Computer Communication Networks

Physical

UNIVERSITY AT ALBANY
State University of New York

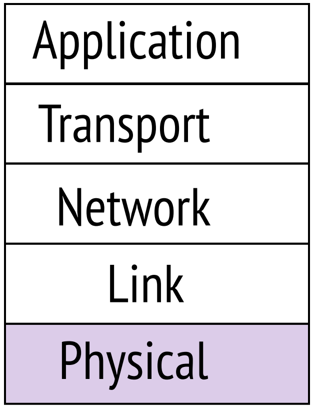
ICEN/ICSI 416 – Fall 2017

Prof. Dola Saha

The Physical Layer

- Foundation on which other layers build
  - Properties of wires, fiber, wireless limit what the network can do

- Key problem is to send (digital) bits using only (analog) signals
  - This is called modulation



Theoretical Basis for Data Communication

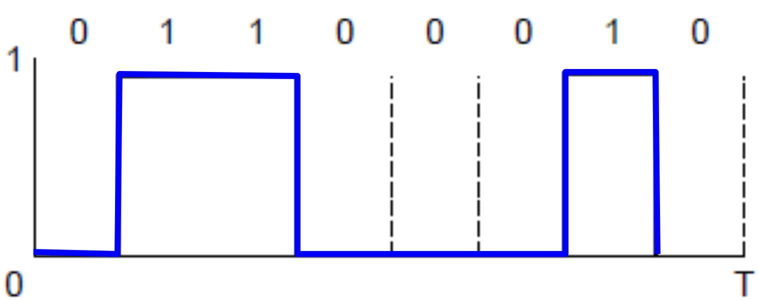
- Communication rates have fundamental limits
  - Fourier analysis »
  - Bandwidth-limited signals »
  - Maximum data rate of a channel »

Fourier Analysis

- A time-varying signal can be equivalently represented as a series of frequency components (harmonics):

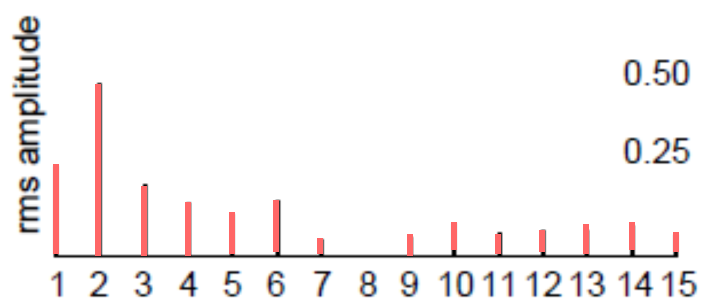
$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi n f t) + \sum_{n=1}^{\infty} b_n \cos(2\pi n f t)$$

Fundamental Frequency *f=1/T*



Signal over time →

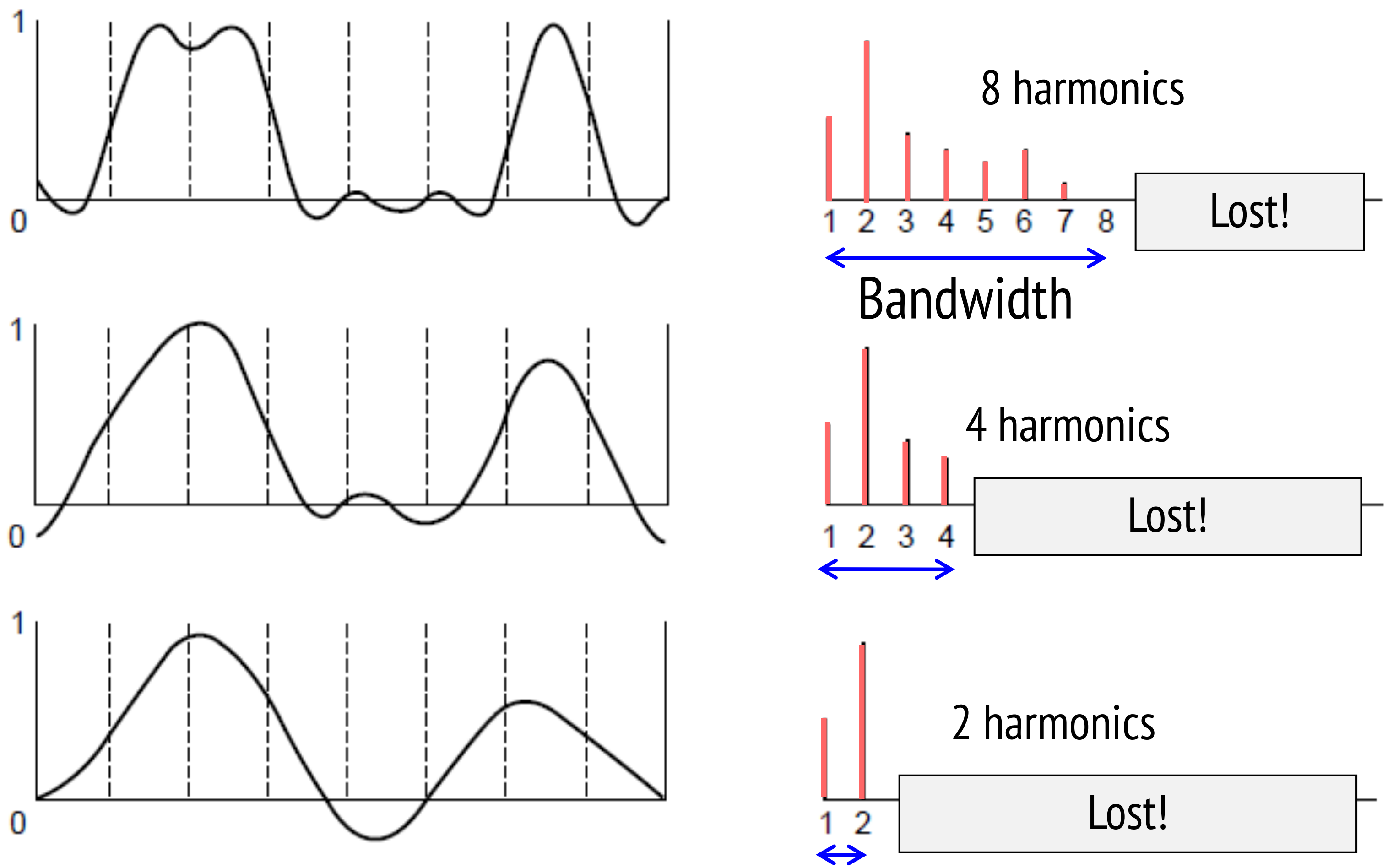
=



a, b weights of harmonics

Bandwidth-Limited Signals

- Having less bandwidth (harmonics) degrades the signal



Maximum Data Rate of a Channel

- Nyquist's theorem (1924) relates the data rate to the bandwidth (B) and number of signal levels (V):

$$\text{Max. data rate} = 2B \log_2 V \text{ bits/sec}$$

- Shannon's theorem (1948) relates the data rate to the bandwidth (B) and signal strength (S) relative to the noise (N):

$$\text{Max. data rate} = B \log_2(1 + S/N) \text{ bits/sec}$$

- Signal to Noise Ratio:

$$SNR = 10 \log_{10}(S/N) \text{ dB}$$

dB = decibels ➔ deci = 10; 'bel' chosen after Alexander Graham Bell

Guided Transmission (Wires & Fiber)

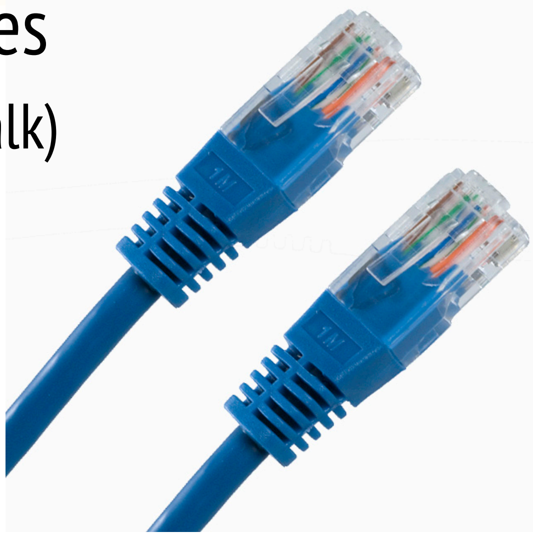
- Media have different properties, hence performance
  - Reality check
    - Storage media »
  - Wires:
    - Twisted pairs »
    - Coaxial cable »
    - Power lines »
  - Fiber cables »

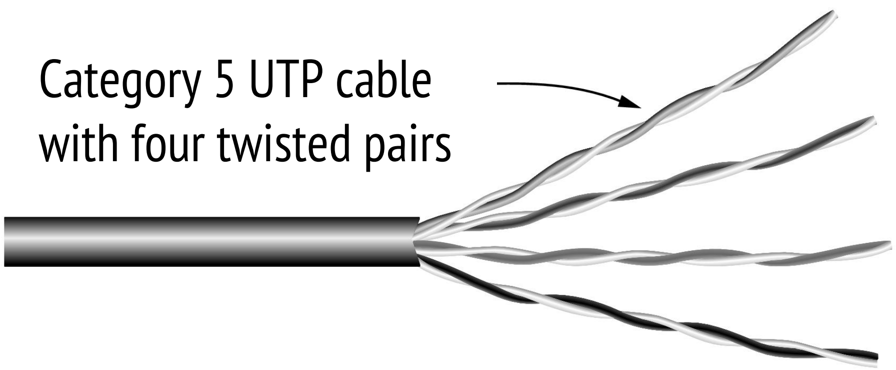
Reality Check: Storage media

- Send data on tape / disk / DVD for a high bandwidth link
  - Mail one box with 1000 800GB tapes (6400 Tbit)
  - Takes one day to send (86,400 secs)
  - Data rate is 70 Gbps.
- Data rate is faster than long-distance networks!
- But, the message delay is very poor.

