CS 4220: Computer Networks

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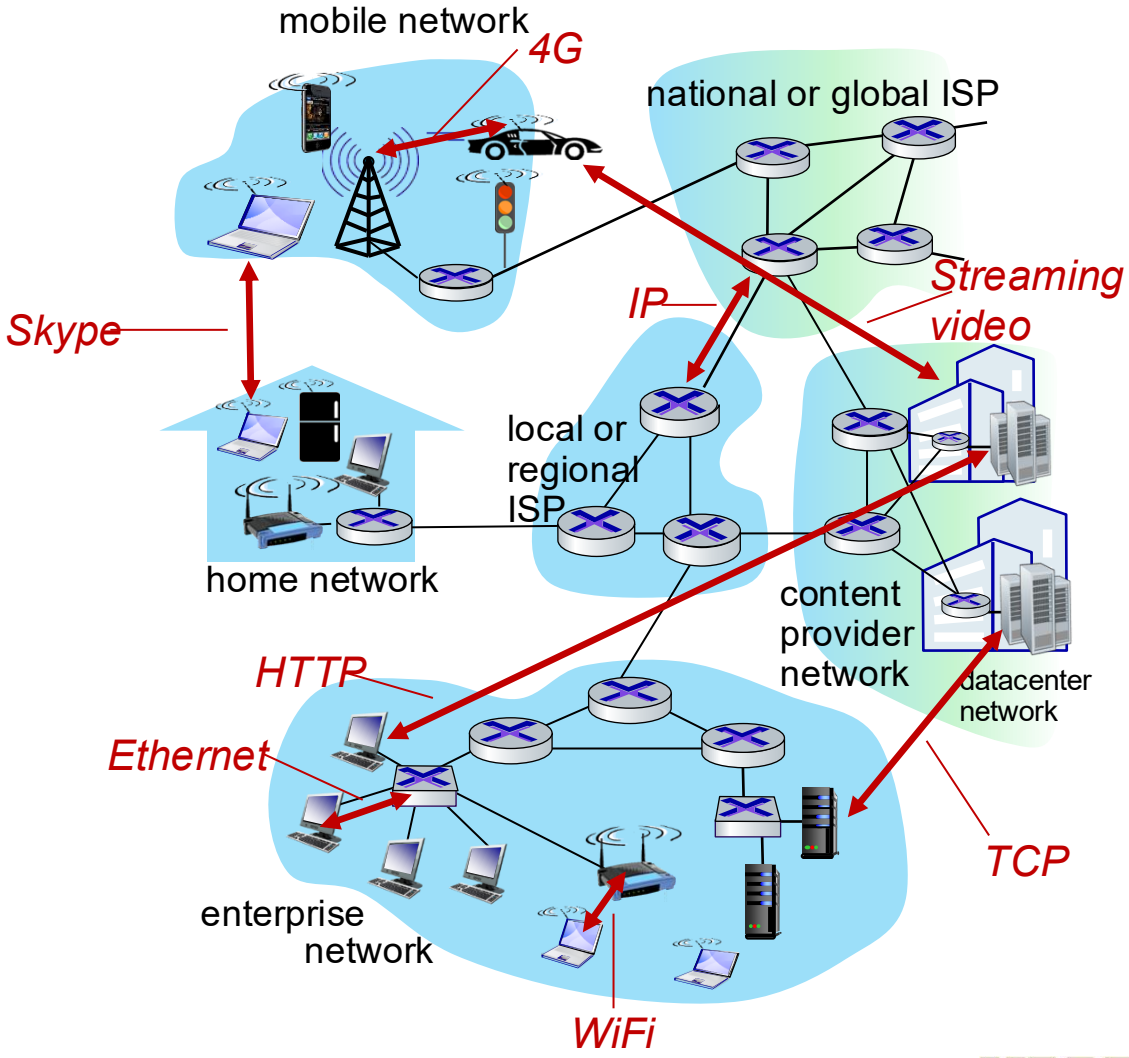
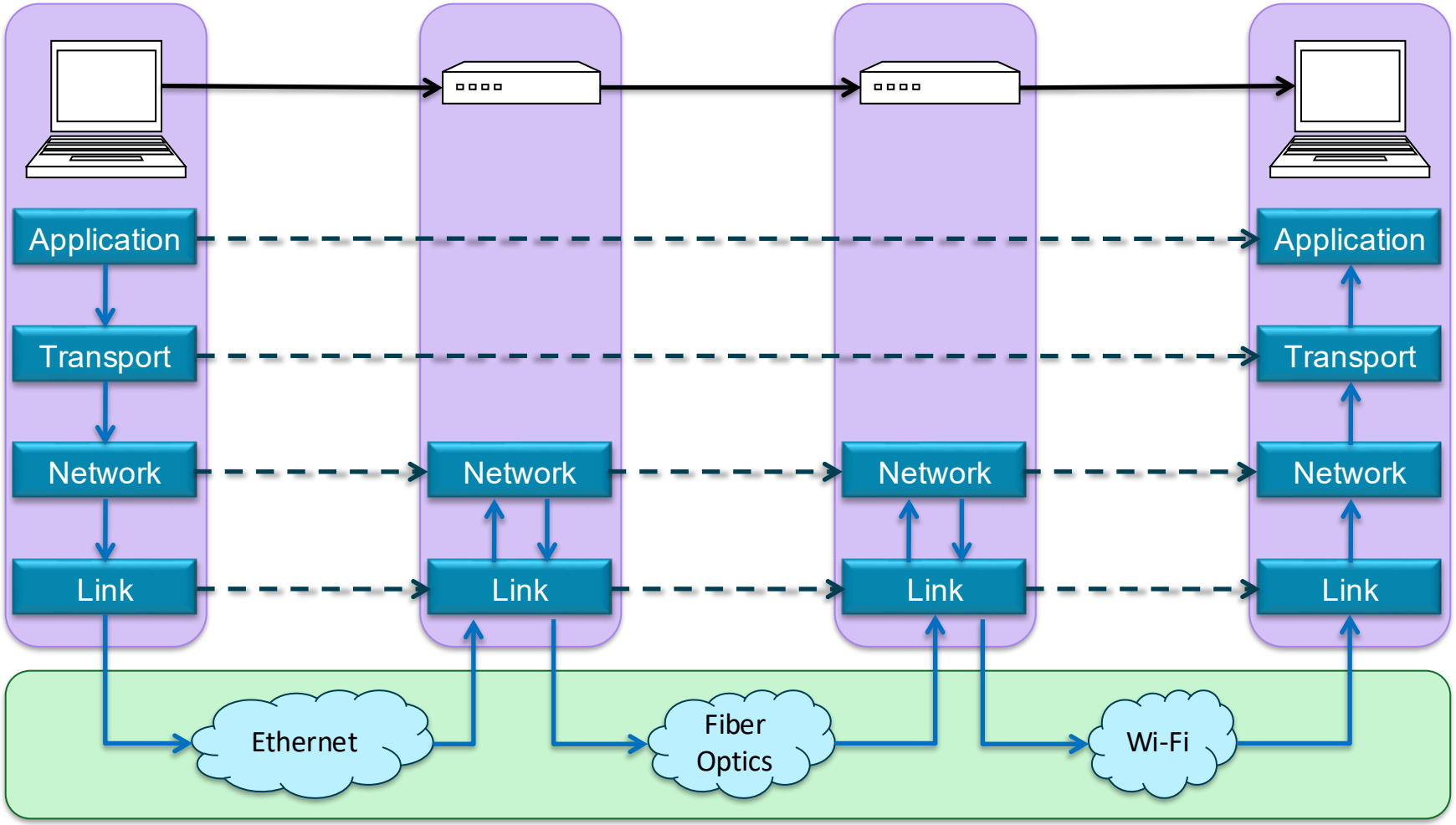
The Internet: a "nuts and bolts" view

