Computer Communication Networks

Physical Layer

IECE / ICSI 416– Spring 2020

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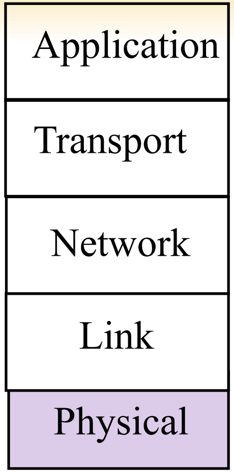
The Physical Layer

- 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

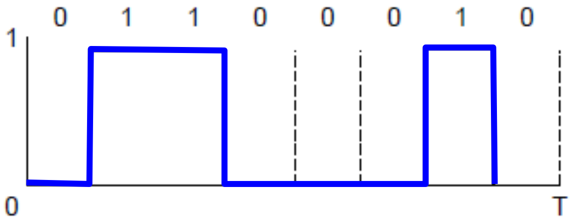
  - Fourier analysis »
  - Bandwidth-limited signals »
  - Maximum data rate of a channel »

Fourier Analysis

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

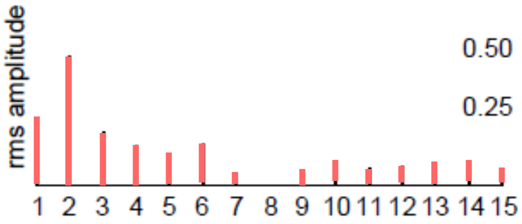
$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$

Fundamental Frequency $f=1/T$



Signal over time

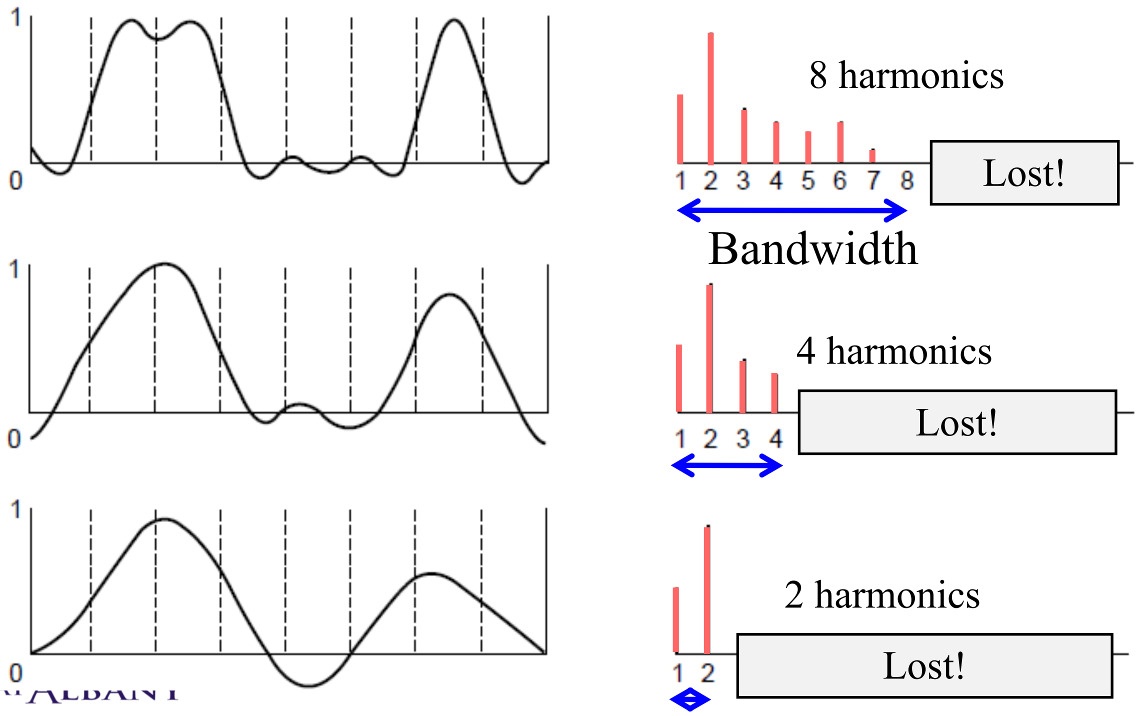
=



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:

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

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 »

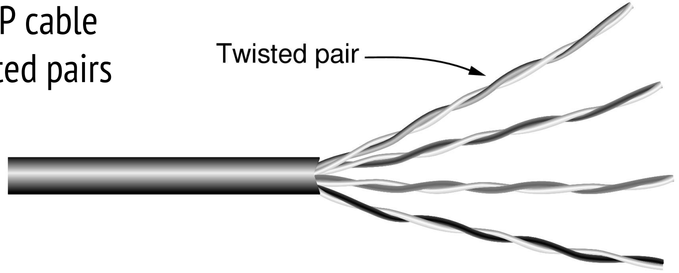
Reality Check: Storage media

- 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

Category 5 UTP cable
with four twisted pairs

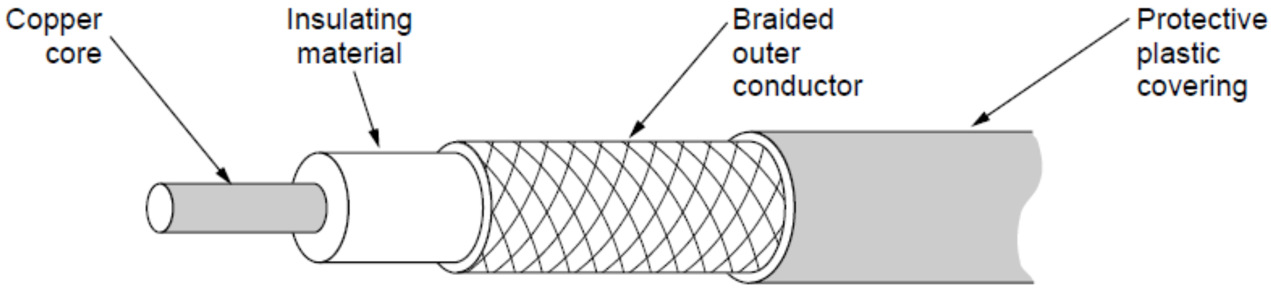


Link Terminology

- 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

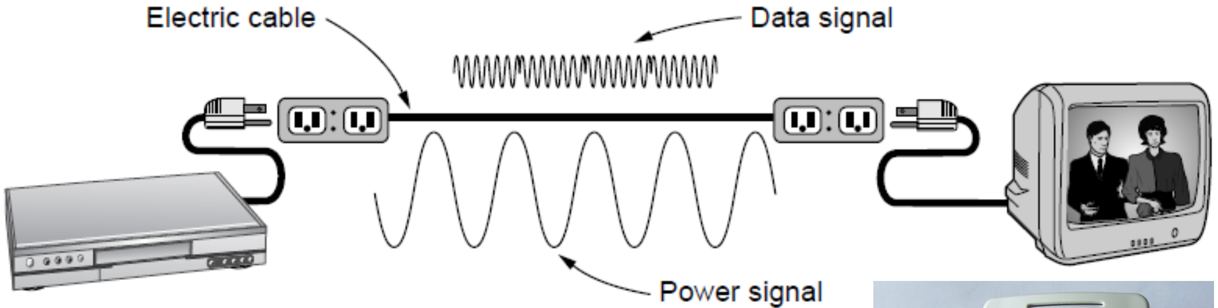
Wires – Coaxial Cable ("Co-ax")

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



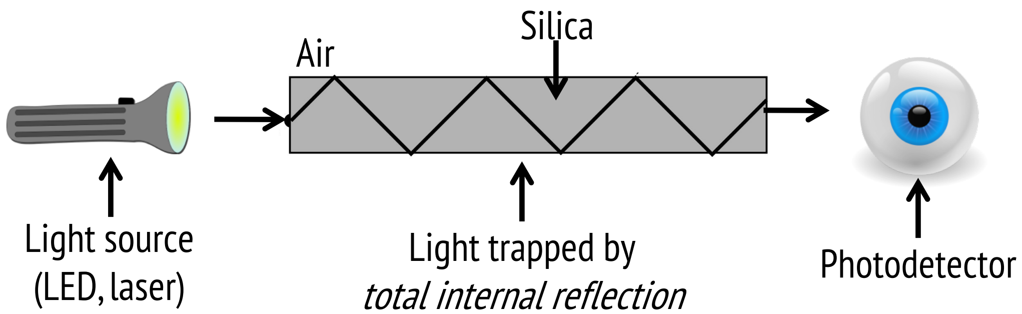
Wires – Power Lines

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



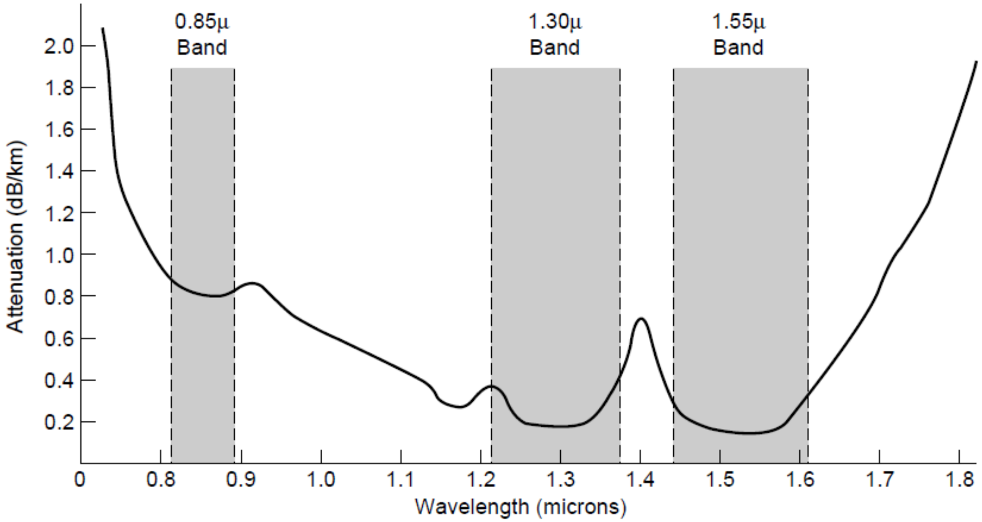
Fiber Cables (1)

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



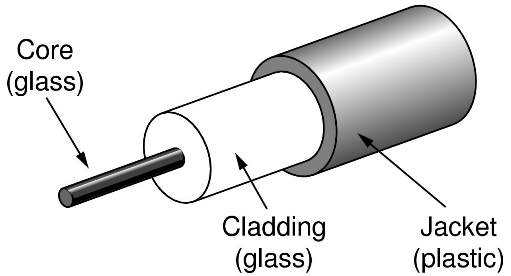
Fiber Cables (2)

- 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

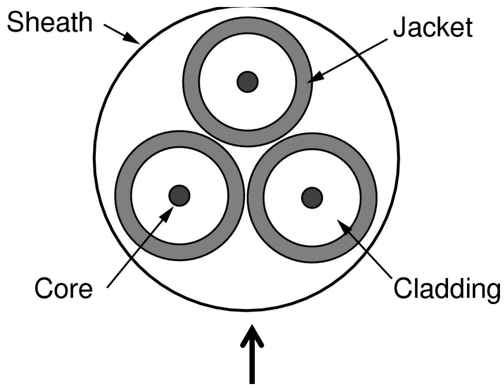


Fiber Cables (3)

- <u>Single-mode</u>
  - Core so narrow (10um) light can't even bounce around
  - Used with lasers for long distances, e.g., 100km



- <u>Multi-mode</u>
  - 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 »