Wires – Twisted Pair

- Very common; used in LANs, telephone lines
  - Twists reduce radiated signal (interference & crosstalk)
  - Cat 3 – initial used
  - Cat 5
    - similar to Cat 3 with more twists
    - 100Mbps & 1-Gbps Ethernet
  - Cat 6
    - Unshielded Twisted Pair (UTP), Wires & insulators
    - 10-Gbps
  - Cat 7
    - Shielding along individual TP
    - 40-Gbps @ 50meters



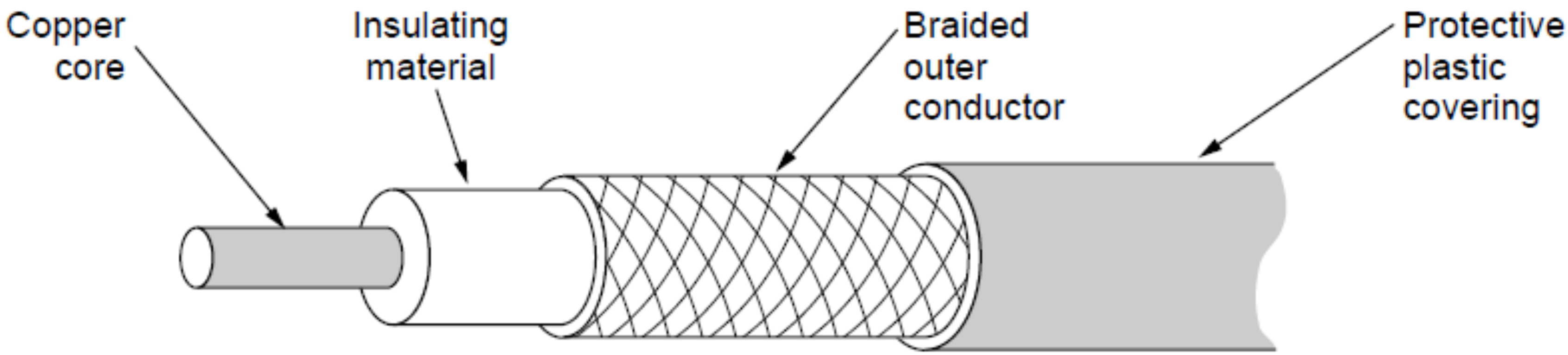


Link Terminology

- Full-duplex link
  - Used for transmission in both directions at once
  - e.g., use different twisted pairs for each direction
- Half-duplex link
  - Both directions, but not at the same time
  - e.g., senders take turns on a wireless channel
- Simplex link
  - Only one fixed direction at all times; not common

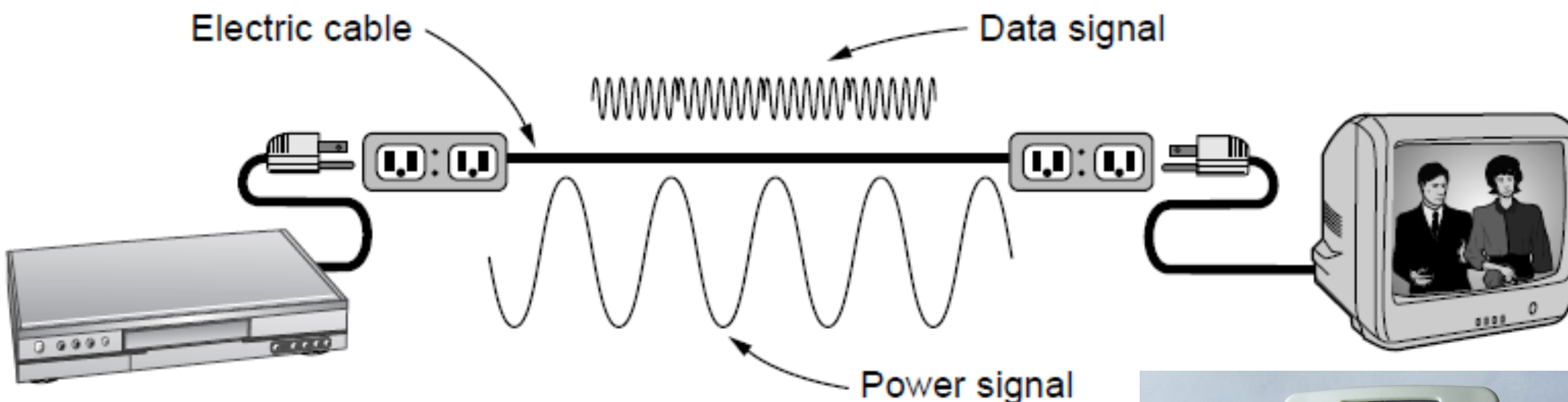
Wires – Coaxial Cable ("Co-ax")

- Also common. Better shielding and more bandwidth for longer distances and higher rates than twisted pair.



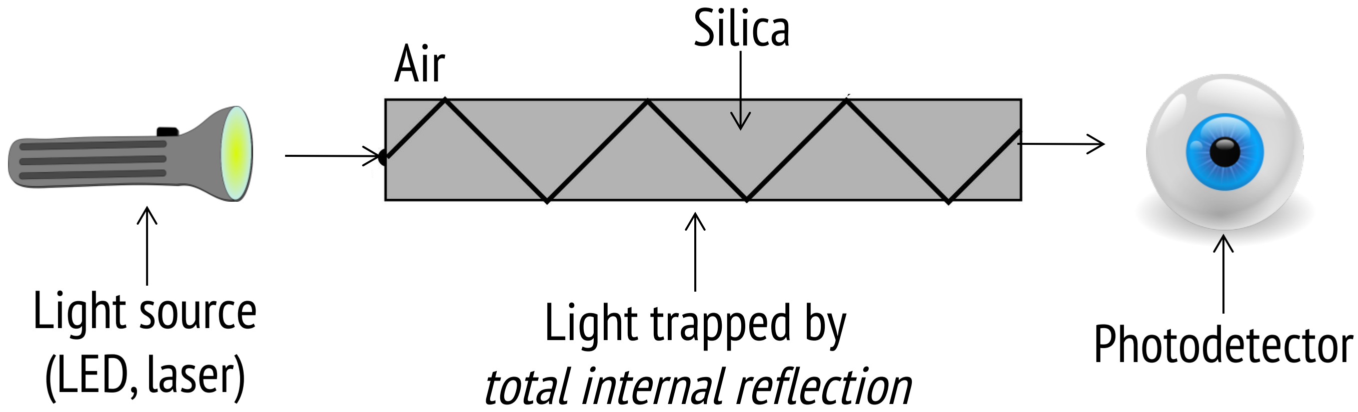
Wires – Power Lines

- Power Line Communication
- Household electrical wiring is another example of wires
  - Convenient to use, but horrible for sending data



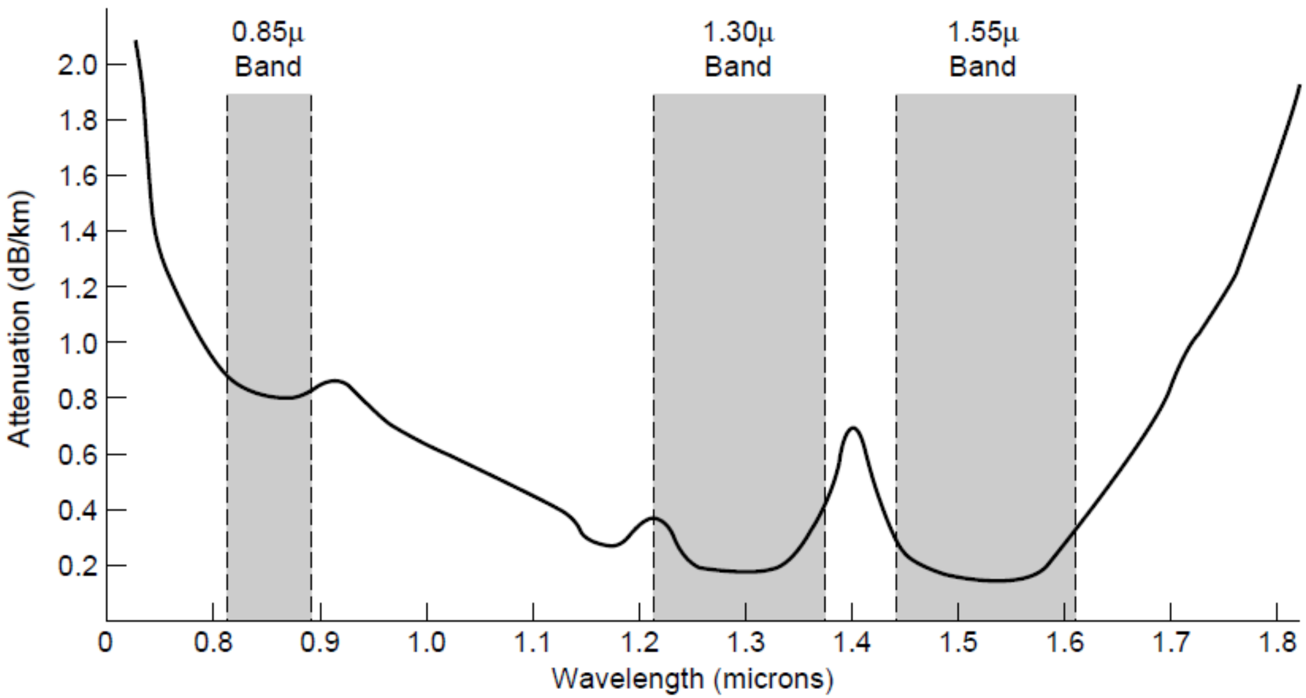
Fiber Cables (1)

- Common for high rates and long distances
  - Long distance ISP links, Fiber-to-the-Home
  - Light carried in very long, thin strand of glass



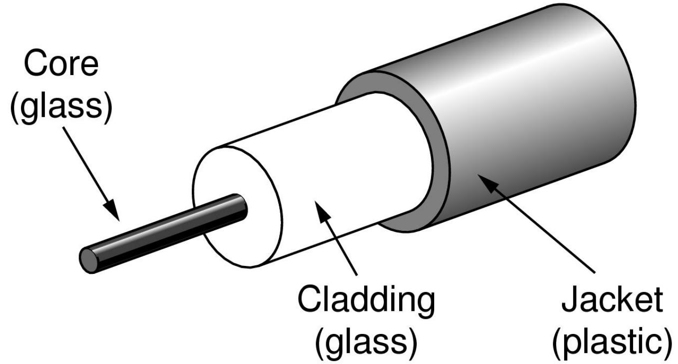
Fiber Cables (2)

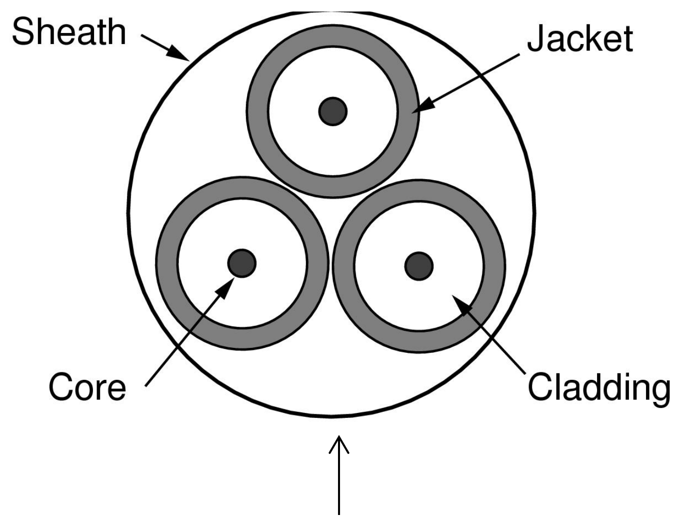
- Fiber has enormous bandwidth (THz) and tiny signal loss – hence high rates over long distances
  - Visible Light – 0.4-0.7 microns
  - Commonly used bands – 0.85, 1.30, 1.55 microns