- *Internet:* "network of networks"
  - Interconnected ISPs
- *protocols* are *everywhere*
  - control sending, receiving of messages
  - e.g., HTTP (Web), streaming video, Zoom, TCP, IP, WiFi, 4/5G, Ethernet
- *Internet standards*
  - RFC: Request for Comments
  - IETF: Internet Engineering Task Force

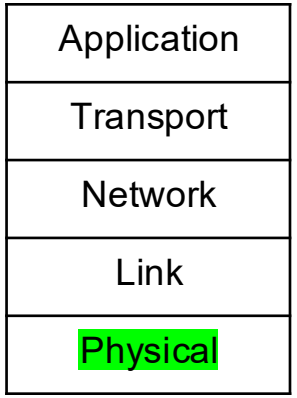


Network Layers



The Physical Layer

- Foundation on which other layers build
  - Properties of wires, fiber, wireless limit that the network can do
- Key problem is to send (digital) bits using only (analog) signals
  - This is called modulation

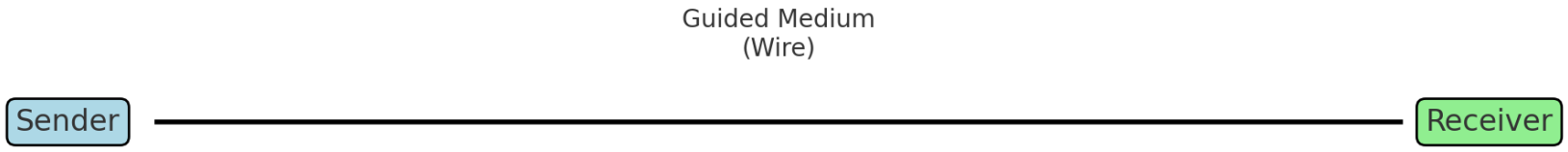


Outline

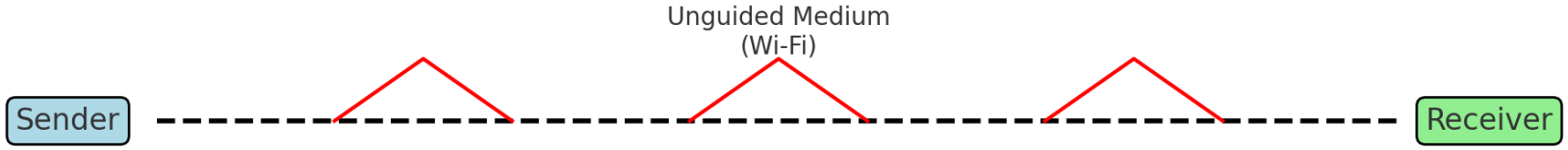
- Transmission media
- From waveforms to bits
- Examples of communication systems
  - Wired LANs
  - Wireless access network