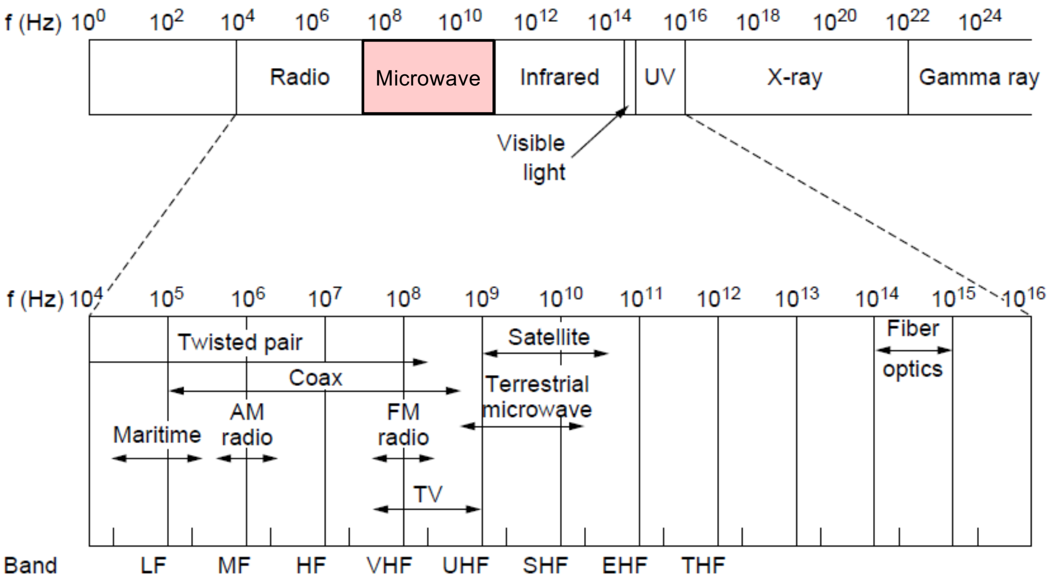
Electromagnetic Spectrum

- $f = c/\lambda$
- 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

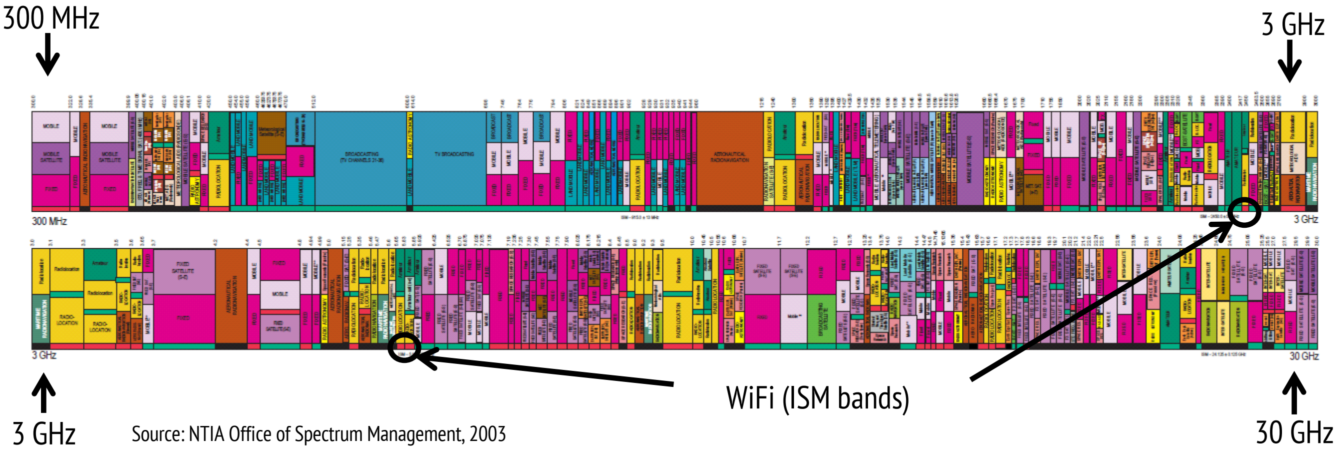
Electromagnetic Spectrum (1)

- 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)

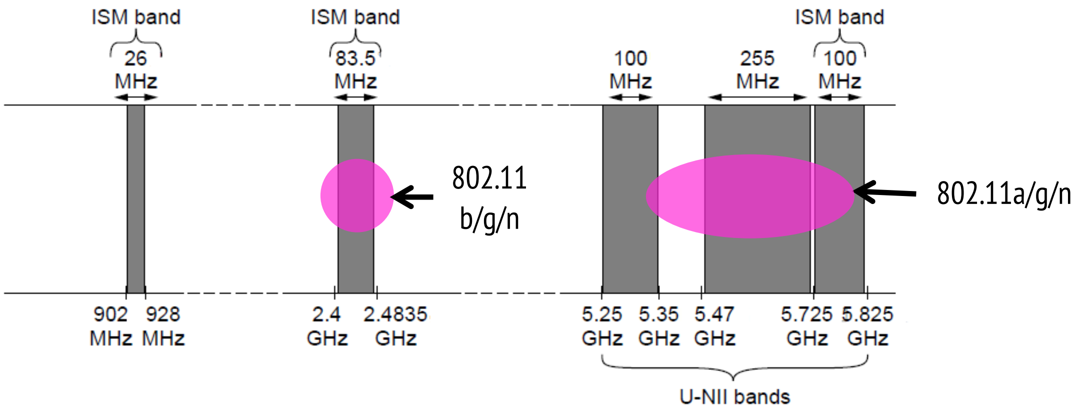
- To manage interference, spectrum is carefully divided, and its use regulated and licensed, e.g., sold at auction.



Part of the US frequency allocations

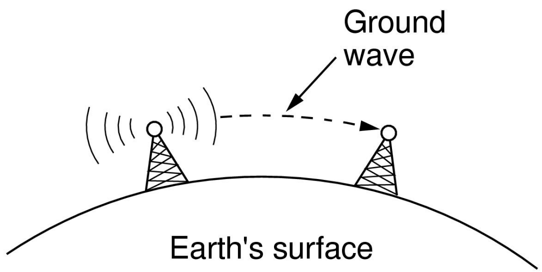
Electromagnetic Spectrum (3)

- 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.

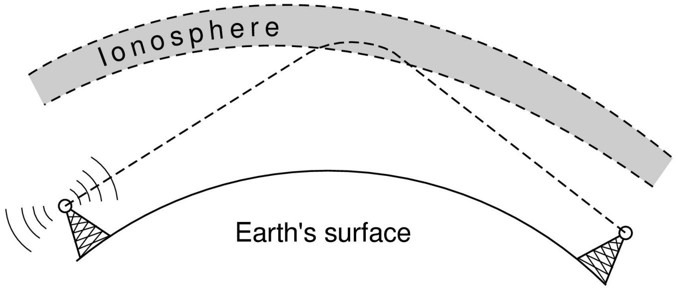


Radio Transmission

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



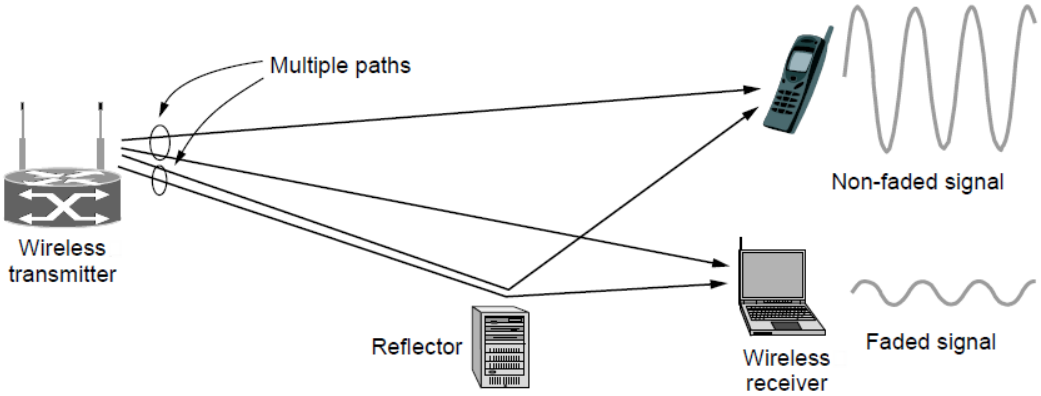
In the VLF, LF, and MF bands, radio waves follow the curvature of the earth



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

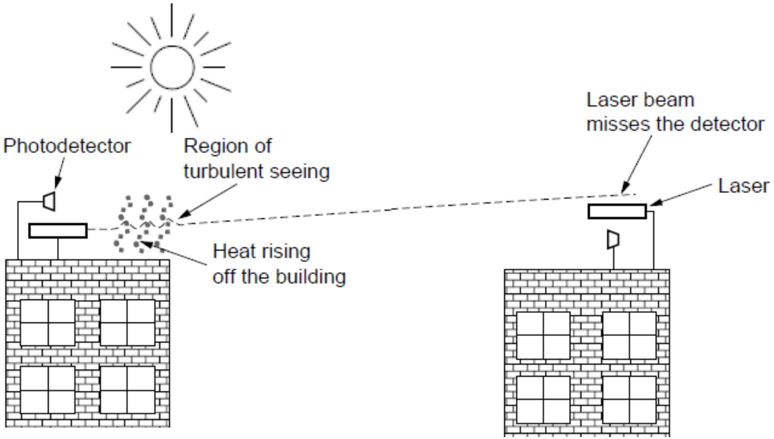
Microwave Transmission

- 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

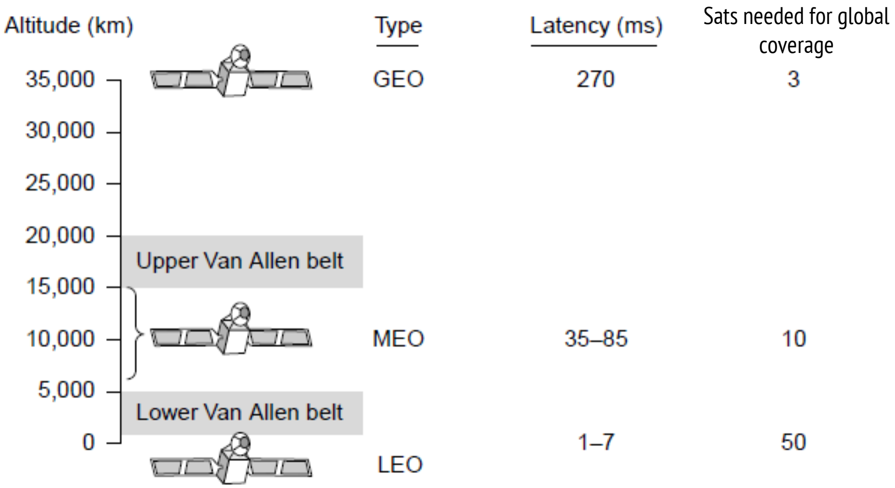
- Wireless:
  - + Easy and inexpensive to deploy
  - + Naturally supports mobility
  - + Naturally supports broadcast
  - o Transmissions interfere and must be managed
  - o Signal strengths hence data rates vary greatly
- Wires/Fiber:
  - + Easy to engineer a fixed data rate over point-to-point links
  - o Can be expensive to deploy, esp. over distances
  - o 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 »