Fiber Cables (3)

- Single-mode
  - Core so narrow (10um) light can't even bounce around
  - Used with lasers for long distances, e.g., 100km
- Multi-mode
  - Other main type of fiber
  - Light can bounce (50um core)
  - Used with LEDs for cheaper, shorter distance links





Fibers in a cable

Fiber Cables (4)

Property	Wires	Fiber
Distance	Short (100s of m)	Long (tens of km)
Bandwidth	Moderate	Very High
Cost	Inexpensive	Less cheap
Convenience	Easy to use	Less easy
Security	Easy to tap	Hard to tap

Wireless Transmission

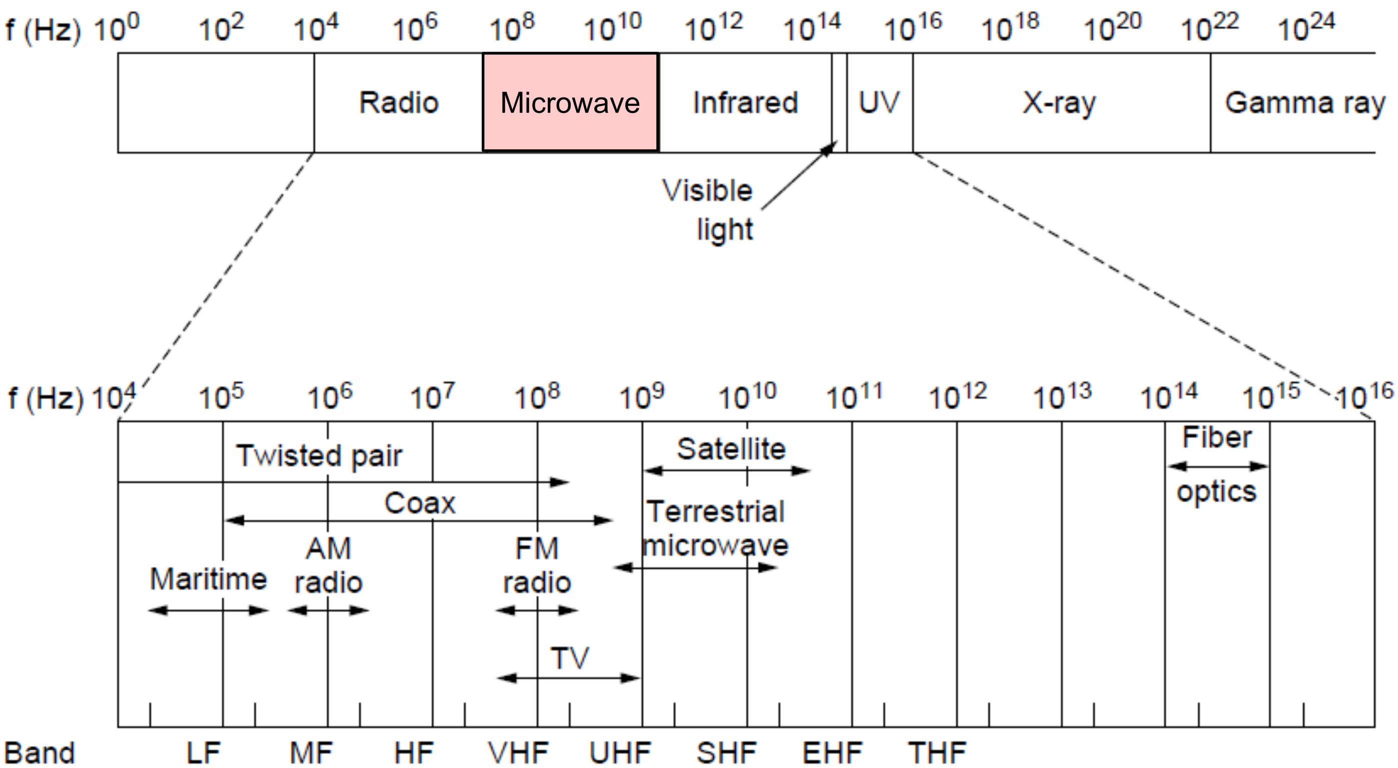
- Electromagnetic Spectrum »
- Radio Transmission »
- Microwave Transmission »
- Light Transmission »
- Wireless vs. Wires/Fiber »

Electromagnetic Spectrum

- $f = c/\lambda$
- f = Frequency = number of oscillations/sec of a wave, measured in Hz
- λ = Wavelength = distance between two maxima (or minima)
- c = constant = speed of light
- *Example*: 100 MHz waves are 3 meters long

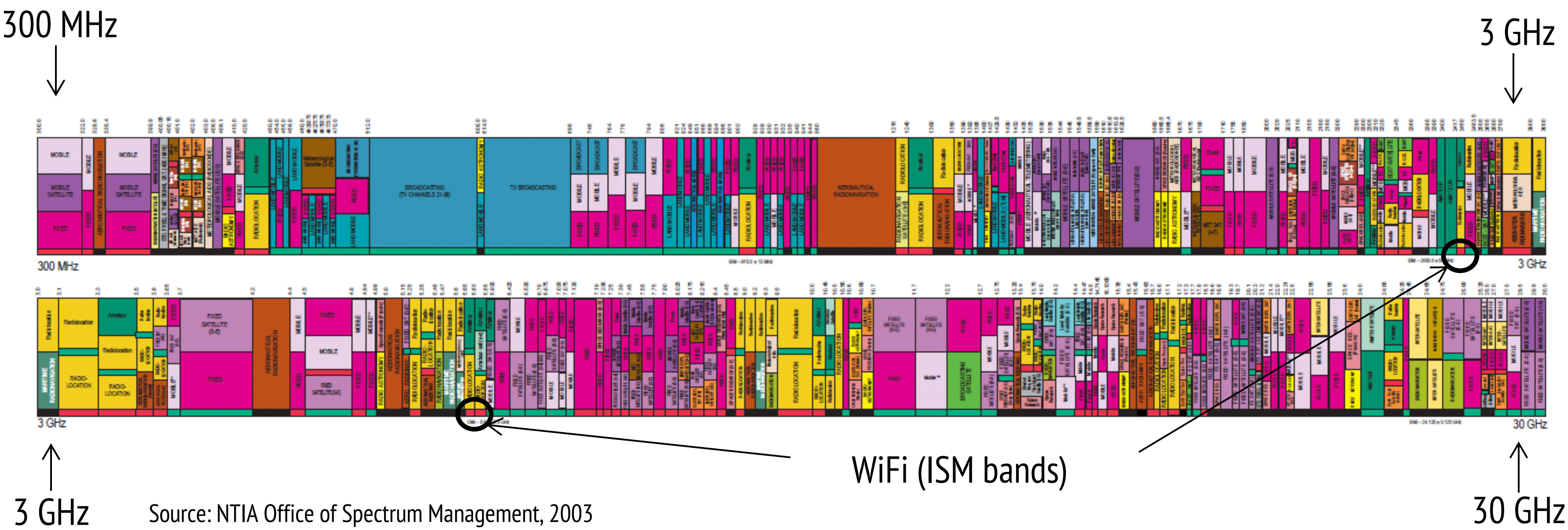
Electromagnetic Spectrum (1)

- Different bands have different uses:
  - Radio: wide-area broadcast; Infrared/Light: line-of-sight
  - Microwave: LANs and 3G/4G/5G; ← Networking focus



Electromagnetic Spectrum (2)

- To manage interference, spectrum is carefully divided, and its use regulated and licensed, e.g., sold at auction.

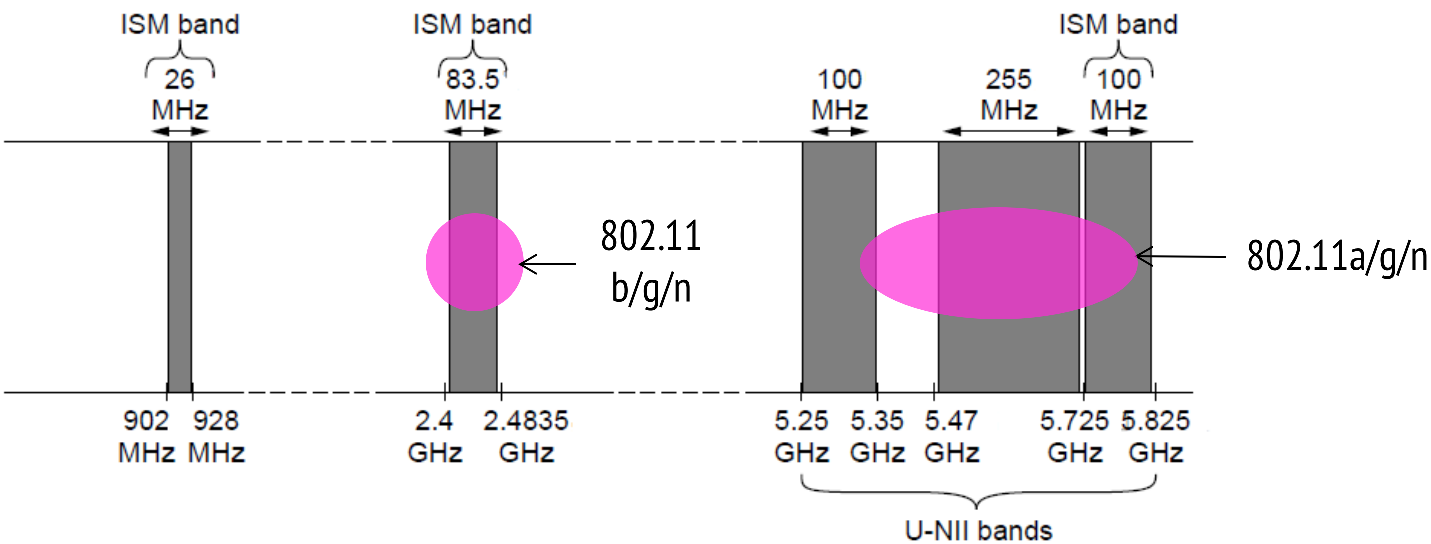


Source: NTIA Office of Spectrum Management, 2003

Part of the US frequency allocations

Electromagnetic Spectrum (3)

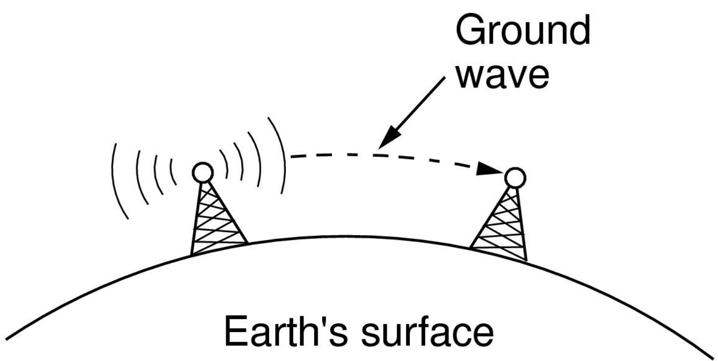
- Fortunately, there are also unlicensed ("ISM") bands:
  - ISM: Industrial Scientific and Medical Radio band
  - Free for use at low power; devices manage interference
  - Widely used for networking; WiFi, Bluetooth, Zigbee, etc.



