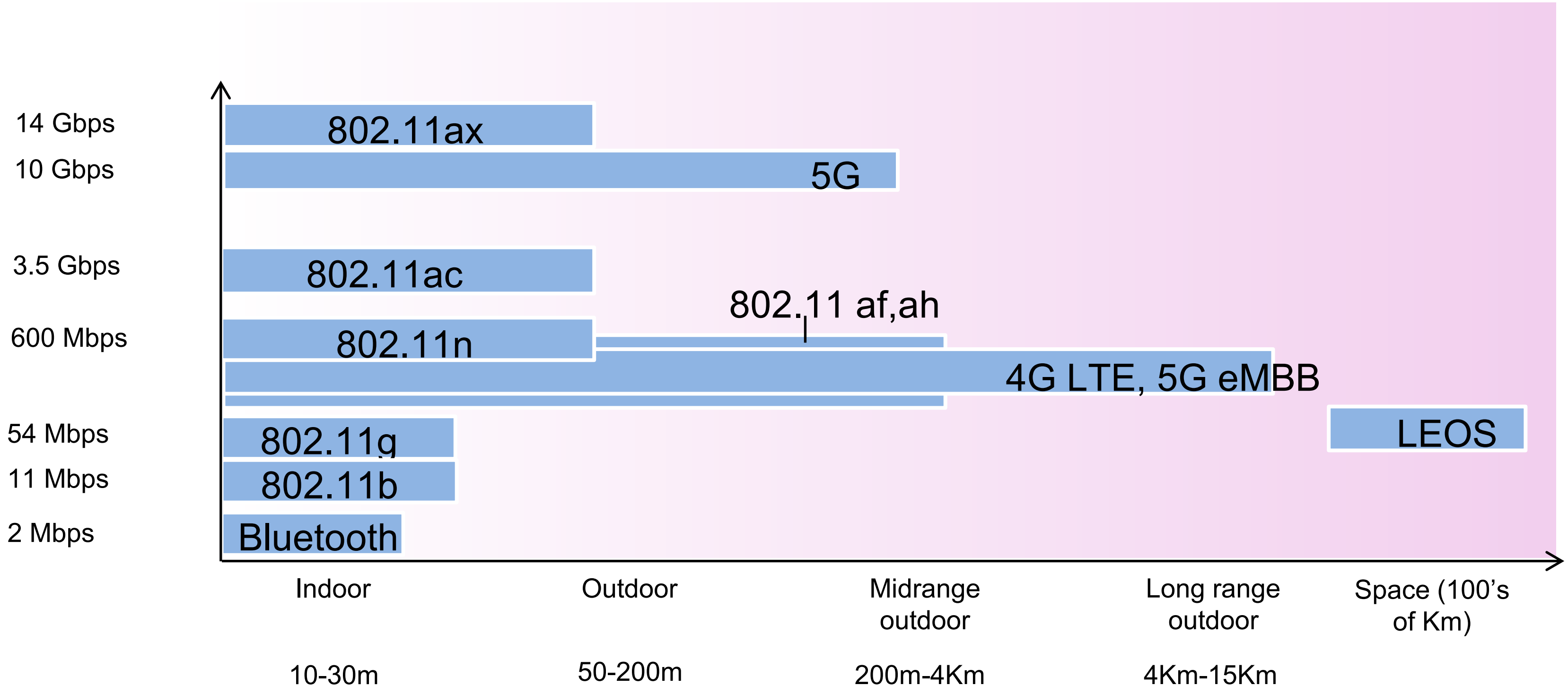
Wavelength Division Multiplexing



Cellular Networks

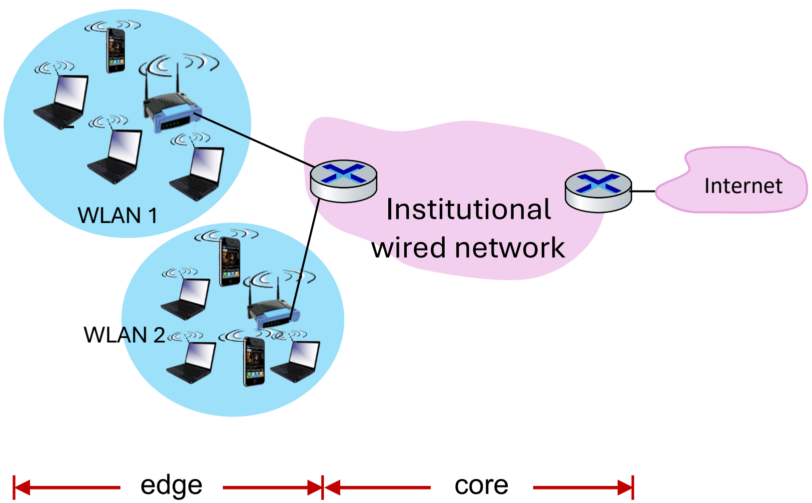
- Initial three generations: 1G, 2G, 3G
  - Provided analog voice, digital voice, and both digital voice and data (e.g. Internet, email), respectively
- 4G
  - Based on packet switching only (no circuit switching)
  - IP network separating voice traffic from the data network
- 5G
  - Supports up to 20 Gbps transmissions and denser deployments
  - Focus on reducing network latency