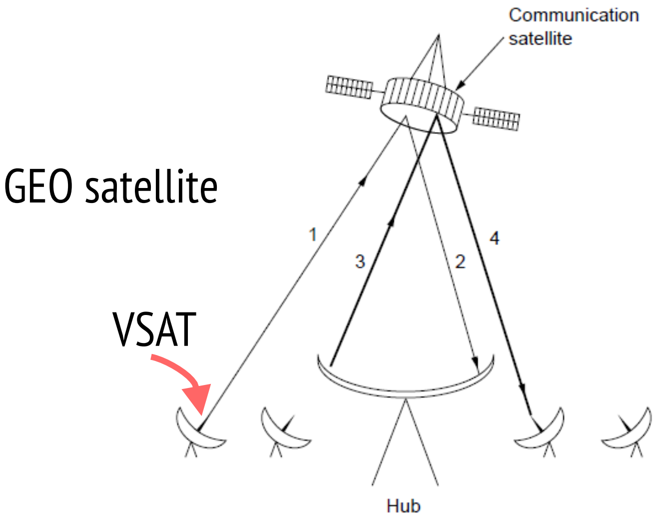
Kinds of Satellites

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



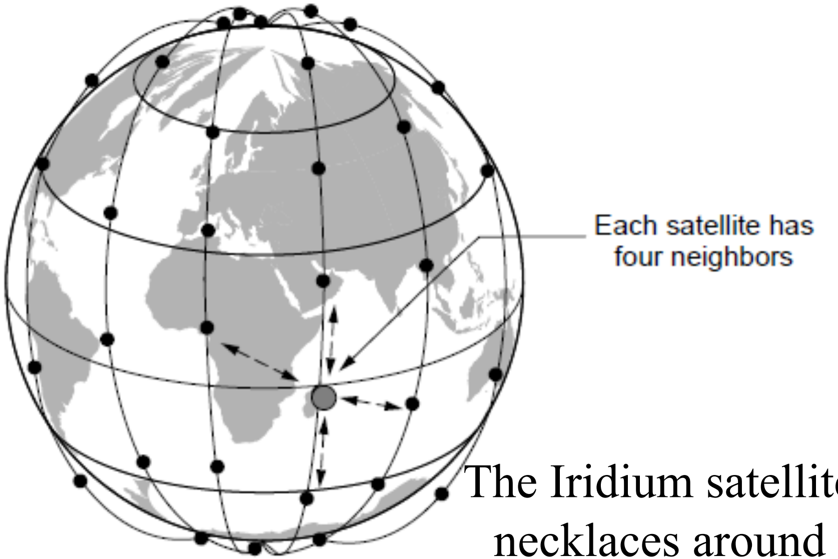
Geostationary Satellites

- 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

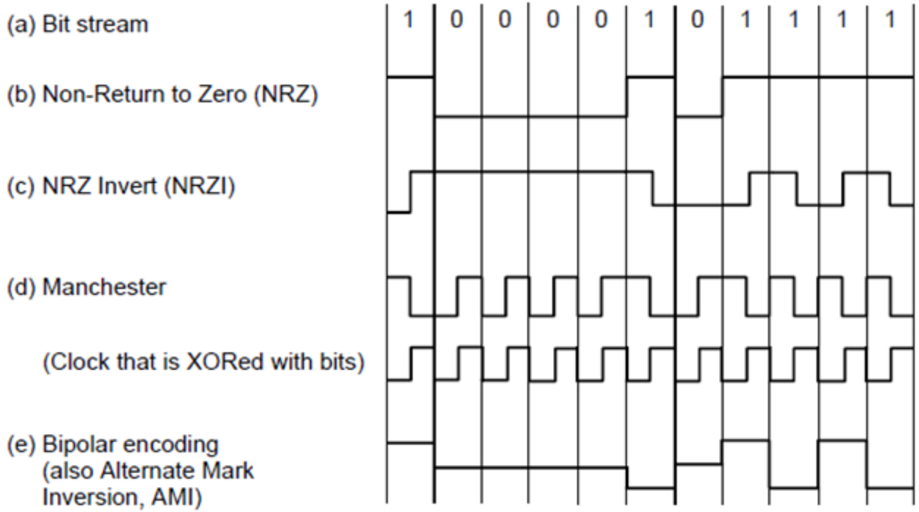
- Satellite:
  - \+ Can rapidly set up anywhere/anytime communications (after satellites have been launched)
  - \+ Can broadcast to large regions
  - o Limited bandwidth and interference to manage
- Fiber:
  - \+ Enormous bandwidth over long distances
  - o Installation can be more expensive/difficult

Digital Modulation and Multiplexing

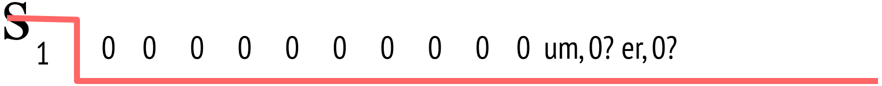
- Modulation schemes send bits as signals; multiplexing schemes share a channel among users.
  - Baseband Transmission »
  - Passband Transmission »
  - Frequency Division Multiplexing »
  - Time Division Multiplexing »
  - Code Division Multiple Access »

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



Clock Recovery

- To decode the symbols, signals need sufficient transitions


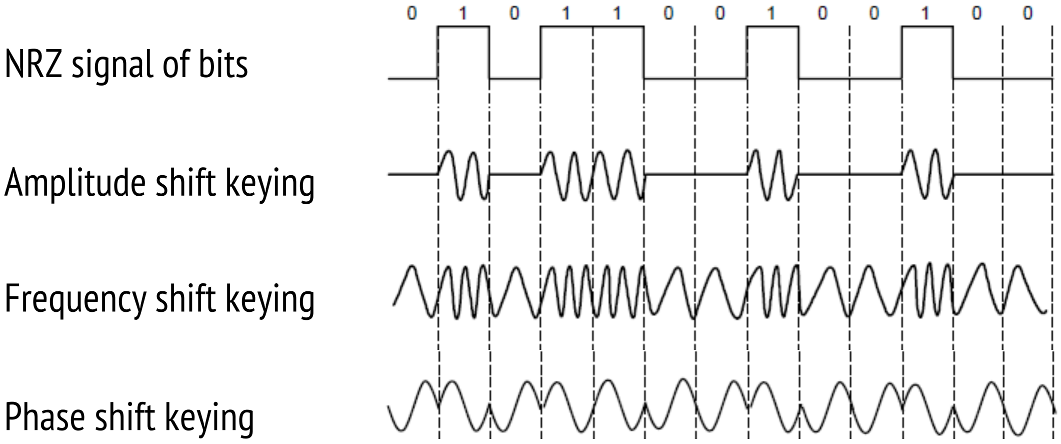
  - Otherwise long runs of 0s (or 1s) are confusing, e.g.:

- 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

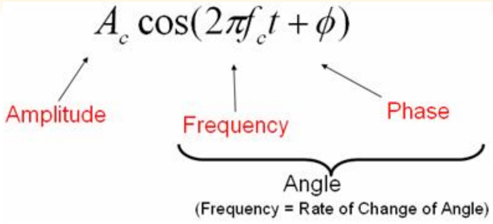
Modulation

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

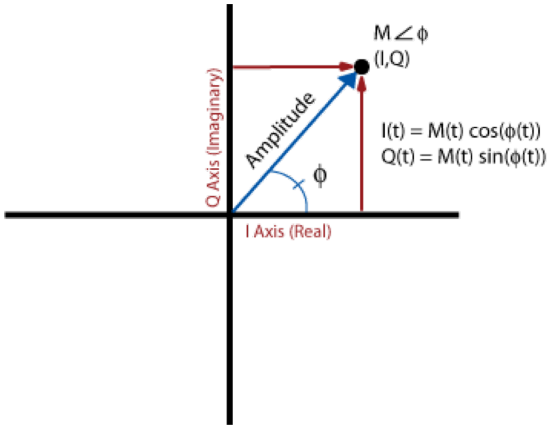


Signal

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

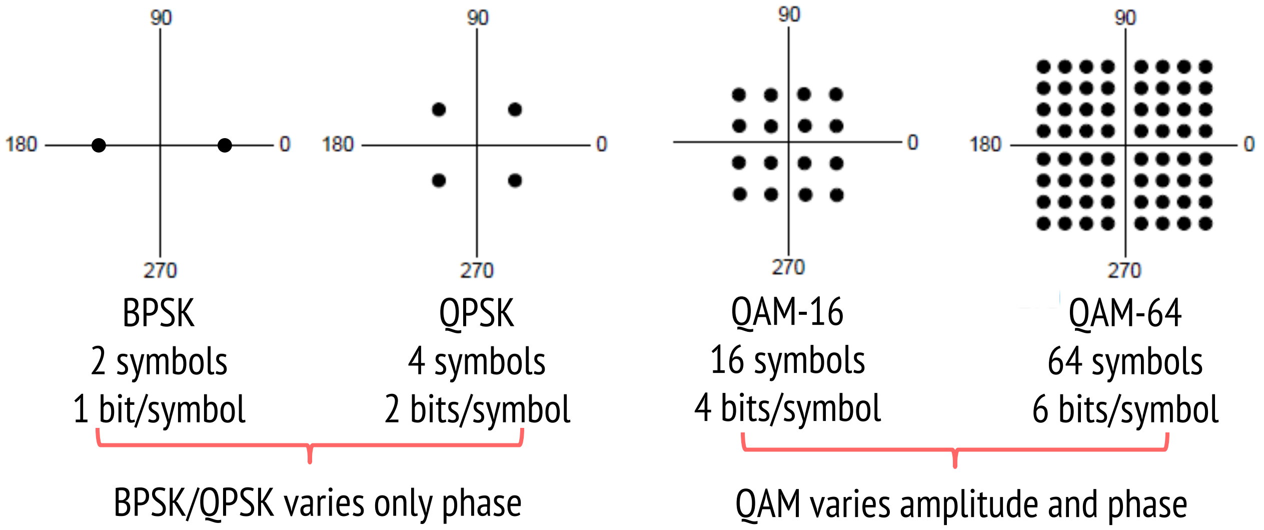


- Instantaneous state of a sine wave with a vector in the complex plane using amplitude (magnitude) and phase coordinates in a polar coordinate system.



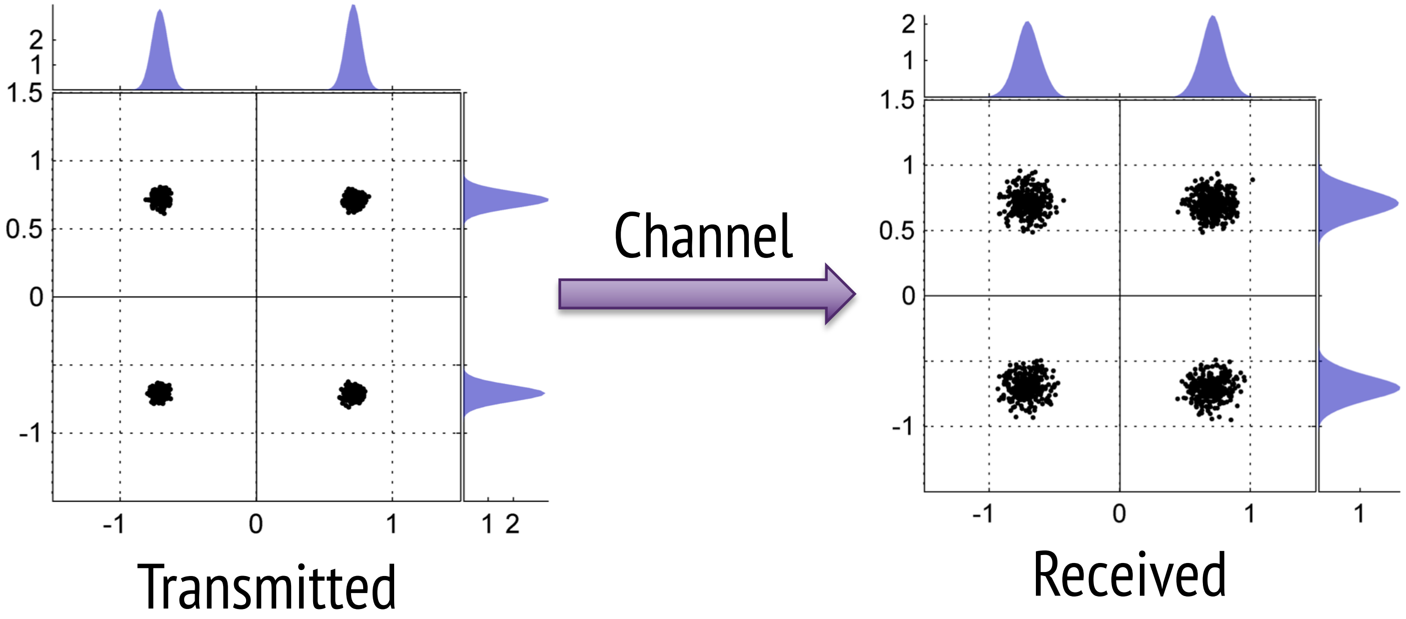
Modulation

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

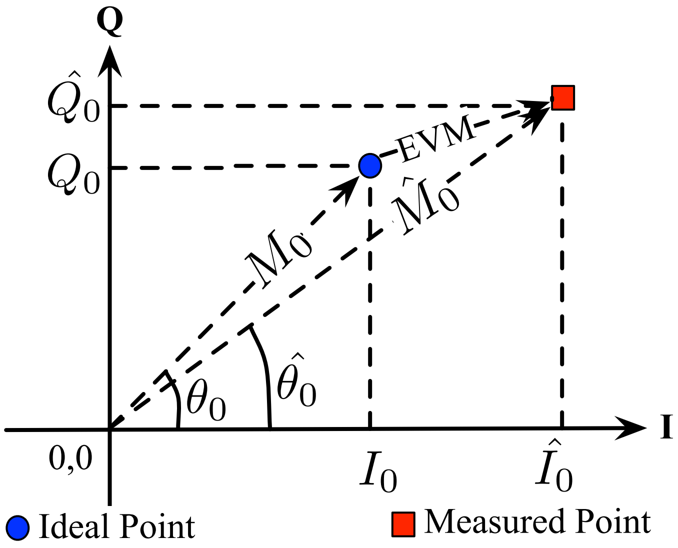


Channel Effects

- 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

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

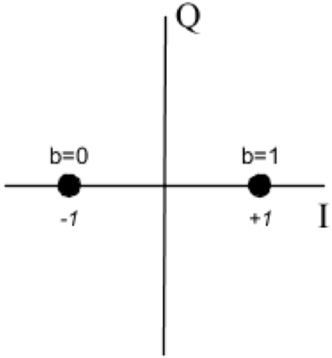
I_{Disp} = Dispersion in I $= I_0 - \hat{I}_0$