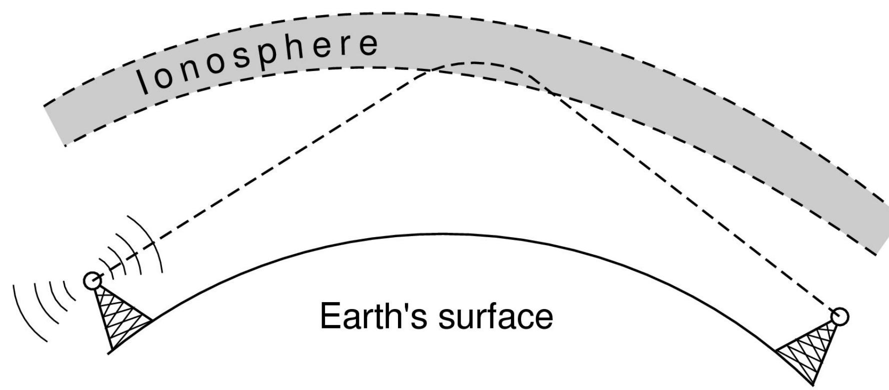
University at Albany
State University of New York

Radio Transmission

- Radio signals penetrate buildings well and propagate for long distances with path loss



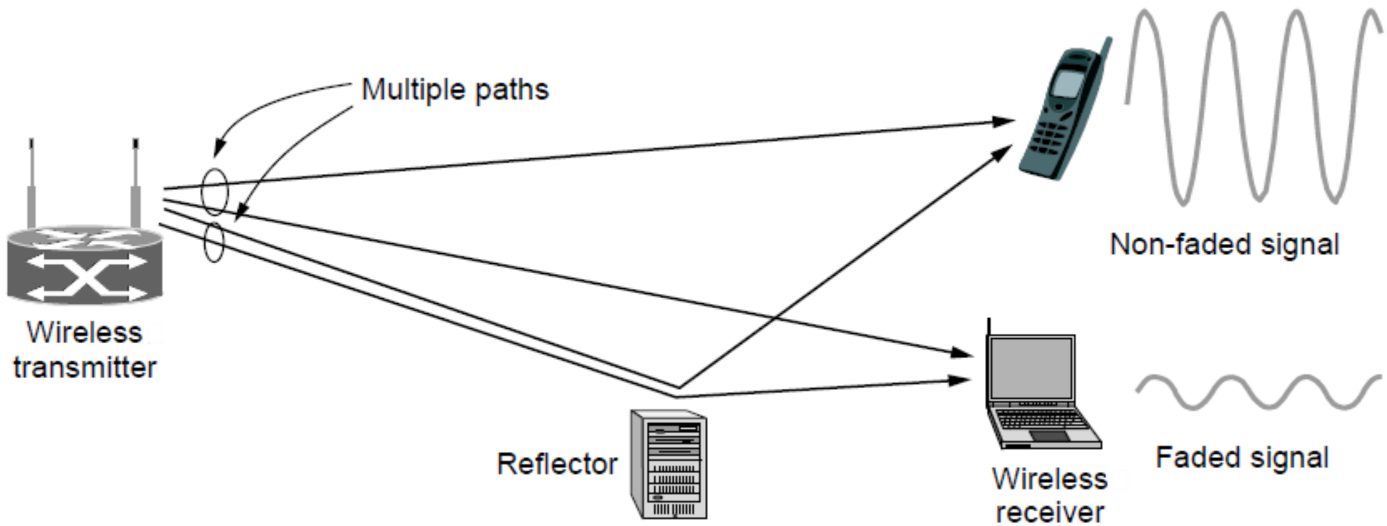
In the VLF, LF, and MF bands, radio waves follow the curvature of the earth



In the HF band, radio waves bounce off the ionosphere.

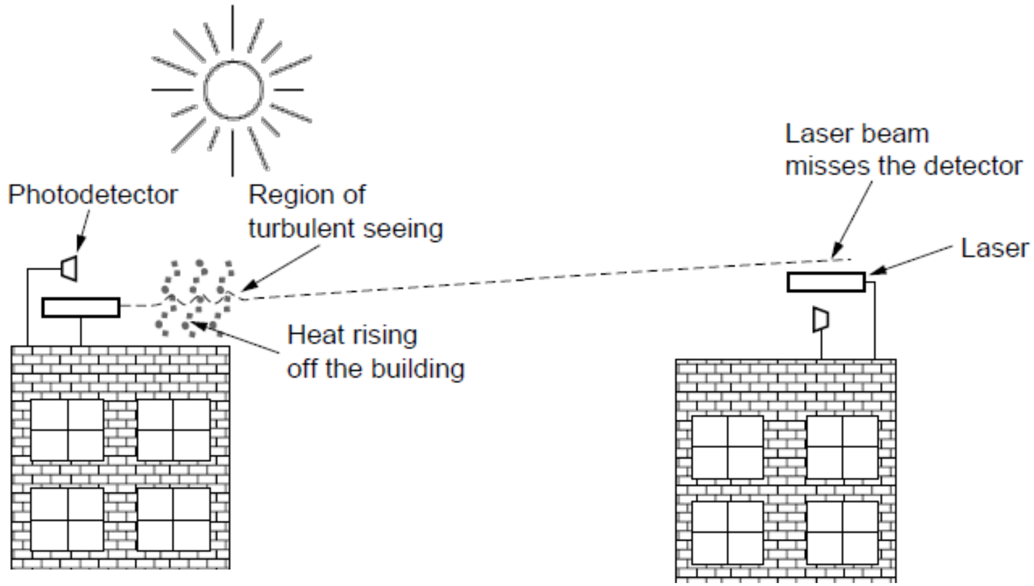
Microwave Transmission

- Microwaves have much bandwidth and are widely used indoors (WiFi) and outdoors (3G, satellites)
  - Signal is attenuated/reflected by everyday objects
  - Strength varies with mobility due multipath fading, etc.



Light Transmission

- Line-of-sight light (no fiber) can be used for links
  - Light is highly directional, has much bandwidth
  - Use of LEDs/cameras and lasers/photodetectors



Wireless vs. Wires/Fiber

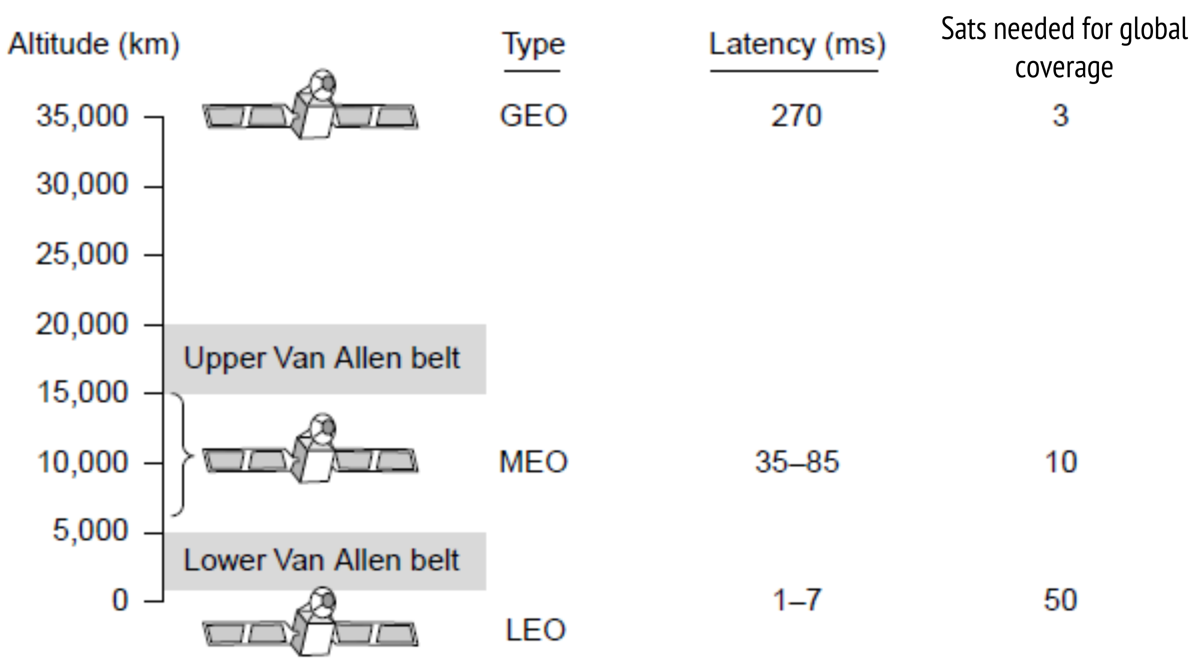
- Wireless:
  - + Easy and inexpensive to deploy
  - + Naturally supports mobility
  - + Naturally supports broadcast
  - ○ Transmissions interfere and must be managed
  - ○ Signal strengths hence data rates vary greatly
- Wires/Fiber:
  - + Easy to engineer a fixed data rate over point-to-point links
  - ○ Can be expensive to deploy, esp. over distances
  - ○ Doesn’t readily support mobility or broadcast

Communication Satellites

- Satellites are effective for broadcast distribution and anywhere/anytime communications
  - Kinds of Satellites »
  - Geostationary (GEO) Satellites »
  - Low-Earth Orbit (LEO) Satellites »
  - Satellites vs. Fiber »