Characteristics of Wireless Links

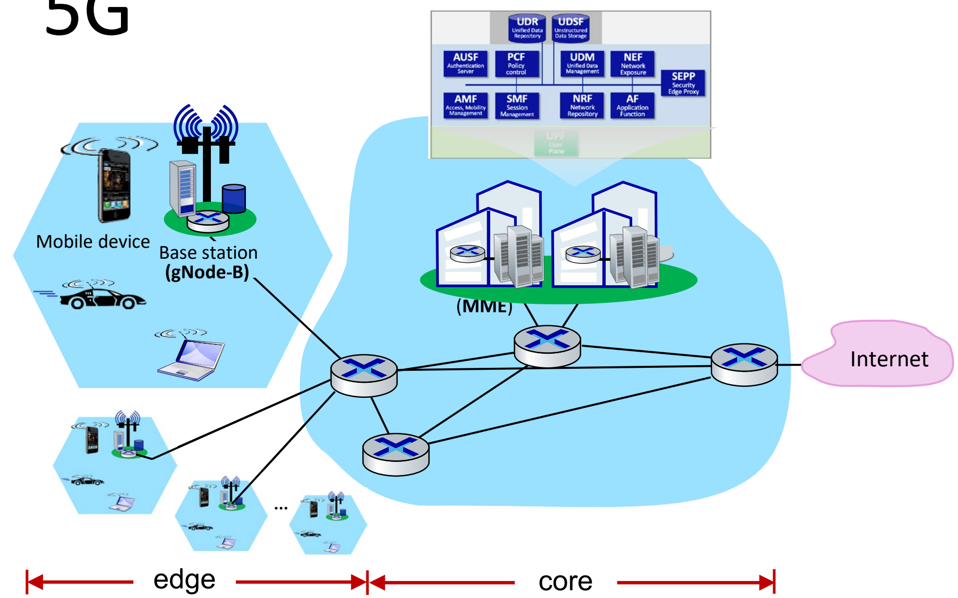


Wireless Networks
Edge and Core Networks

WiFi



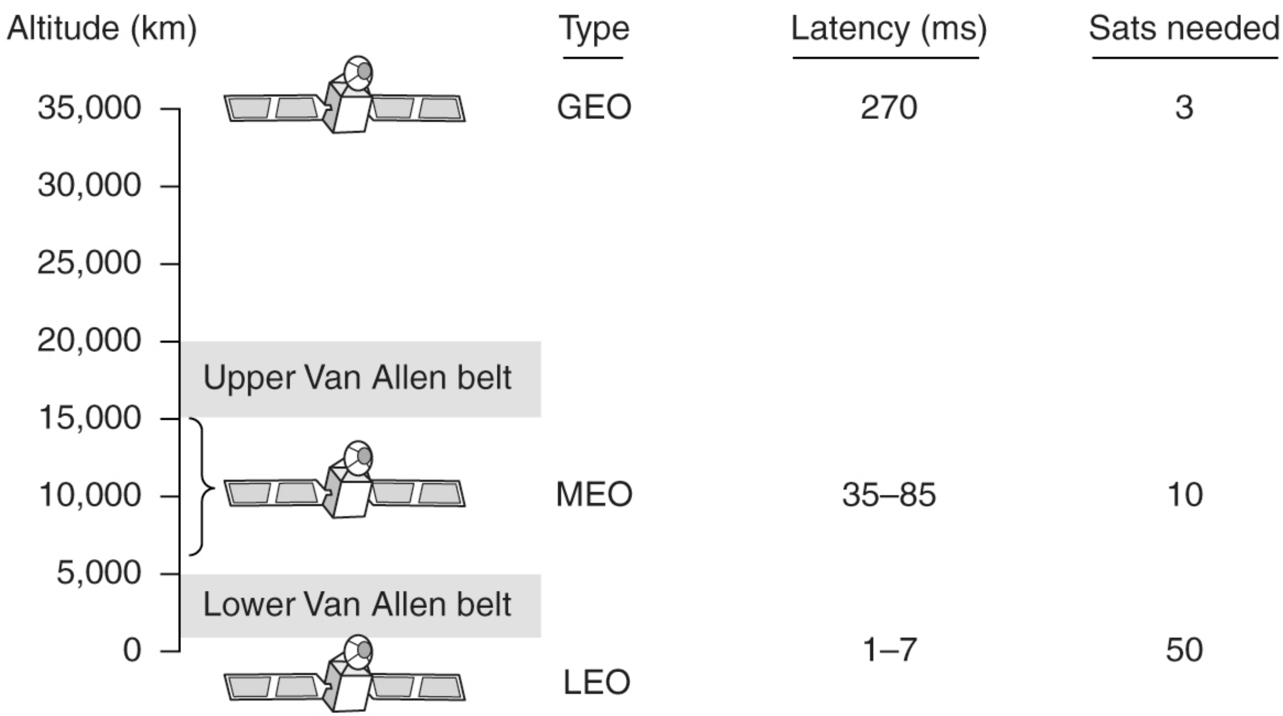
5G



Terrestrial Access Networks Cable, Fiber, and ADSL

- Similarities
  - Comparable service and comparable prices
  - Use fiber in the backbone
- Differences
  - Last-mile access technology at the physical and link layers
  - Bandwidth consistency
  - Cable subscribers share the capacity of a single node
  - Maximum speeds
  - Availability
  - Security

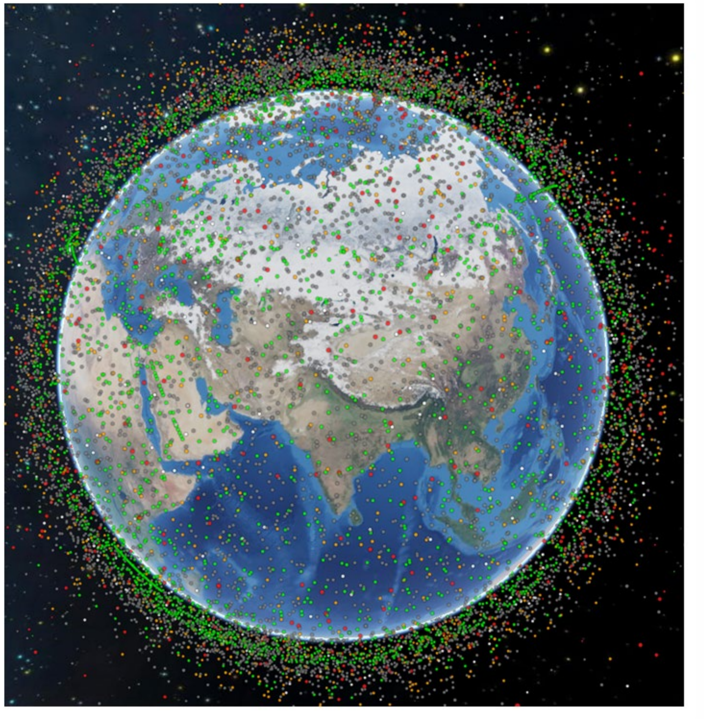
Communication Satellites



Communication satellites and some of their properties, including altitude above the earth, round-trip delay time, and number of satellites needed for global coverage.

Low Earth Orbit (LEO) Satellite Communication

- LEO constellations now provide global connectivity through thousands of satellites
- LEO satellites are characterized by low cost, attenuation, and latency
- Satellite constellations
  - Iridium: 95 satellites (Iridium)
  - Project Kuiper: 54 satellites (Amazon)
  - OneWeb: 648 satellites (Eutelsat)
  - Starlink: 7875 satellites (SpaceX)
  - Hongyan/Hongyun: ~500 satellites (China)



Satellites Versus Terrestrial Networks

- Communication satellite niche markets
  - Rapid deployments
  - Where terrestrial infrastructure is poor
  - When broadcasting is essential
- Several competing satellite-based Internet providers
- Satellite Internet access is growing
  - In-flight Internet access