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

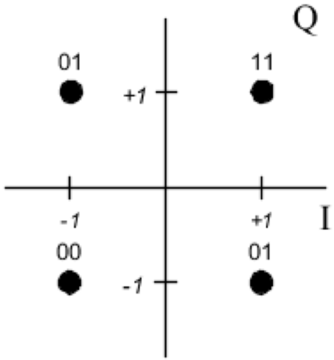
M_{Disp} = Dispersion in Magnitude $= M_0 - \hat{M}_0$

Demodulating the signal

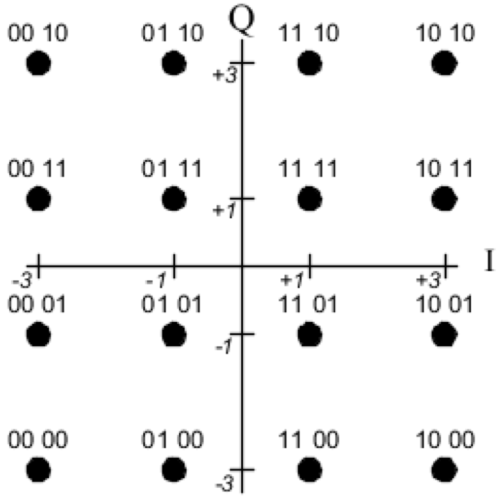
- Use threshold to decide



BPSK



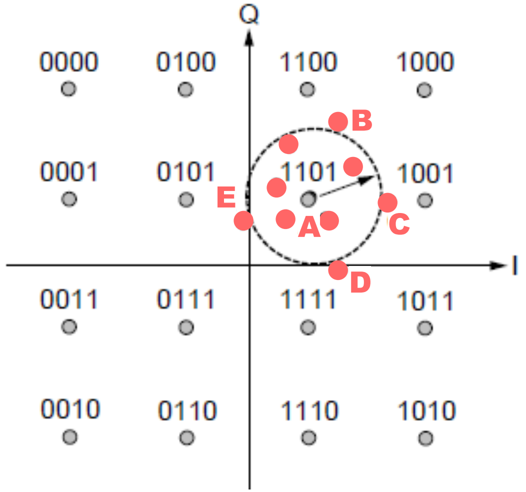
QPSK



16 QAM

Gray Coding

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

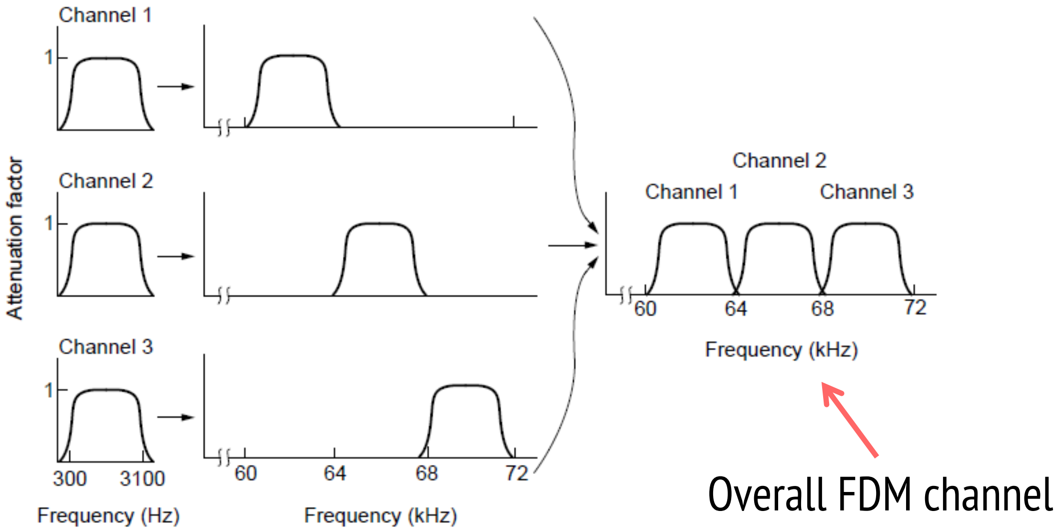


When 1101 is sent:

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

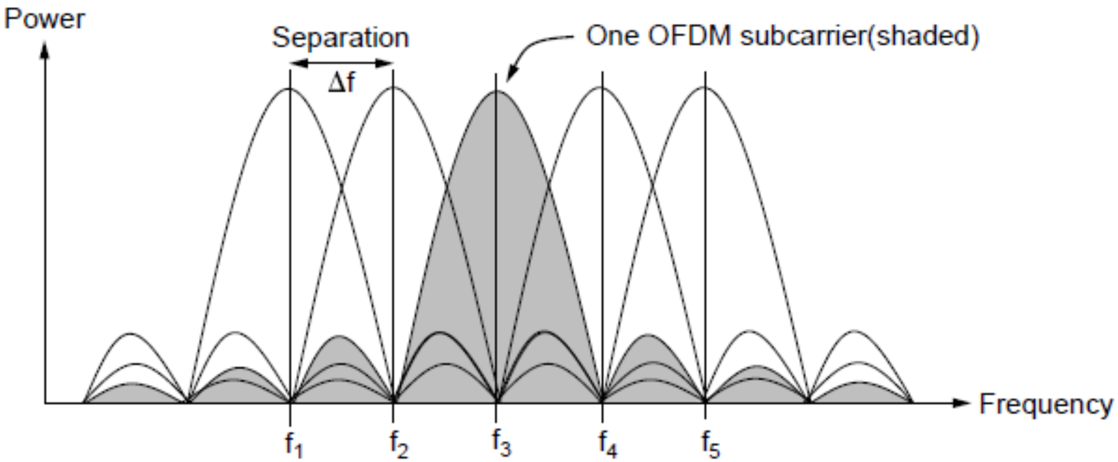
Frequency Division Multiplexing (1)

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



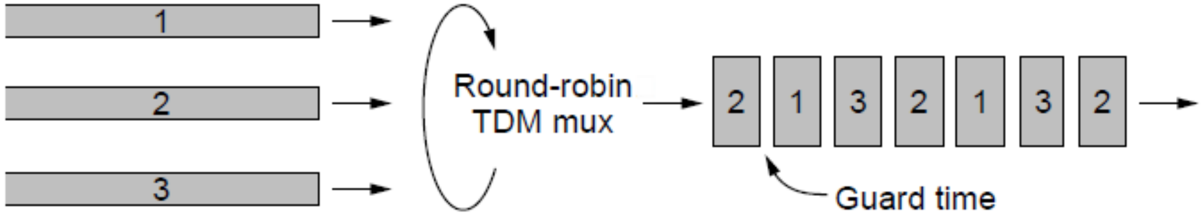
Frequency Division Multiplexing (2)

- 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)

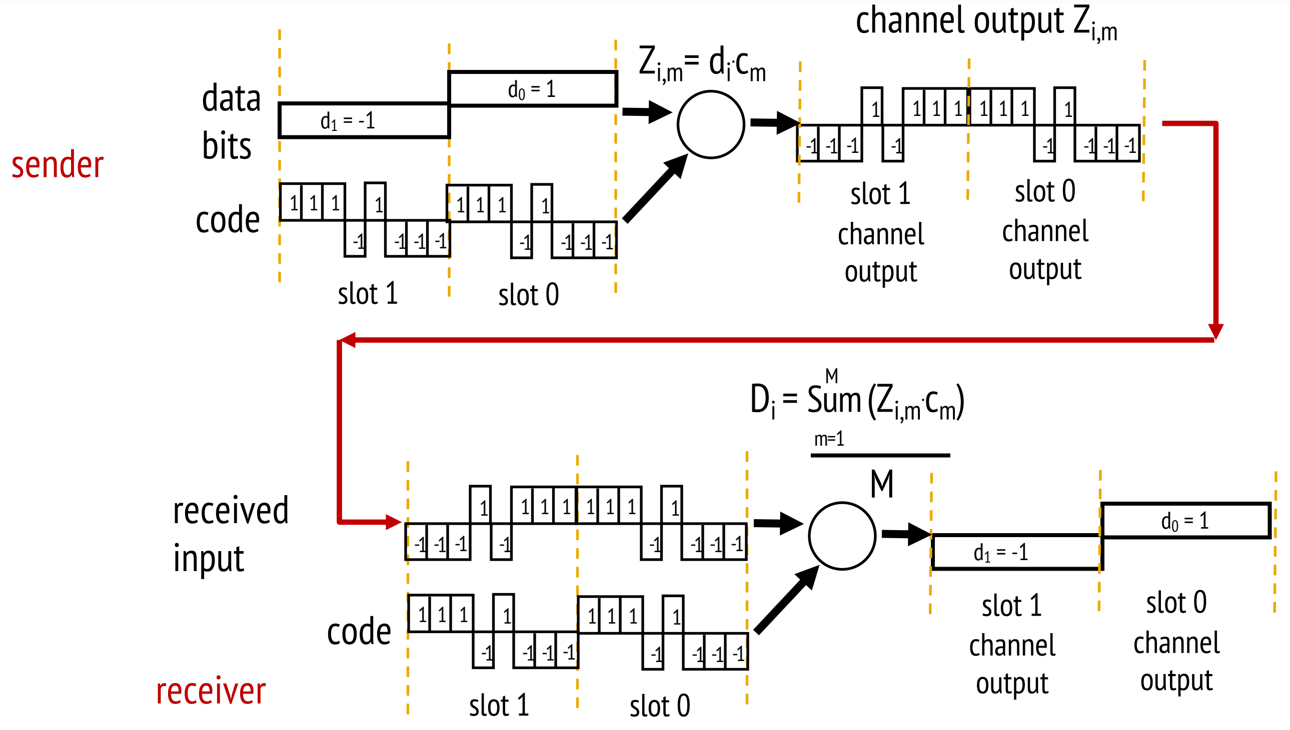
- Time division multiplexing shares a channel over time:
  - Users take turns on a fixed schedule; this is not packet switching or STDM (Statistical TDM)
  - Widely used in telephone / cellular systems



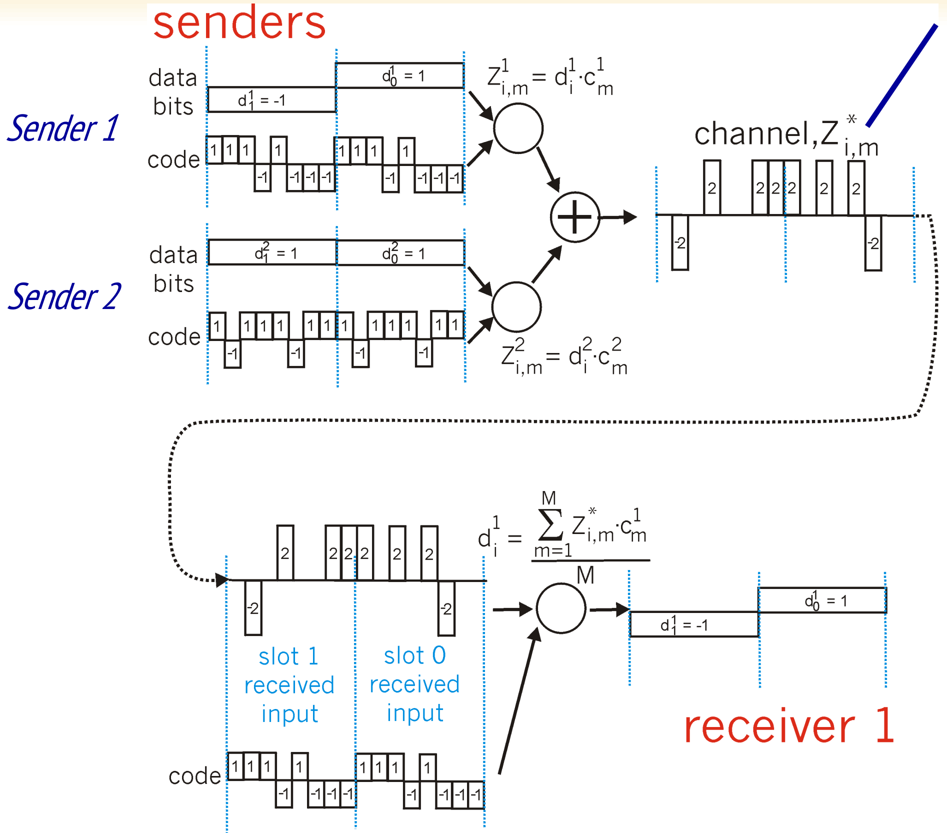
Code Division Multiple Access (CDMA)