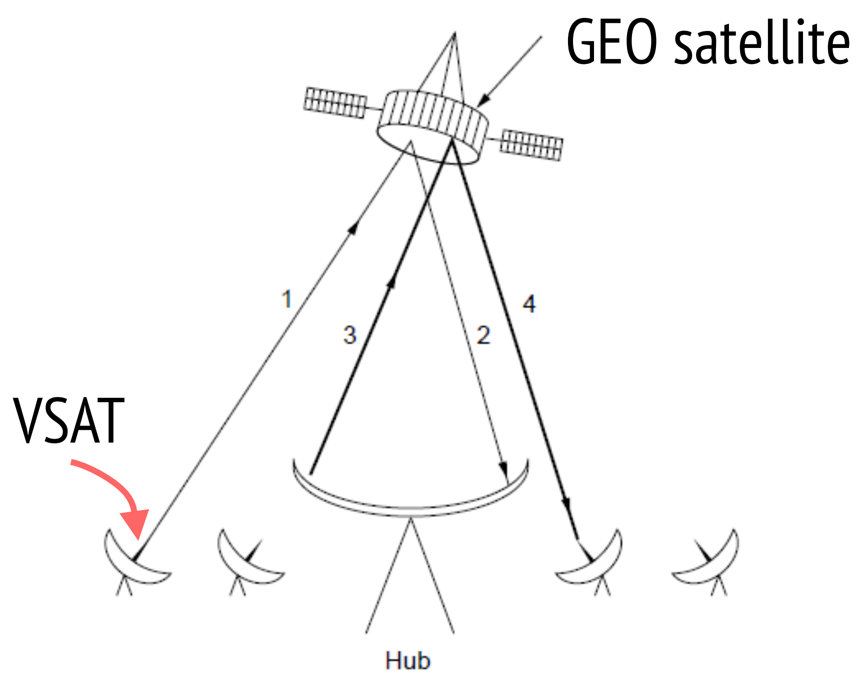
Kinds of Satellites

- Satellites and their properties vary by altitude:
  - Geostationary (GEO), Medium-Earth Orbit (MEO), and Low-Earth Orbit (LEO)



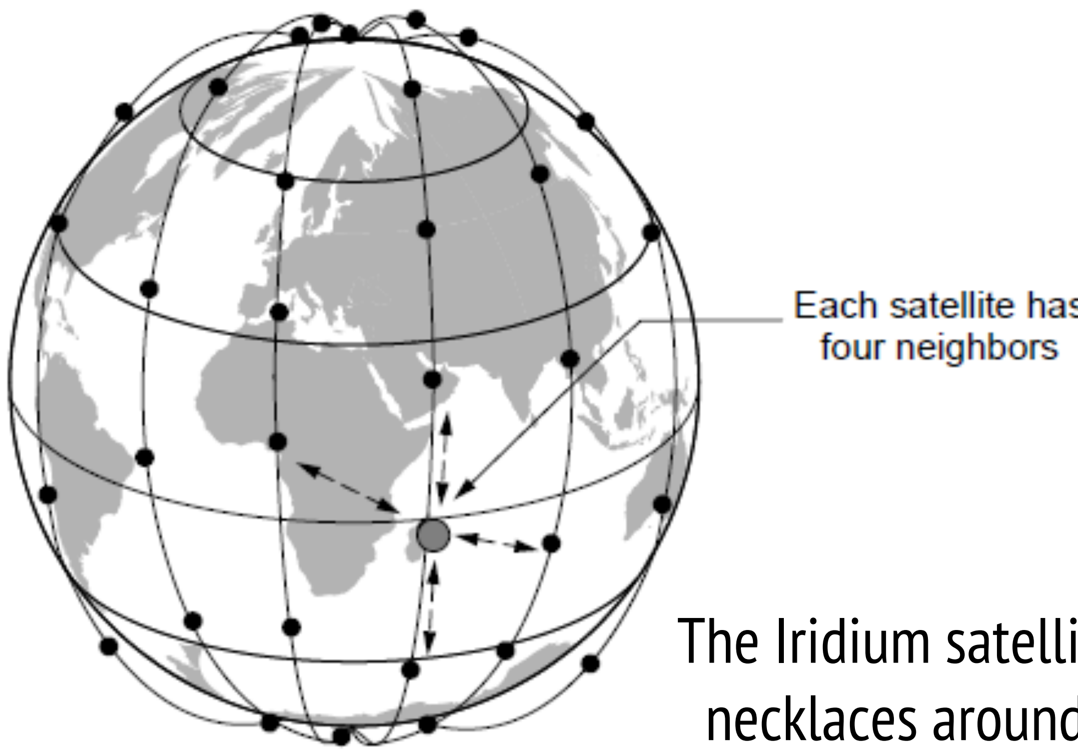
Geostationary Satellites

- GEO satellites orbit 35,000 km above a fixed location
  - VSAT (computers) can communicate with the help of a hub.
  - Different bands (L, S, C, Ku, Ka) in the GHz are in use but may be crowded or susceptible to rain.



Low-Earth Orbit Satellites

- Systems such as Iridium (voice and data coverage to satellite phones) use many low-latency satellites for coverage and route communications via them



The Iridium satellites form six necklaces around the earth.

Satellite vs. Fiber

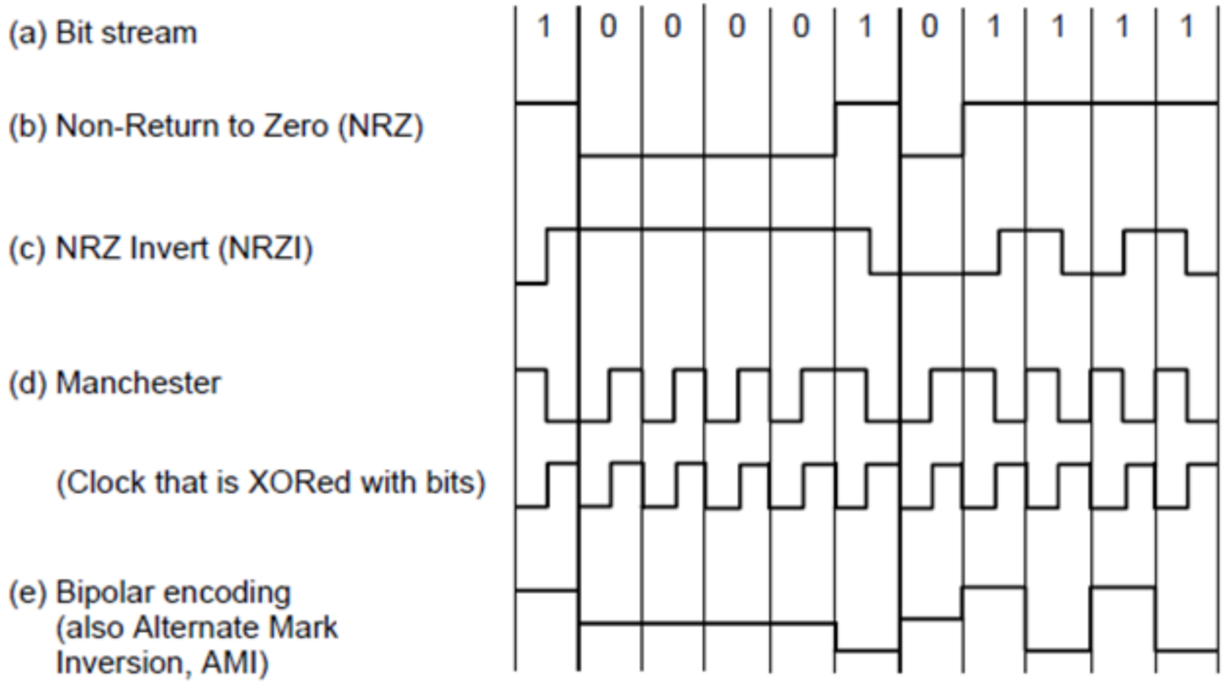
- Satellite:
  - \+ Can rapidly set up anywhere/anytime communications (after satellites have been launched)
  - \+ Can broadcast to large regions
  - ○ Limited bandwidth and interference to manage
- Fiber:
  - \+ Enormous bandwidth over long distances
  - ○ Installation can be more expensive/difficult

Digital Modulation and Multiplexing

- Modulation schemes send bits as signals; multiplexing schemes share a channel among users.
  - Baseband Transmission »
  - Passband Transmission »
  - Frequency Division Multiplexing »
  - Time Division Multiplexing »
  - Code Division Multiple Access »

Baseband Transmission

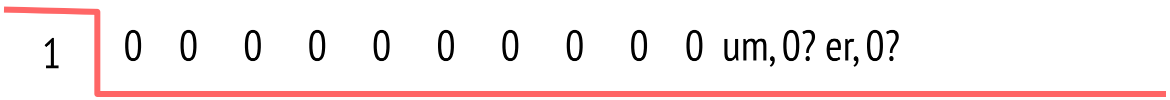
- Line codes send <u>symbols</u> that represent one or more bits
  - NRZ is the simplest, literal line code (+1V="1", -1V="0")
  - Other codes tradeoff bandwidth and signal transitions



Four different line codes

Clock Recovery

- To decode the symbols, signals need sufficient transitions
  - Otherwise long runs of 0s (or 1s) are confusing, e.g.:



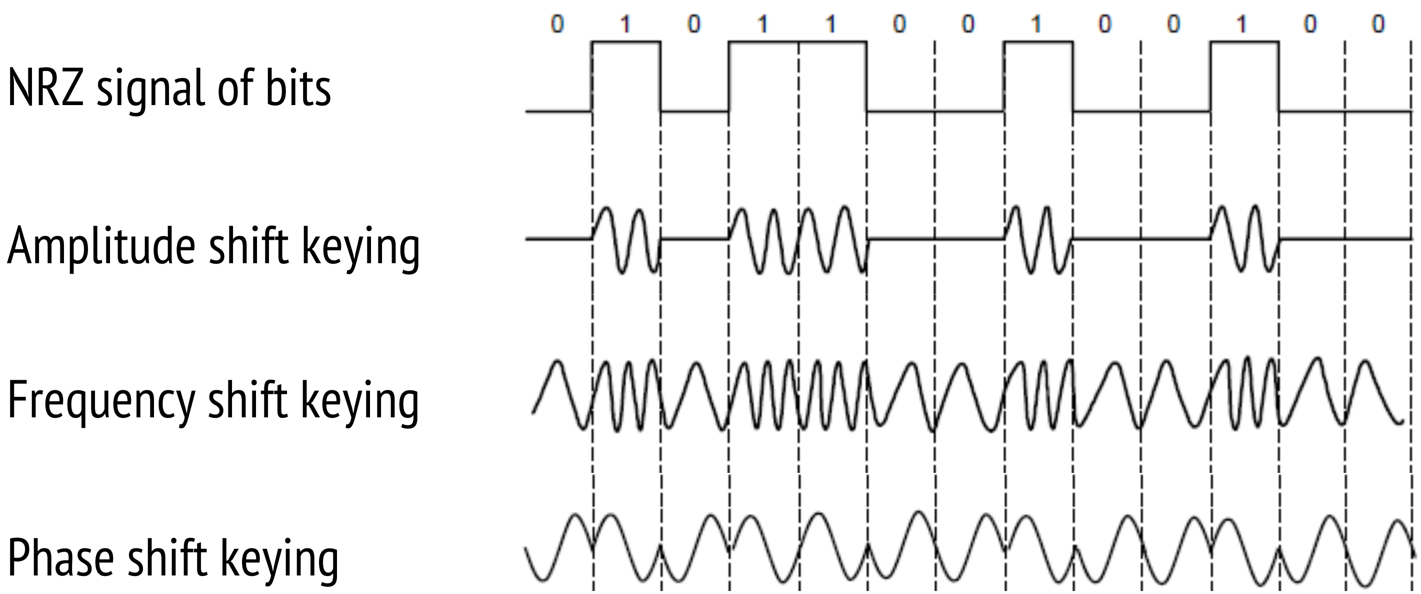
- Strategies:
  - Manchester coding, mixes clock signal in every symbol
  - 4B/5B maps 4 data bits to 5 coded bits with 1s and 0s:

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

  - Scrambler XORs tx/rx data with pseudorandom bits

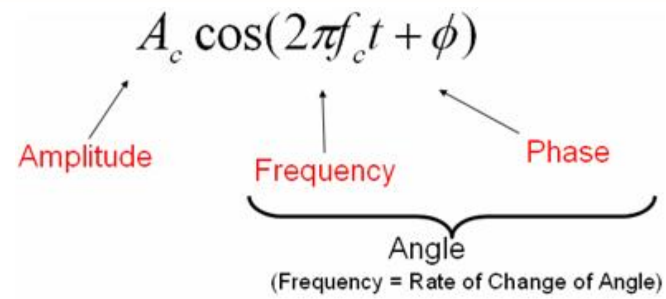
Modulation

- Modulating the amplitude, frequency/phase of a carrier signal sends bits in a (non-zero) frequency range

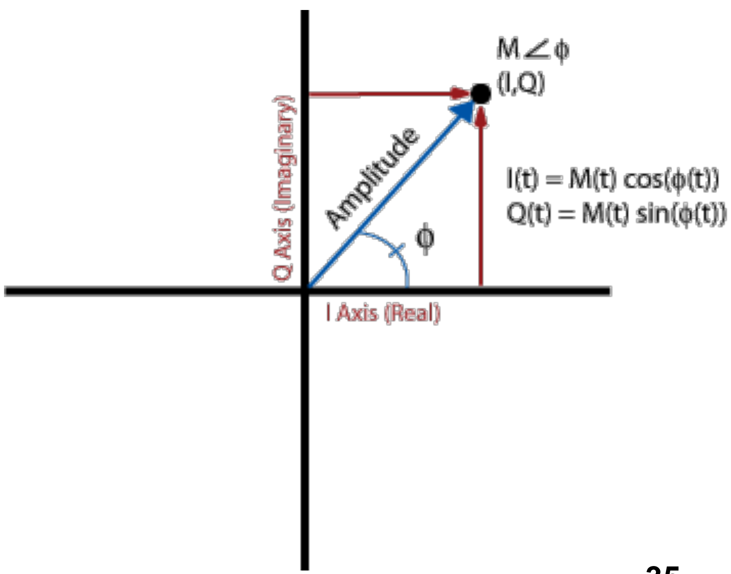


Signal

- Signal modulation changes a sine wave to encode information. The equation representing a sine wave is shown:

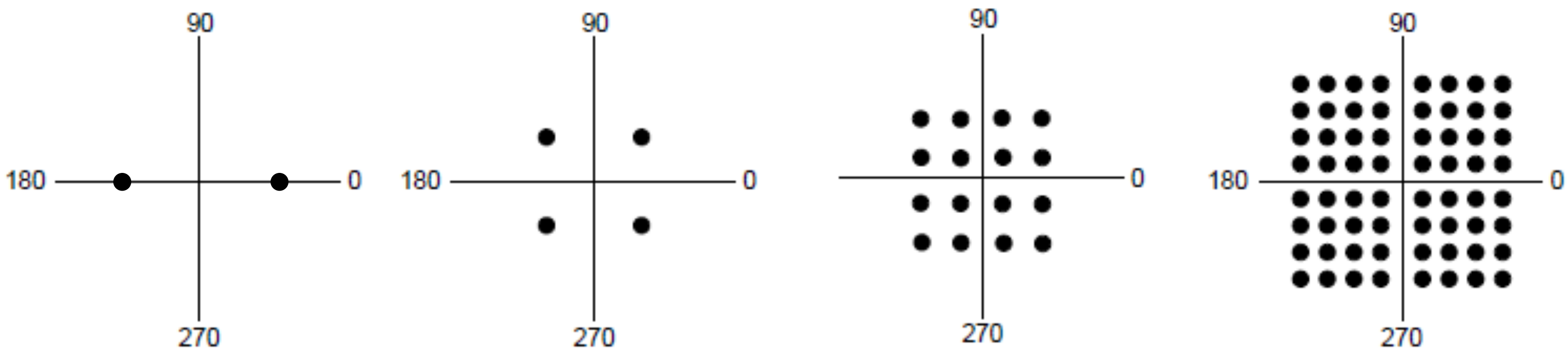


- Instantaneous state of a sine wave with a vector in the complex plane using amplitude (magnitude) and phase coordinates in a polar coordinate system.



Modulation

➢ *Constellation diagrams* are a shorthand to capture the amplitude and phase modulations of symbols:



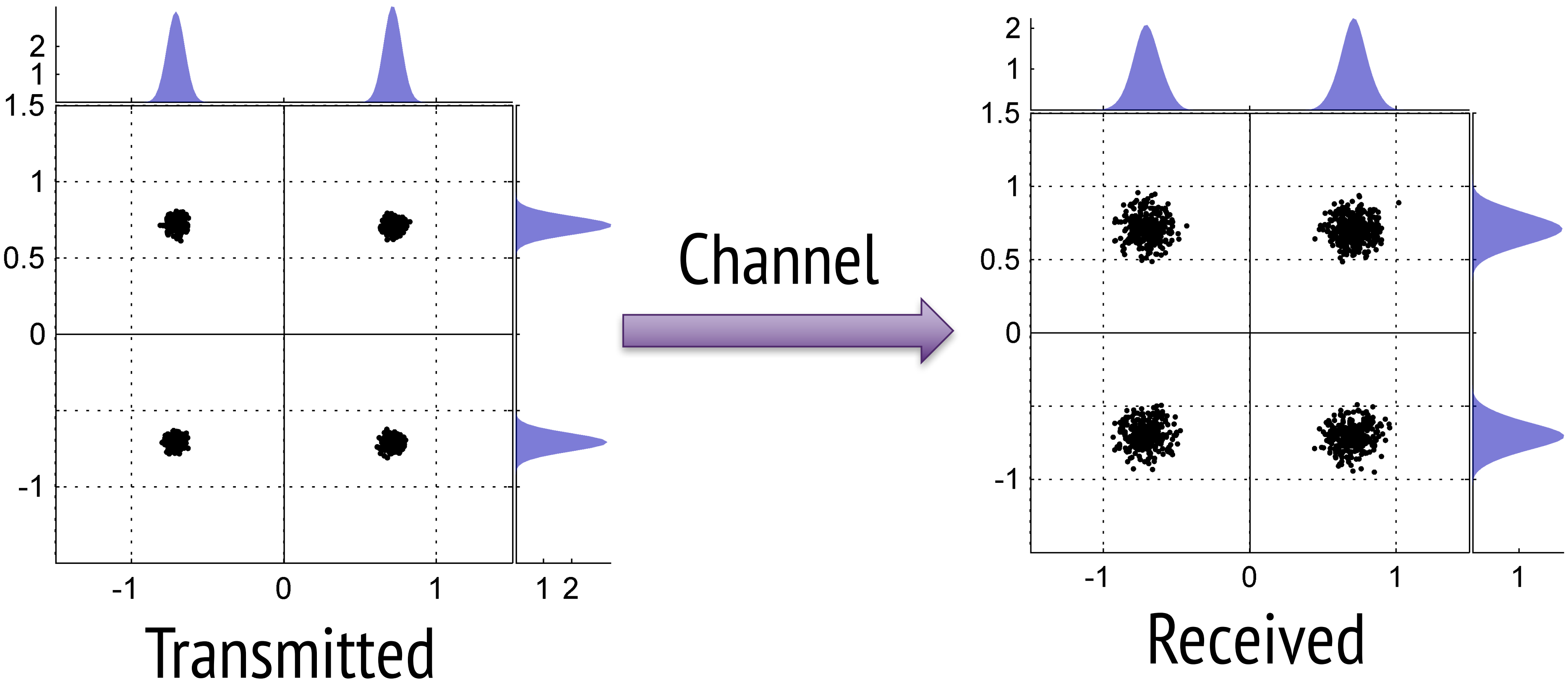
BPSK	QPSK	QAM-16	QAM-64
2 symbols	4 symbols	16 symbols	64 symbols
1 bit/symbol	2 bits/symbol	4 bits/symbol	6 bits/symbol

BPSK/QPSK varies only phase

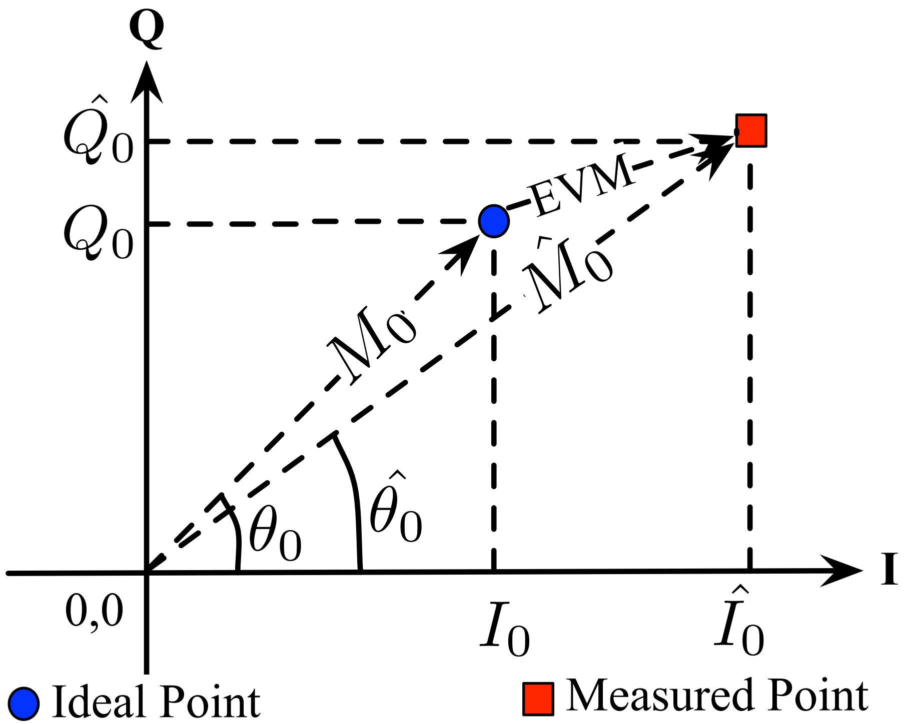
QAM varies amplitude and phase

Channel Effects

- Transmitted and Received QPSK Signal



Error Vector Magnitude (EVM)