- 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

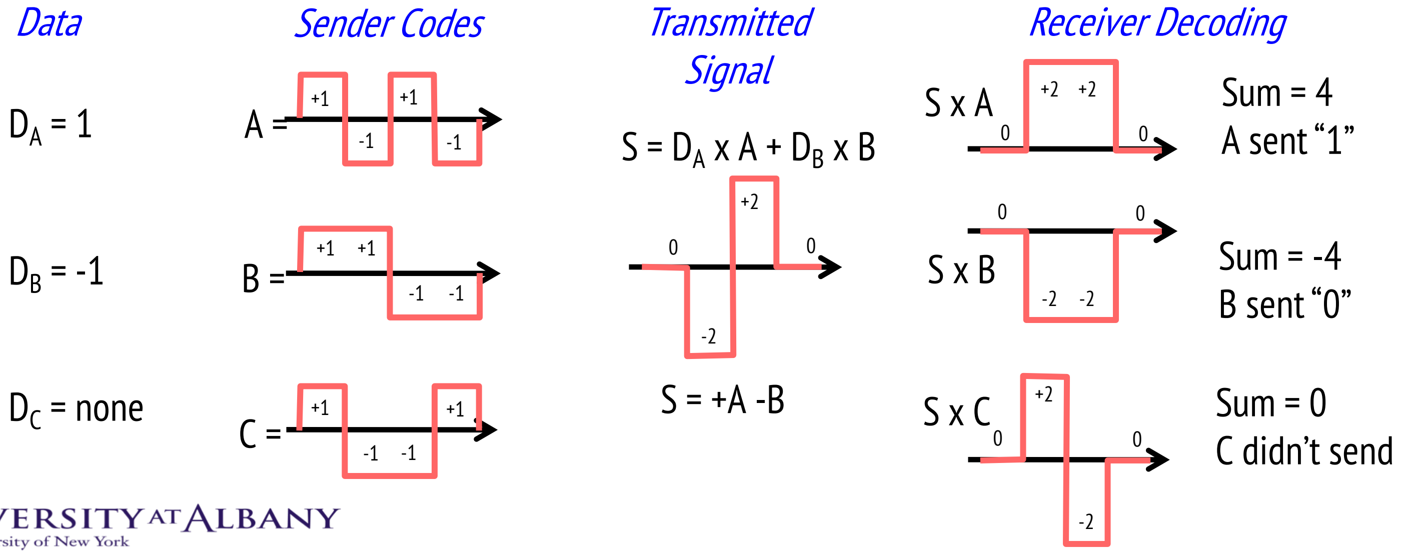


channel sums together transmissions by sender 1 and 2

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



Mobile Telephone System

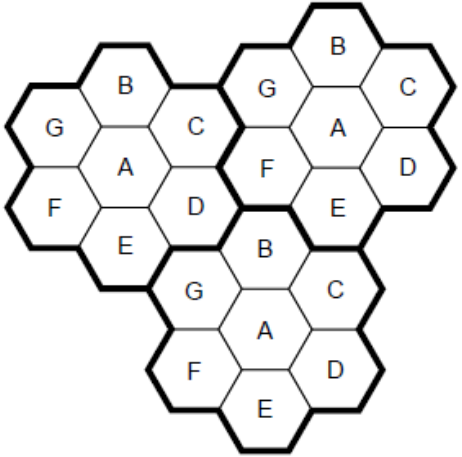
- Generations of mobile telephone systems »
- Cellular mobile telephone systems »
- GSM, a 2G system »
- UMTS, a 3G system »

Generations of mobile telephone systems

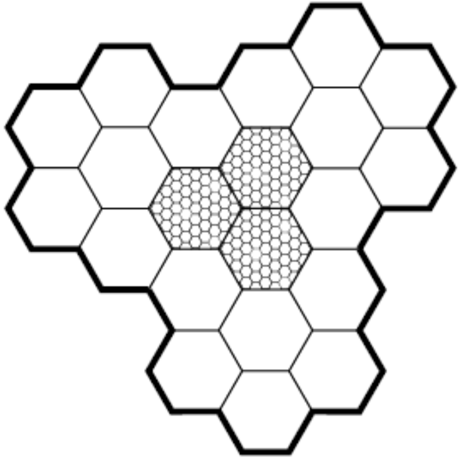
- 1G, analog voice
  - AMPS (Advanced Mobile Phone System) is example, deployed from 1980s. Modulation based on FM (as in radio).
- 2G, analog voice and digital data
  - GSM (Global System for Mobile communications) is example, deployed from 1990s. Modulation based on QPSK.
- 3G, digital voice and data
  - UMTS (Universal Mobile Telecommunications System) is example, deployed from 2000s. Modulation based on CDMA
- 4G, digital data including voice
  - LTE (Long Term Evolution) is example, deployed from 2010s. Modulation based on OFDM

Cellular mobile phone systems

- All based on notion of spatial regions called cells
  - Each mobile uses a frequency in a cell; moves cause <u>handoff</u>
  - Frequencies are reused across non-adjacent cells
  - To supp



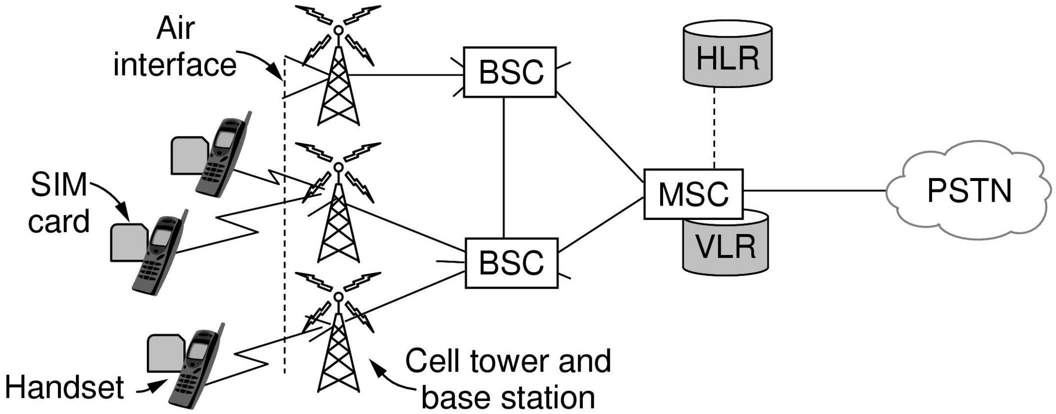
Cellular reuse pattern



Smaller cells for dense mobiles

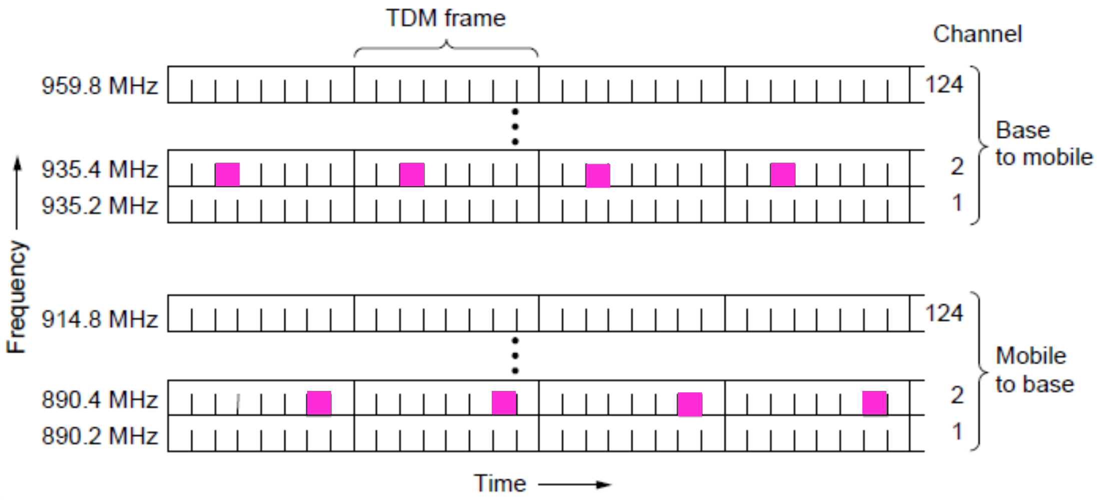
GSM – Global System for Mobile Communications

- Mobile is divided into handset and SIM card (Subscriber Identity Module) with credentials
- Mobiles tell their HLR (Home Location Register) their current whereabouts for incoming calls
- Cells keep track of visiting mobiles (in the Visitor LR)



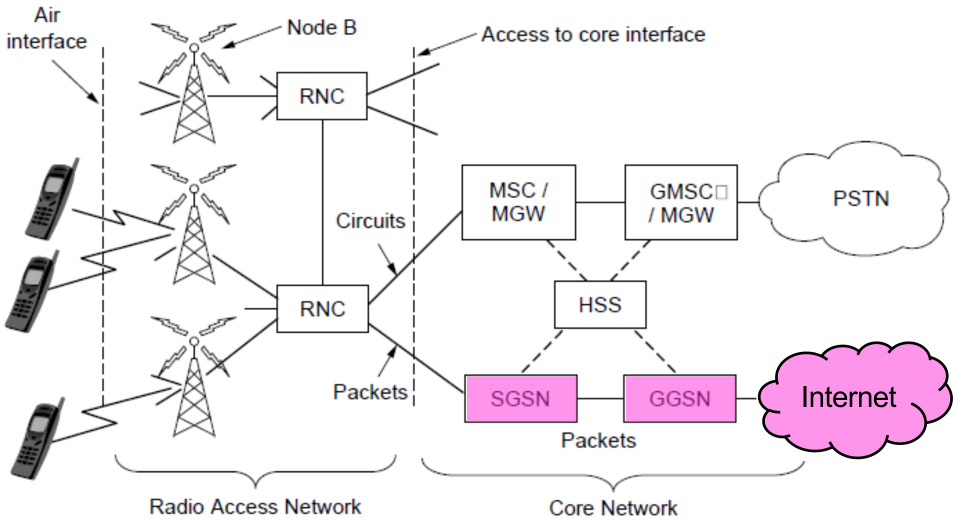
GSM – Global System for Mobile Communications

- Air interface is based on FDM channels of 200 KHz divided in an eight-slot TDM frame every 4.615 ms
  - Mobile is assigned up- and down-stream slots to use
  - Each slot is 148 bits long, gives rate of 27.4 kbps



UMTS – Universal Mobile Telecommunications System

- Architecture is an evolution of GSM; terminology differs
- Packets goes to/from the Internet via SGSN/GGSN

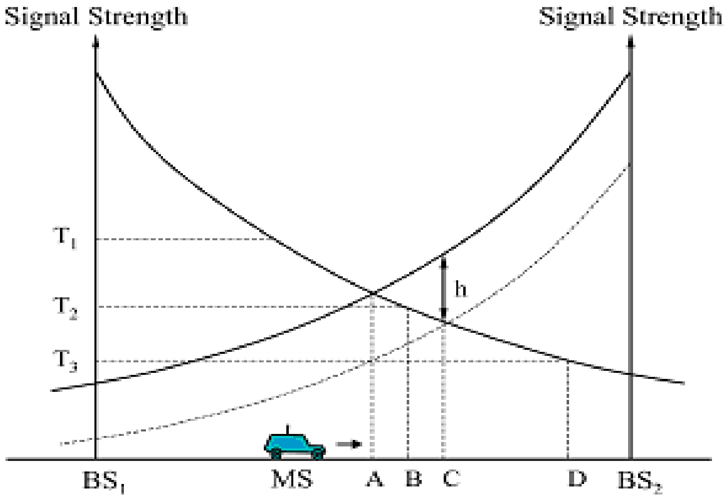


UMTS – Universal Mobile Telecommunications System

- Air interface based on CDMA over 5 MHz channels
  - Rates over users < 14.4 Mbps (HSPDA) per 5 MHz
  - CDMA allows frequency reuse over all cells
  - CDMA permits soft handoff (connected to both cells)