$\{I_0, Q_0, M_0, \theta_0\}$ = Ideal I, Q, Magnitude, Phase

$\{\hat{I}_0, \hat{Q}_0, \hat{M}_0, \hat{\theta}_0\}$ = Measured I, Q, Magnitude, Phase

$$EVM = \sqrt{\left(I_0 - \hat{I}_0\right)^2 + \left(Q_0 - \hat{Q}_0\right)^2}$$

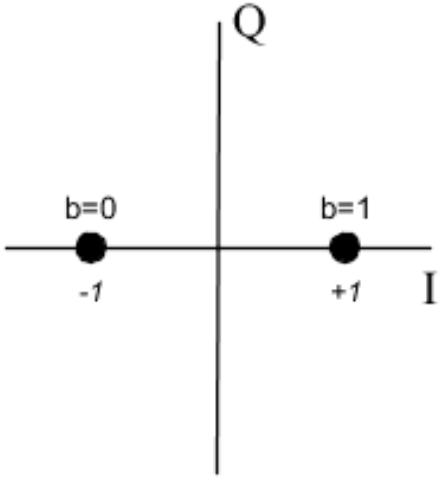
I_{Disp} = Dispersion in I = $I_0 - \hat{I}_0$

Q_{Disp} = Dispersion in Q = $Q_0 - \hat{Q}_0$

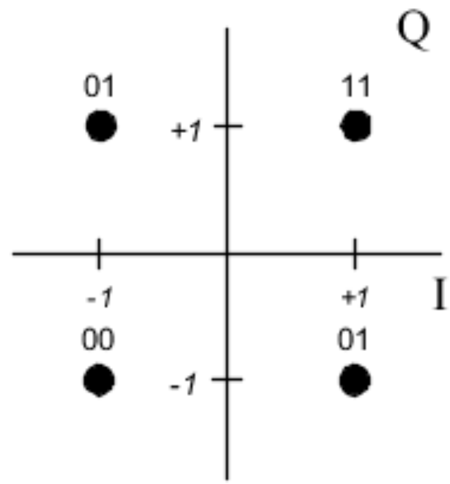
M_{Disp} = Dispersion in Magnitude = $M_0 - \hat{M}_0$

Demodulating the signal

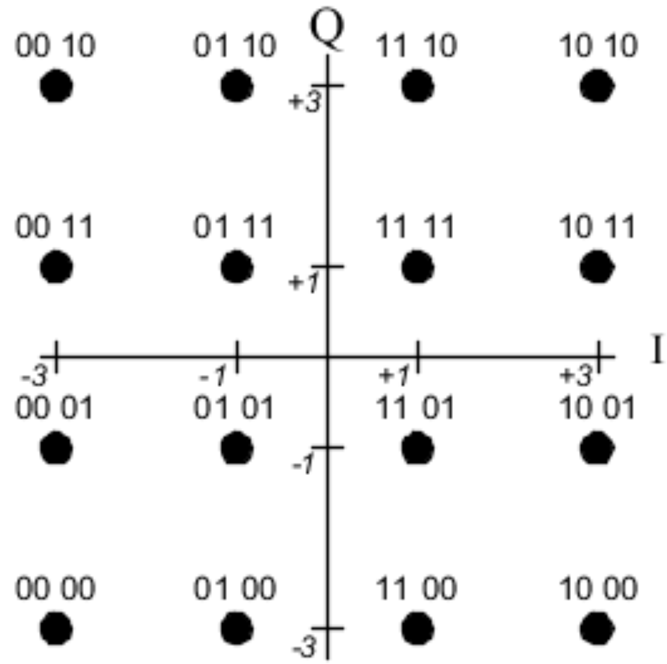
- Use threshold to decide



BPSK



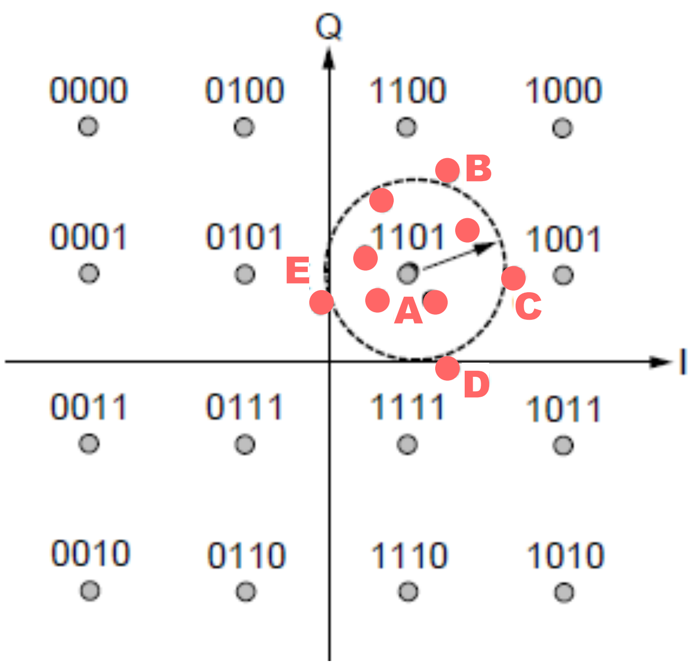
QPSK



16 QAM

Gray Coding

- Gray-coding assigns bits to symbols so that small symbol errors cause few bit errors:

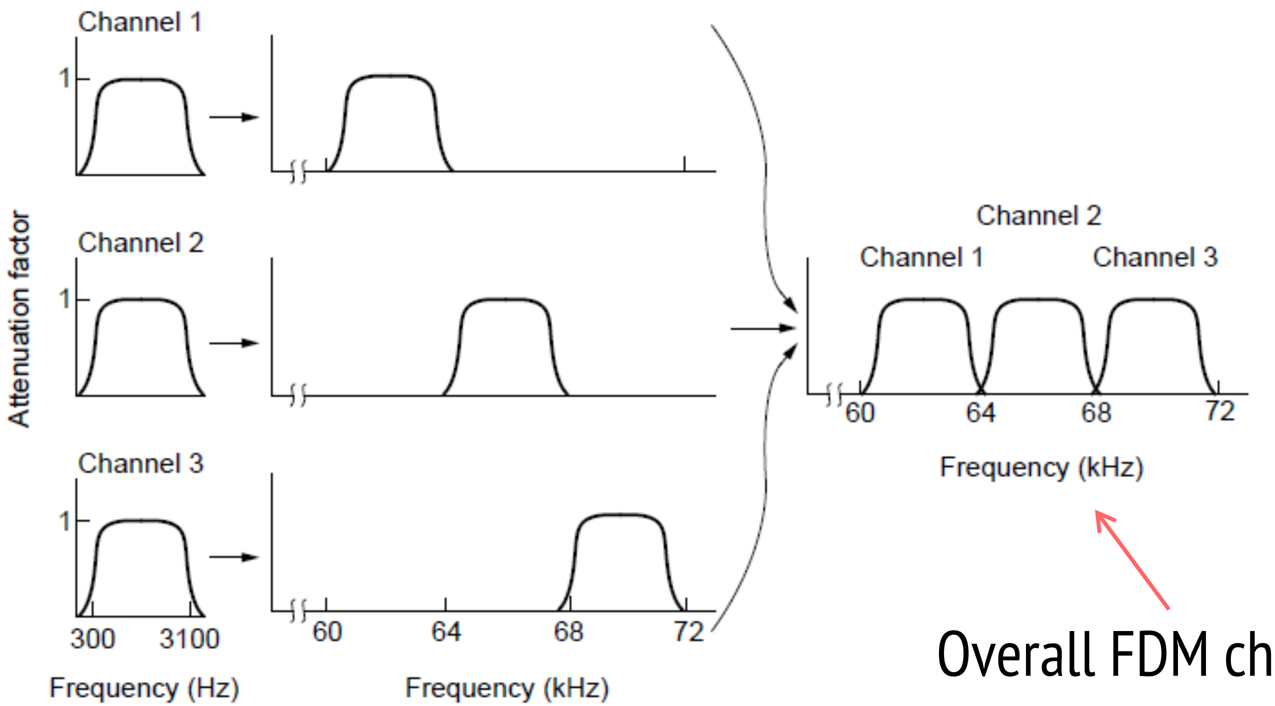


When 1101 is sent:

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

Frequency Division Multiplexing (1)

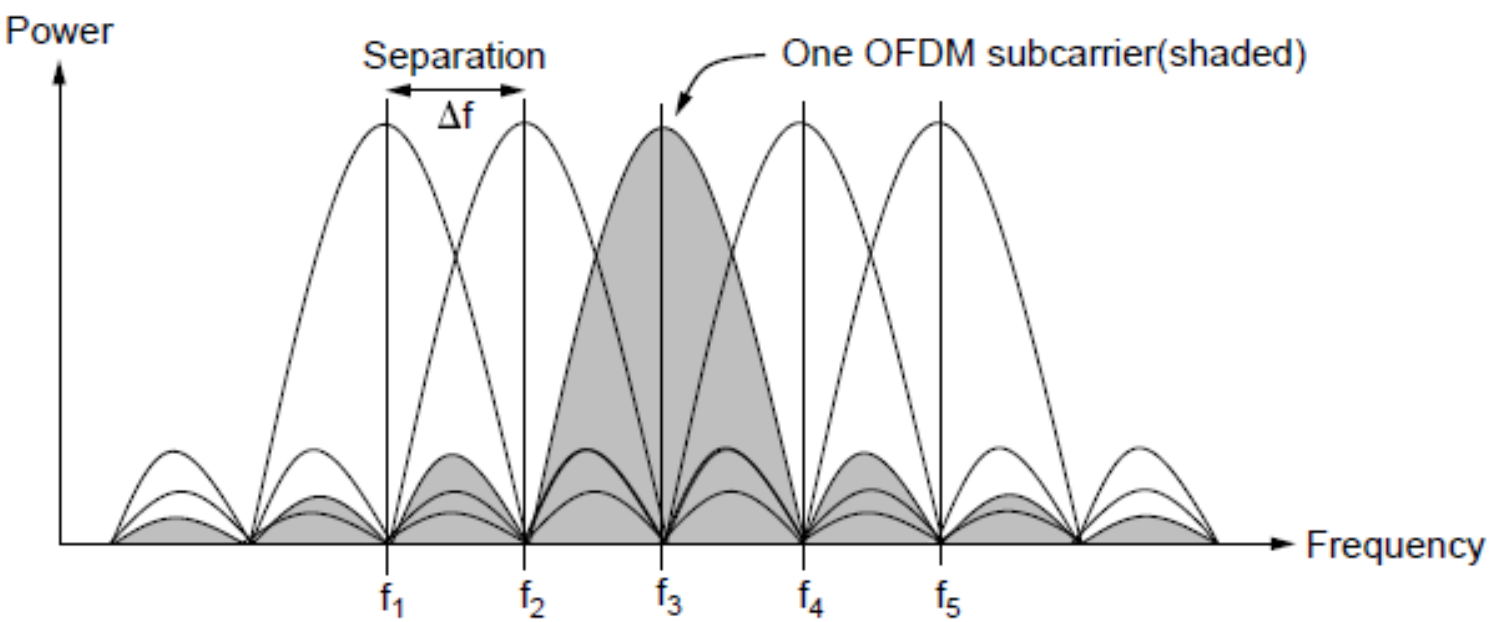
- FDM (Frequency Division Multiplexing) shares the channel by placing users on different frequencies:



Overall FDM channel

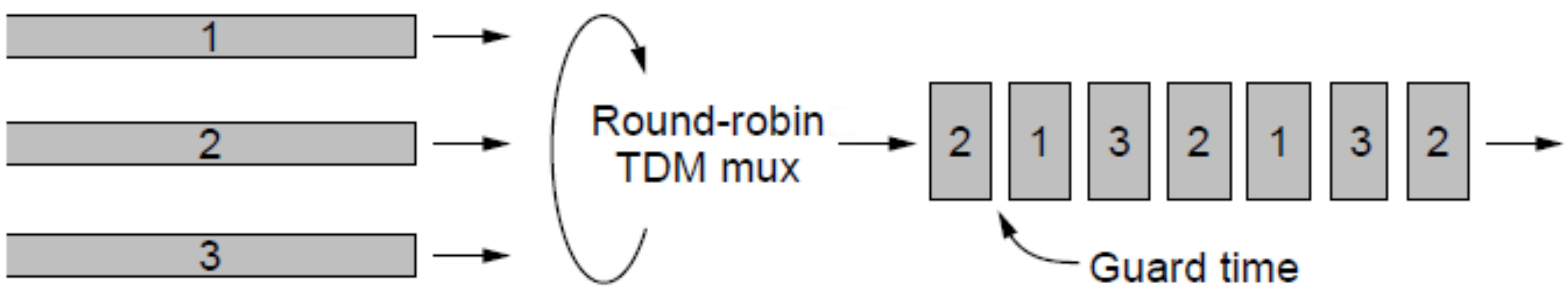
Frequency Division Multiplexing (2)

- OFDM (Orthogonal FDM) is an efficient FDM technique used for 802.11, 4G cellular (LTE) and other communications
  - Subcarriers are coordinated to be tightly packed



Time Division Multiplexing (TDM)

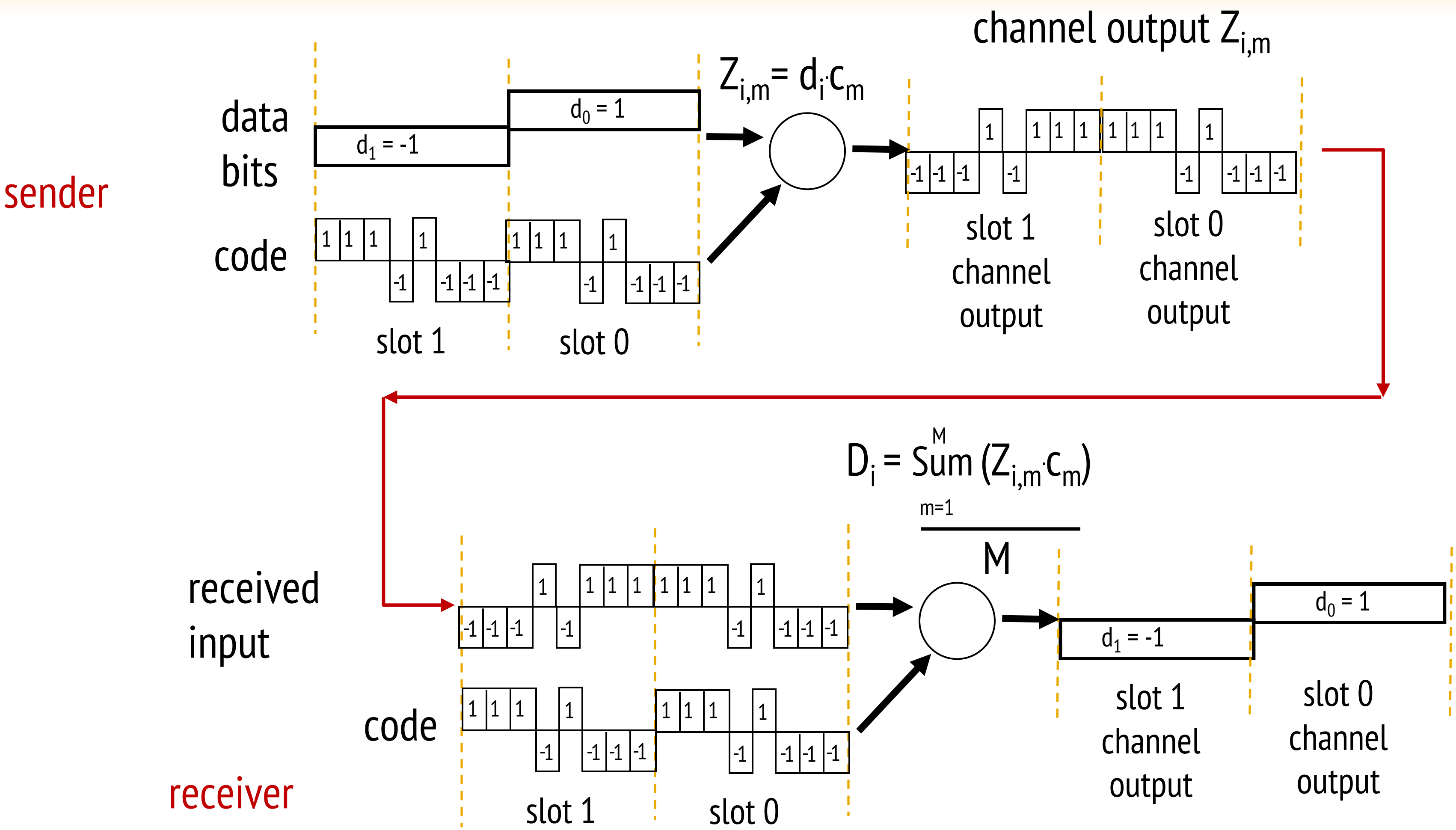
- Time division multiplexing shares a channel over time:
  - Users take turns on a fixed schedule; this is not packet switching or STDM (Statistical TDM)
  - Widely used in telephone / cellular systems



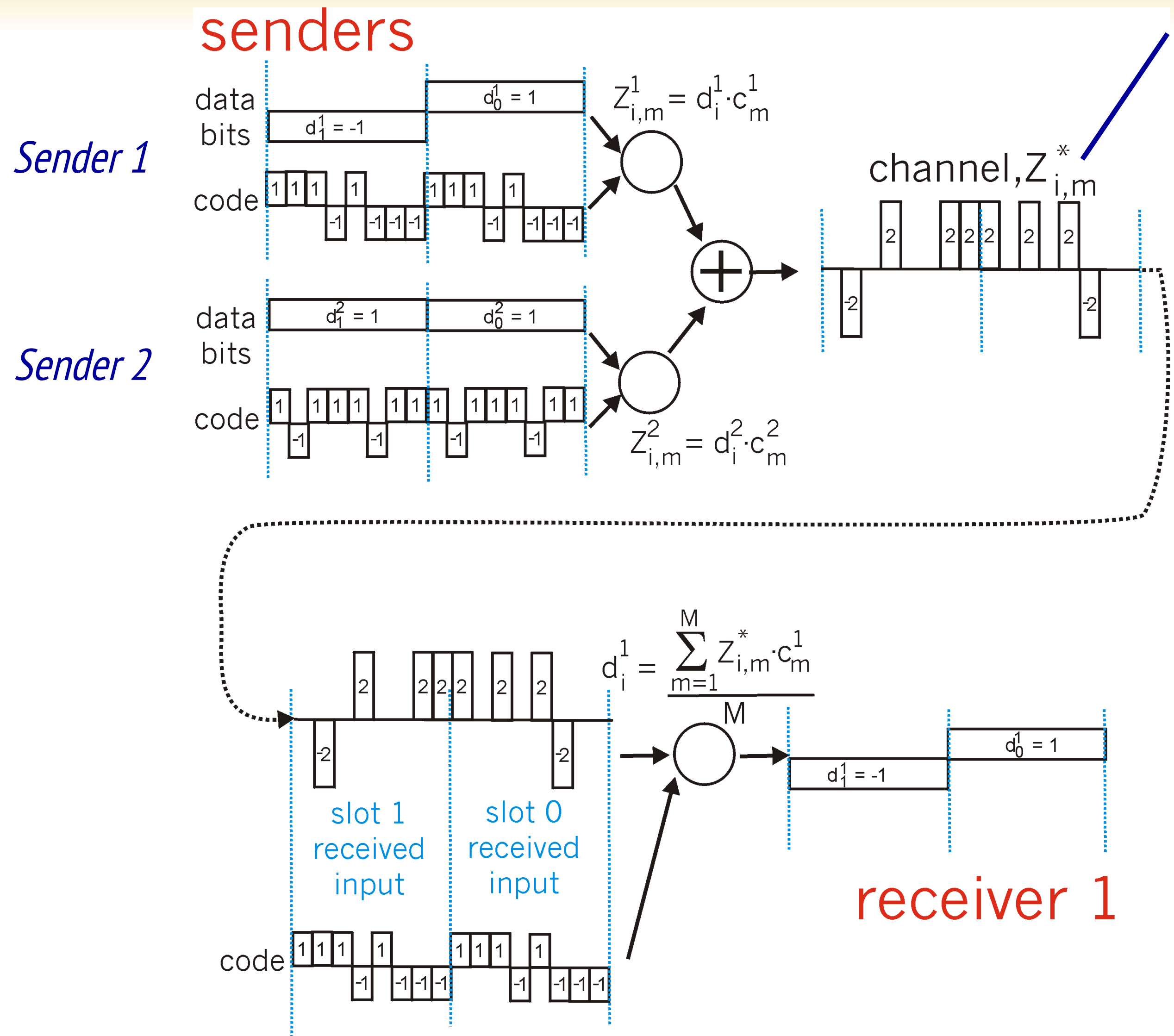
Code Division Multiple Access (CDMA)

- unique "code" assigned to each user; i.e., code set partitioning
  - all users share same frequency, but each user has own "chipping" sequence (i.e., code) to encode data
  - allows multiple users to "coexist" and transmit simultaneously with minimal interference (if codes are "orthogonal")
- *encoded signal* = (original data) X (chipping sequence)
- *decoding:* inner-product of encoded signal and chipping sequence

CDMA encode/decode



CDMA: two-sender interference



channel sums together transmissions by sender 1 and 2

using same code as sender 1, receiver recovers sender 1's original data from summed channel data!

Code Division Multiple Access (CDMA)

- CDMA shares the channel by giving users a code
  - Codes are orthogonal; can be sent at the same time
  - Widely used as part of 3G networks
  - Gold code (GPS Signals), Walsh-Hadamard code, Zadoff-chu sequence