Handoff

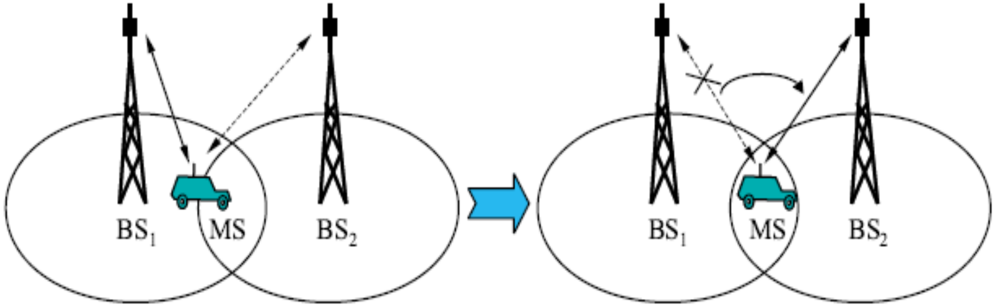
- Handoff and it's decision time



$$RSS\_AVG = RSS\_AVG_T - RSS\_AVG_S \geq h$$

Hard Handoff

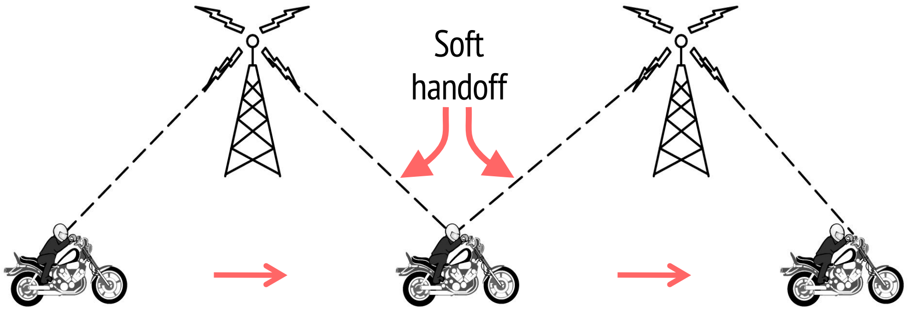
- Hard handoff: "*break before make*" connection
  - Intra and inter-cell handoffs



Hard Handoff between the MS and BSs

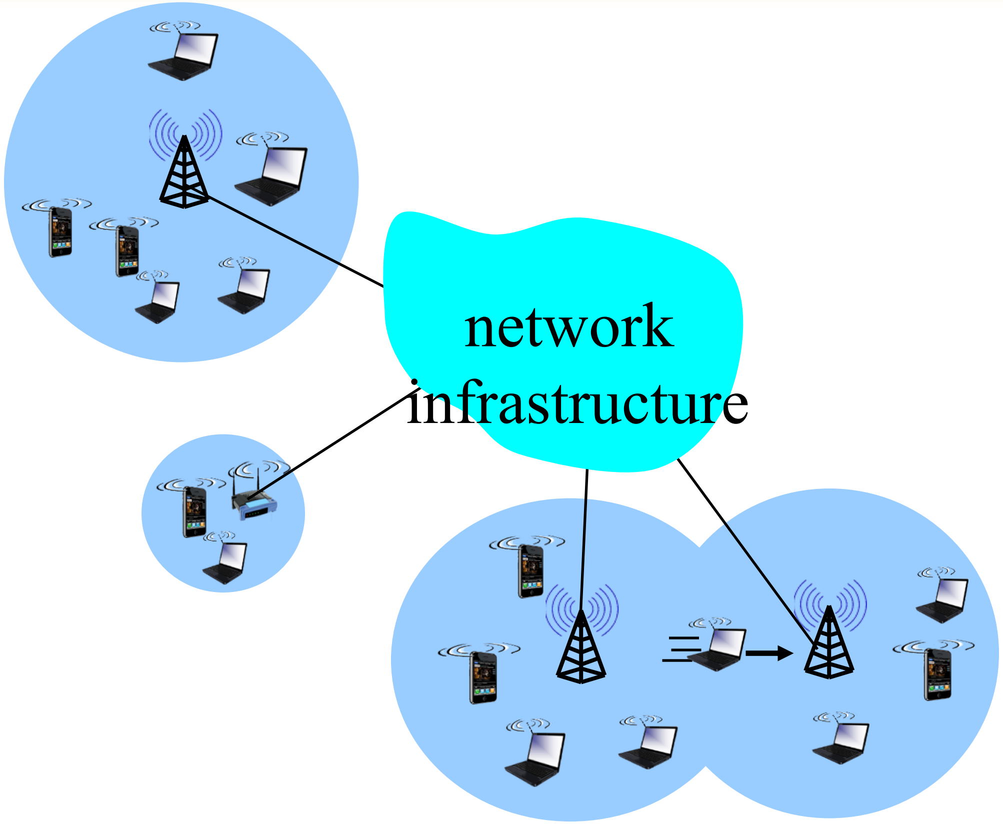
Soft Handoff

- Soft handoff: *"make-before-break" connection.*
- *Mobile directed handoff.*
  - Multiways and softer handoffs

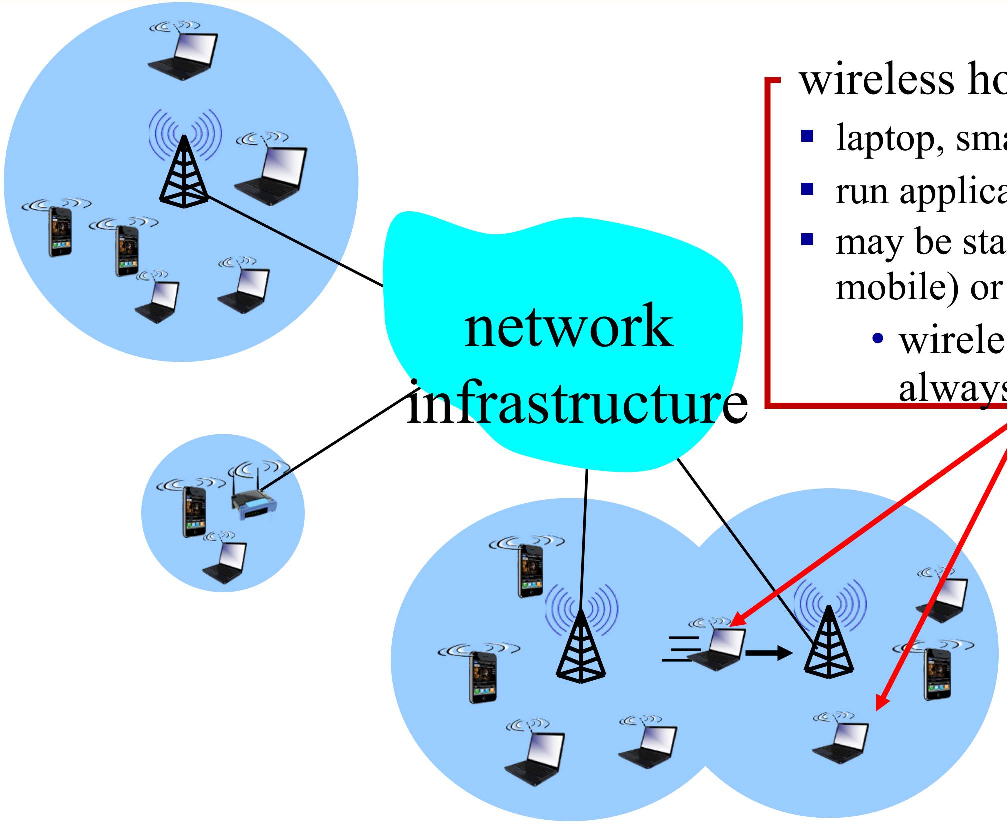


Soft Handoff between MS and BSTs

Elements of a wireless network



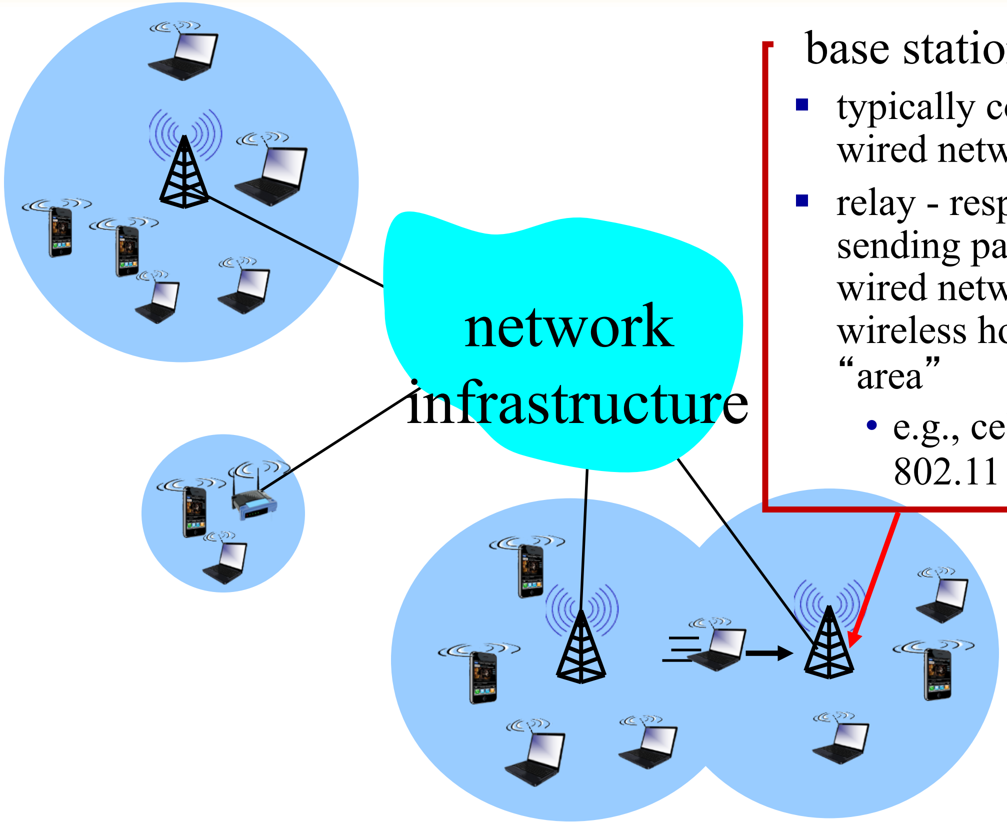
Elements of a wireless network



wireless hosts

- laptop, smartphone
- run applications
- may be stationary (non-mobile) or mobile
  - wireless does *not* always mean mobility

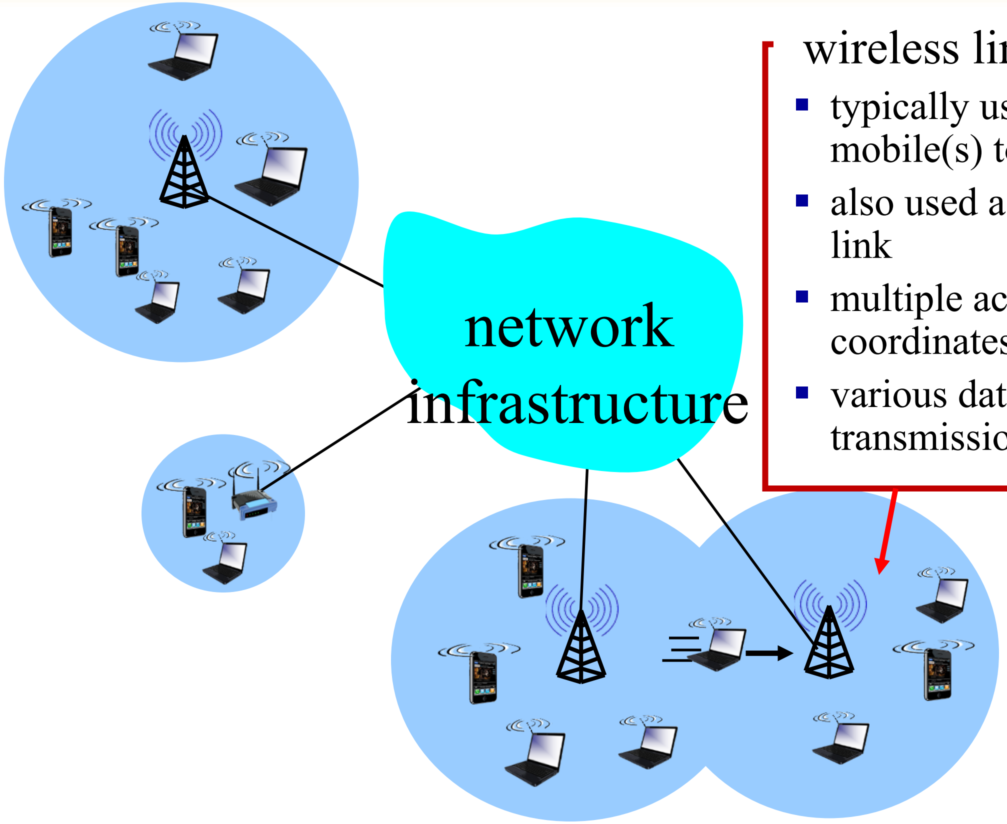
Elements of a wireless network



base station 

- typically connected to wired network
- relay - responsible for sending packets between wired network and wireless host(s) in its "area"
  - e.g., cell towers, 802.11 access points

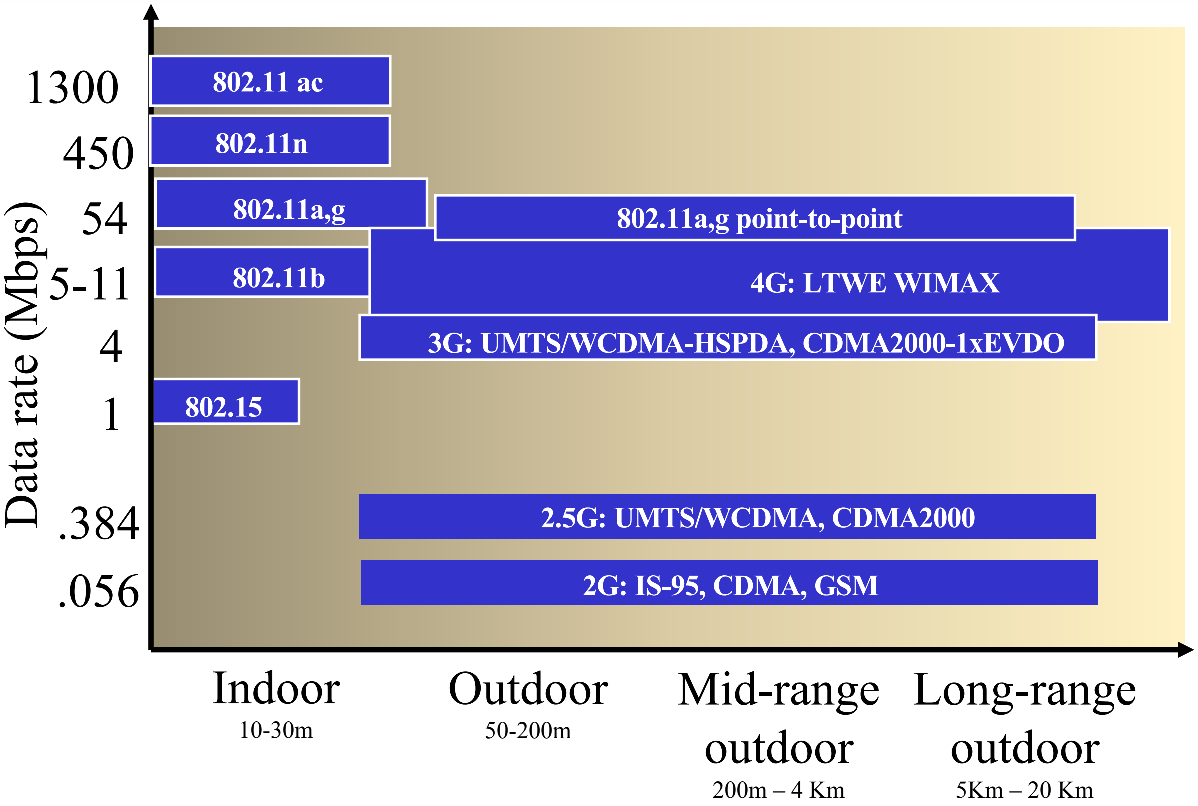
Elements of a wireless network



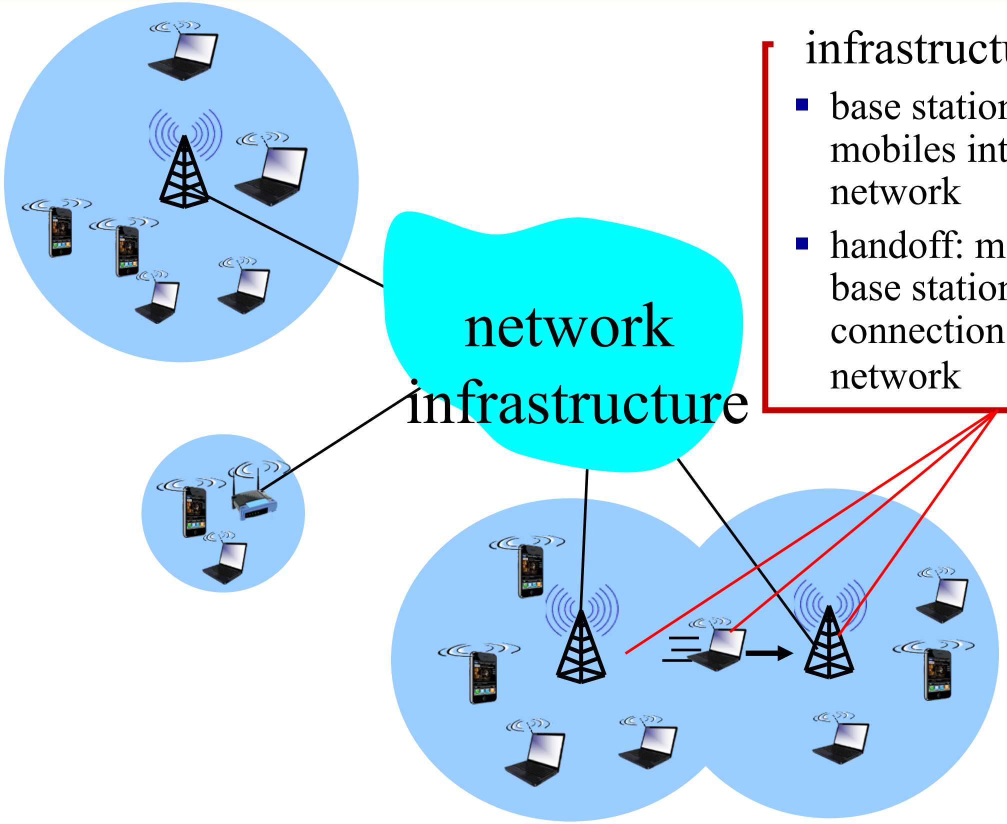
wireless link

- typically used to connect mobile(s) to base station
- also used as backbone link
- multiple access protocol coordinates link access
- various data rates, transmission distance

Characteristics of selected wireless links



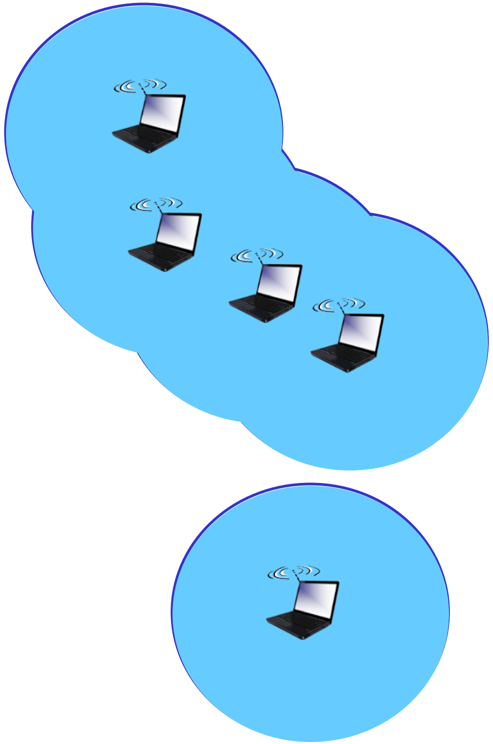
Elements of a wireless network



infrastructure mode

- base station connects mobiles into wired network
- handoff: mobile changes base station providing connection into wired network

Elements of a wireless network



ad hoc mode

- no base stations
- nodes can only transmit to other nodes within link coverage
- nodes organize themselves into a network: route among themselves

Wireless network taxonomy

	single hop	multiple hops
infrastructure (e.g., APs)	host connects to base station (WiFi, WiMAX, cellular) which connects to larger Internet	host may have to relay through several wireless nodes to connect to larger Internet: *mesh net*
no infrastructure	no base station, no connection to larger Internet (Bluetooth, ad hoc nets)	no base station, no connection to larger Internet. May have to relay to reach other a given wireless node MANET, VANET

Wireless Link Characteristics (1)

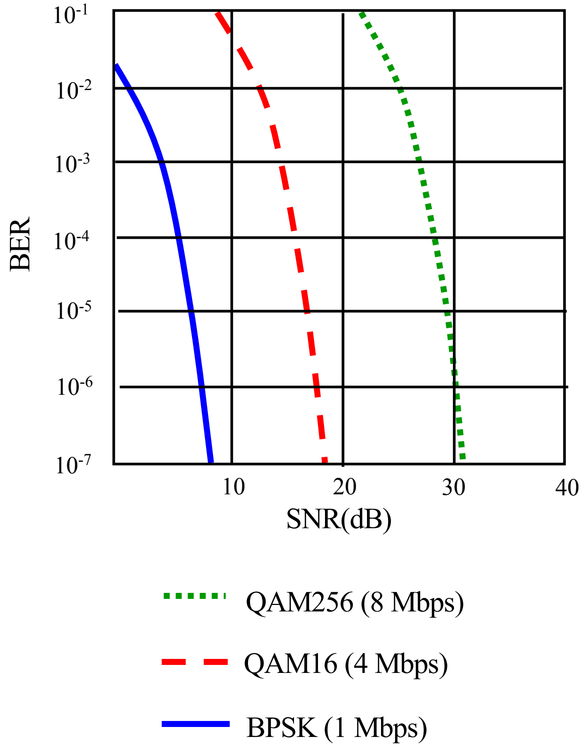
important differences from wired link ….

- *decreased signal strength:* radio signal attenuates as it propagates through matter (path loss)
- *interference from other sources:* standardized wireless network frequencies (e.g., 2.4 GHz) shared by other devices (e.g., phone); devices (motors) interfere as well
- *multipath propagation:* radio signal reflects off objects ground, arriving ad destination at slightly different times

…. make communication across (even a point to point) wireless link much more "difficult"

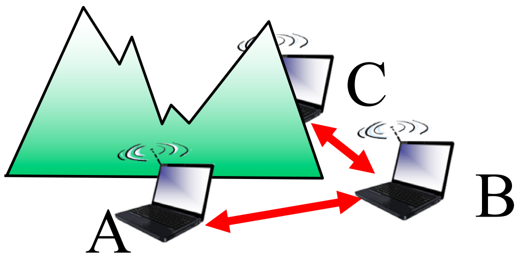
Wireless Link Characteristics (2)

- SNR: signal-to-noise ratio
  - larger SNR – easier to extract signal from noise (a "good thing")
- *SNR versus BER tradeoffs*
  - *given physical layer:* increase power -> increase SNR->decrease BER
  - *given SNR:* choose physical layer that meets BER requirement, giving highest thruput
    - SNR may change with mobility: dynamically adapt physical layer (modulation technique, rate)



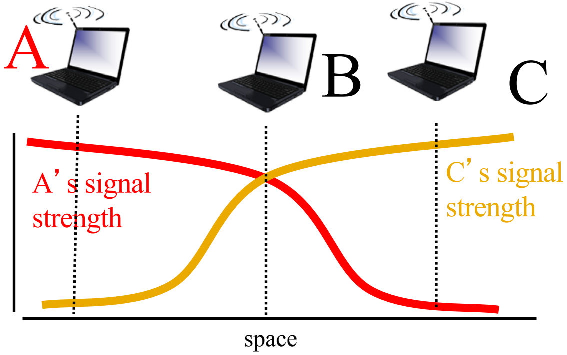
Wireless network characteristics

Multiple wireless senders and receivers create additional problems (beyond multiple access):



Hidden terminal problem

- B, A hear each other
- B, C hear each other
- A, C can not hear each other means A, C unaware of their interference at B



Signal attenuation:

- B, A hear each other
- B, C hear each other
- A, C can not hear each other interfering at B

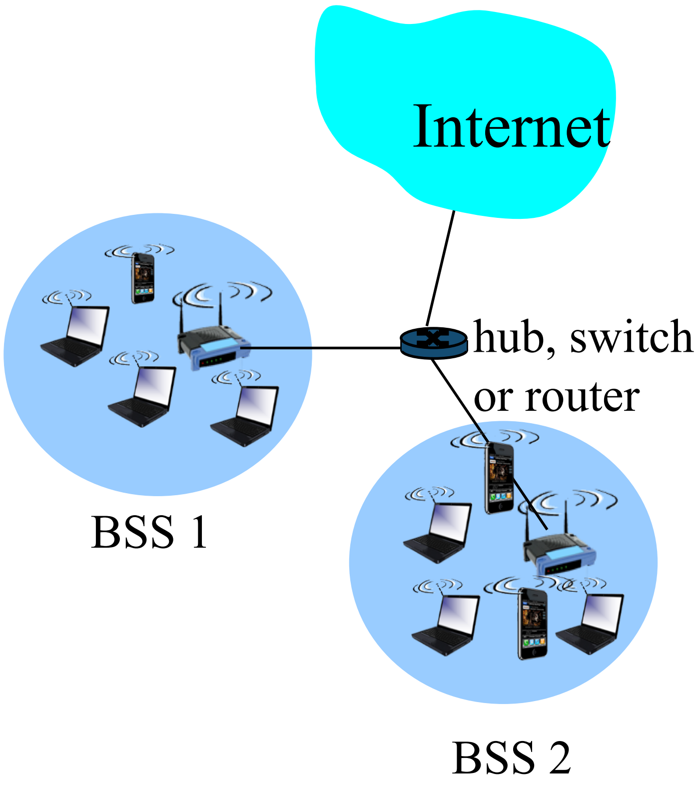
IEEE 802.11 Wireless LAN

- 802.11b
- 2.4-5 GHz unlicensed spectrum
- up to 11 Mbps
- direct sequence spread spectrum (DSSS) in physical layer
  - all hosts use same chipping code

- all use CSMA/CA for multiple access
- all have base-station and ad-hoc network versions

- 802.11a
  - 5-6 GHz range
  - up to 54 Mbps
- 802.11g
  - 2.4-5 GHz range
  - up to 54 Mbps
- 802.11n: multiple antennae
  - 2.4-5 GHz range
  - up to 200 Mbps

802.11 LAN architecture

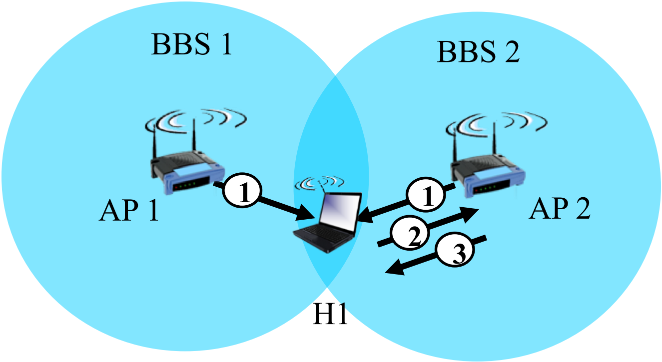


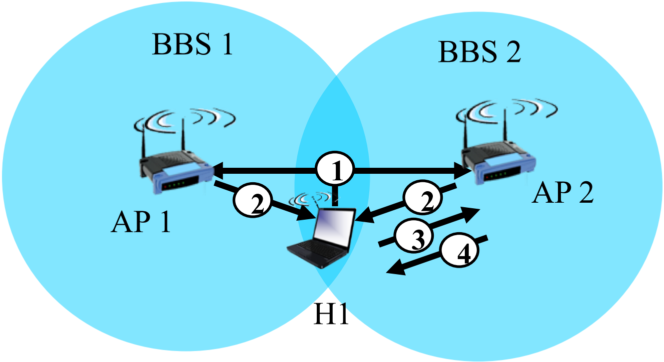
- wireless host communicates with base station
  - base station = access point (AP)
- Basic Service Set (BSS) (aka “cell”) in infrastructure mode contains:
  - wireless hosts
  - access point (AP): base station
  - ad hoc mode: hosts only

802.11: Channels, association

- 802.11b: 2.4GHz-2.485GHz spectrum divided into 11 channels at different frequencies
  - AP admin chooses frequency for AP
  - interference possible: channel can be same as that chosen by neighboring AP!
- host: must *associate* with an AP
  - scans channels, listening for *beacon frames* containing AP's name (SSID) and MAC address
  - selects AP to associate with
  - may perform authentication
  - will typically run DHCP to get IP address in AP's subnet

802.11: passive/active scanning





passive scanning:

(1) beacon frames sent from APs

(2) association Request frame sent: H1 to selected AP

(3) association Response frame sent from selected AP to H1

active scanning:

(1) Probe Request frame broadcast from H1

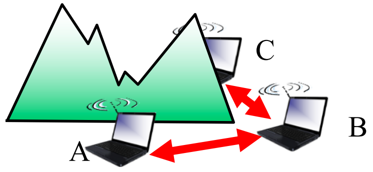
(2) Probe Response frames sent from APs

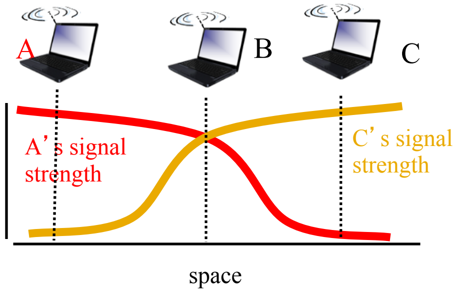
(3) Association Request frame sent: H1 to selected AP

(4) Association Response frame sent from selected AP to H1

IEEE 802.11: multiple access

- avoid collisions: 2^+ nodes transmitting at same time
- 802.11: CSMA - sense before transmitting
  - don't collide with ongoing transmission by other node
- 802.11: *no* collision detection!
  - difficult to receive (sense collisions) when transmitting due to weak received signals (fading)
  - can't sense all collisions in any case: hidden terminal, fading
  - goal: *avoid collisions:* CSMA/C(ollision)A(voidance)





IEEE 802.11 MAC Protocol: CSMA/CA

802.11 sender

1 if sense channel idle for **DIFS** then

transmit entire frame (no CD)

2 if sense channel busy then

start random backoff time

timer counts down while channel idle

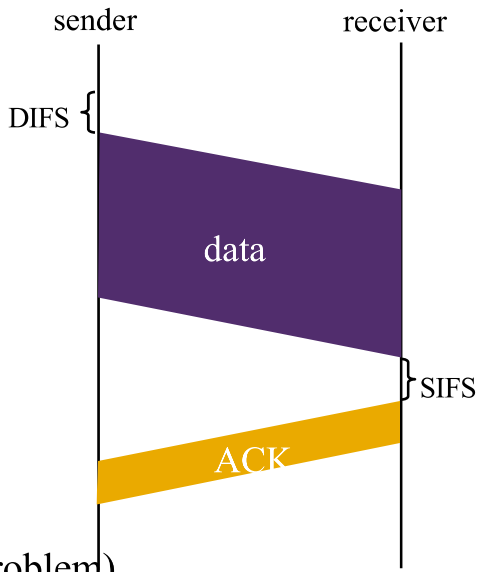
transmit when timer expires

if no ACK, increase random backoff interval, repeat 2

802.11 receiver

- if frame received OK

return ACK after **SIFS** (ACK needed due to hidden terminal problem)



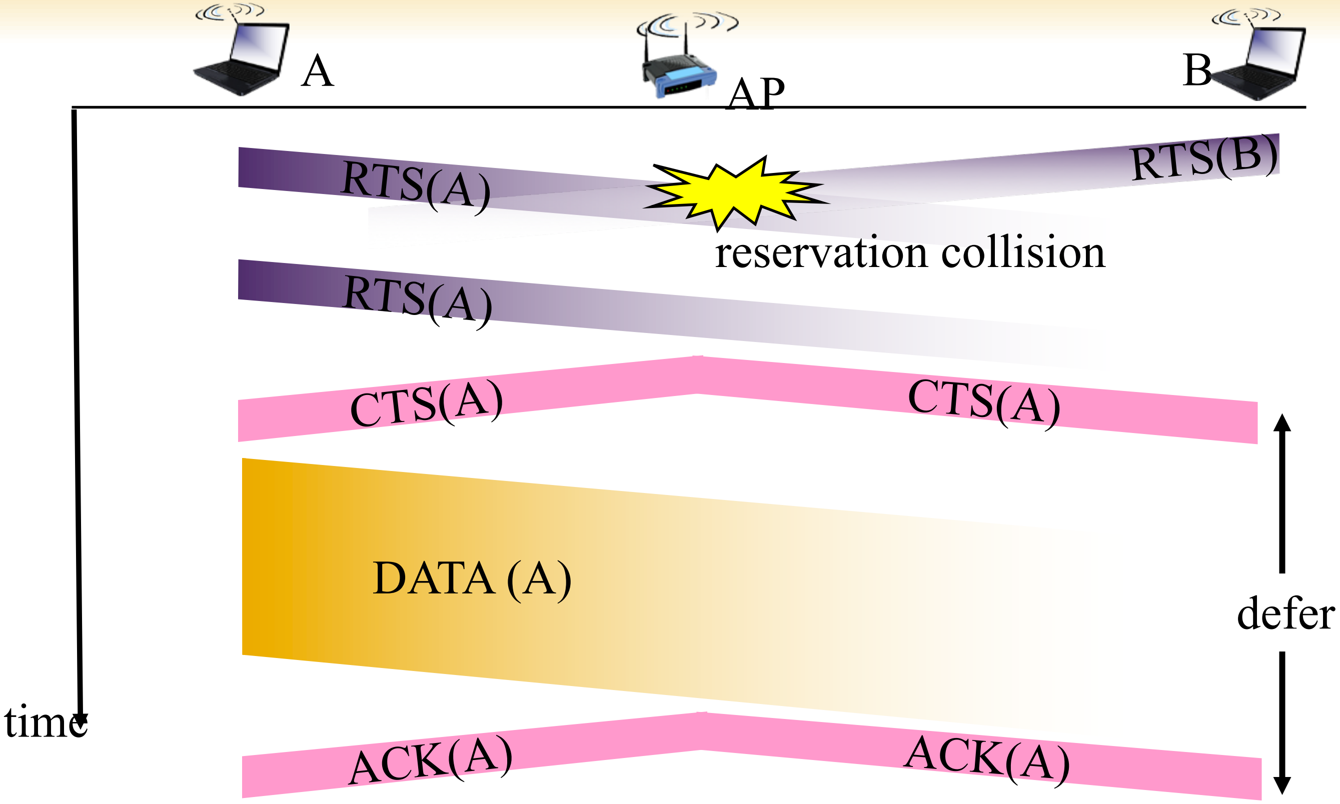
Avoiding collisions (more)

idea: allow sender to "reserve" channel rather than random access of data frames: avoid collisions of long data frames

- sender first transmits *small* request-to-send (RTS) packets to BS using CSMA
  - RTSs may still collide with each other (but they're short)
- BS broadcasts clear-to-send CTS in response to RTS
- CTS heard by all nodes
  - sender transmits data frame
  - other stations defer transmissions

avoid data frame collisions completely using small reservation packets!

Collision Avoidance: RTS-CTS exchange



802.11 frame: addressing

2	2	6	6	6	2	6	0 - 2312	4
frame control	duration	address 1	address 2	address 3	Seq control	address 4	payload	CRC

Address 1: MAC address of wireless host or AP to receive this frame

Address 2: MAC address of wireless host or AP transmitting this frame

Address 3: MAC address of router interface to which AP is attached

Address 4: used only in ad hoc mode

802.11 Frame: Addressing