Transmission Media

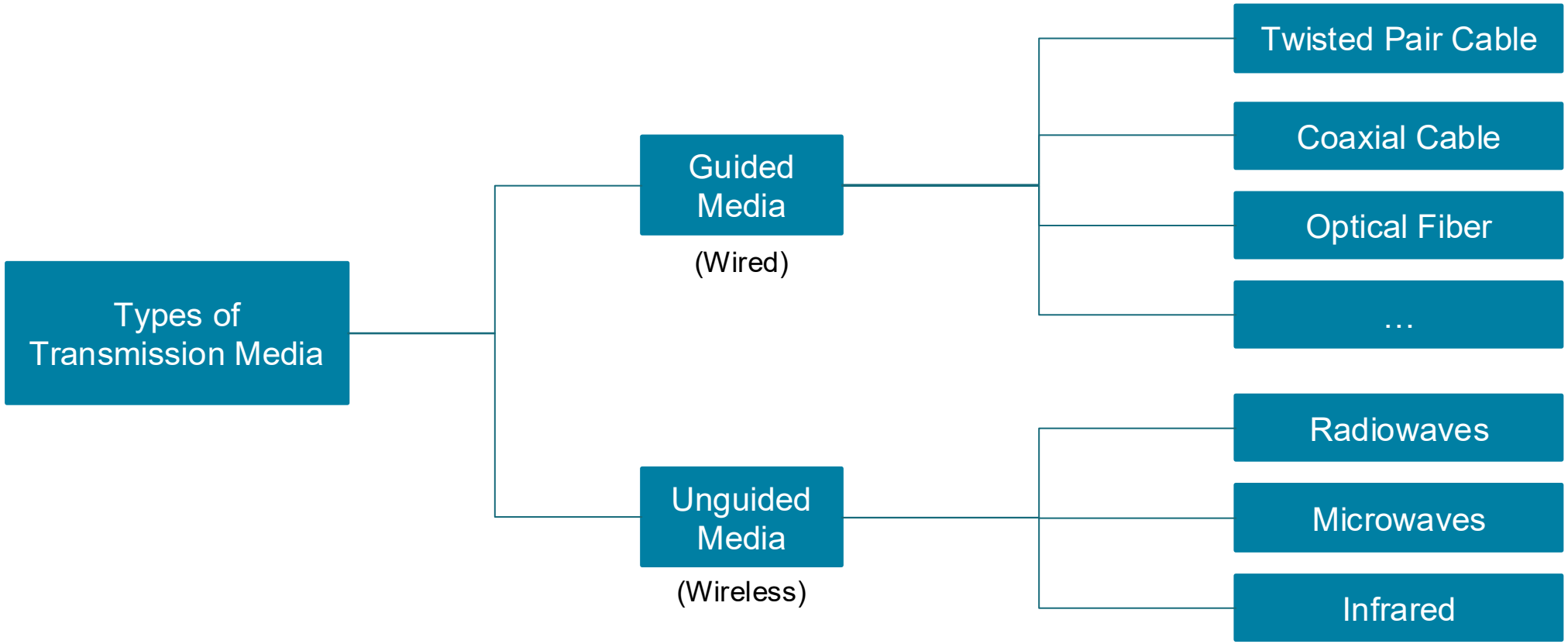
- The physical path or channel that carries signals from sender to receiver
- Provides the means for data to travel in a communication system
- Can be:
  - **Guided (wired):** signals follow a physical path (copper, fiber)
    - e.g.,



  - **Unguided (wireless):** signals travel freely through air or space
    - e.g.,



Transmission Media

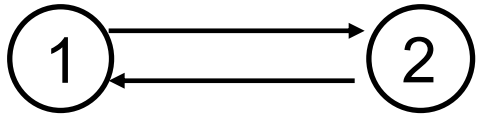


- **NOTE**: Besides guided and unguided media, data can also be moved using persistent storage (e.g., USB drives, hard disks). This is not real-time transmission but a *store-and-carry* method — sometimes even faster for large volumes of data.

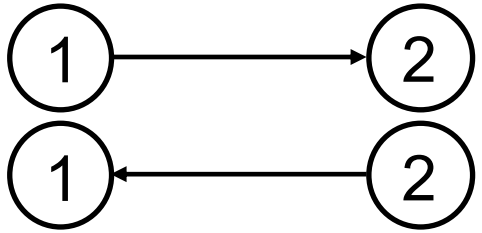
Transmission Media

Link Terminology

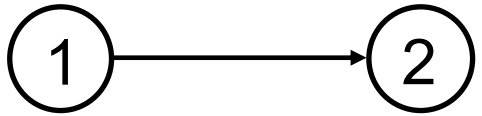
- Full-duplex link
  - Used for transmission in both directions at once
  - E.g., use different twisted pairs for each direction



- Half-duplex link
  - Both directions, but not at the same time
  - E.g., sends take turns on a wireless channel

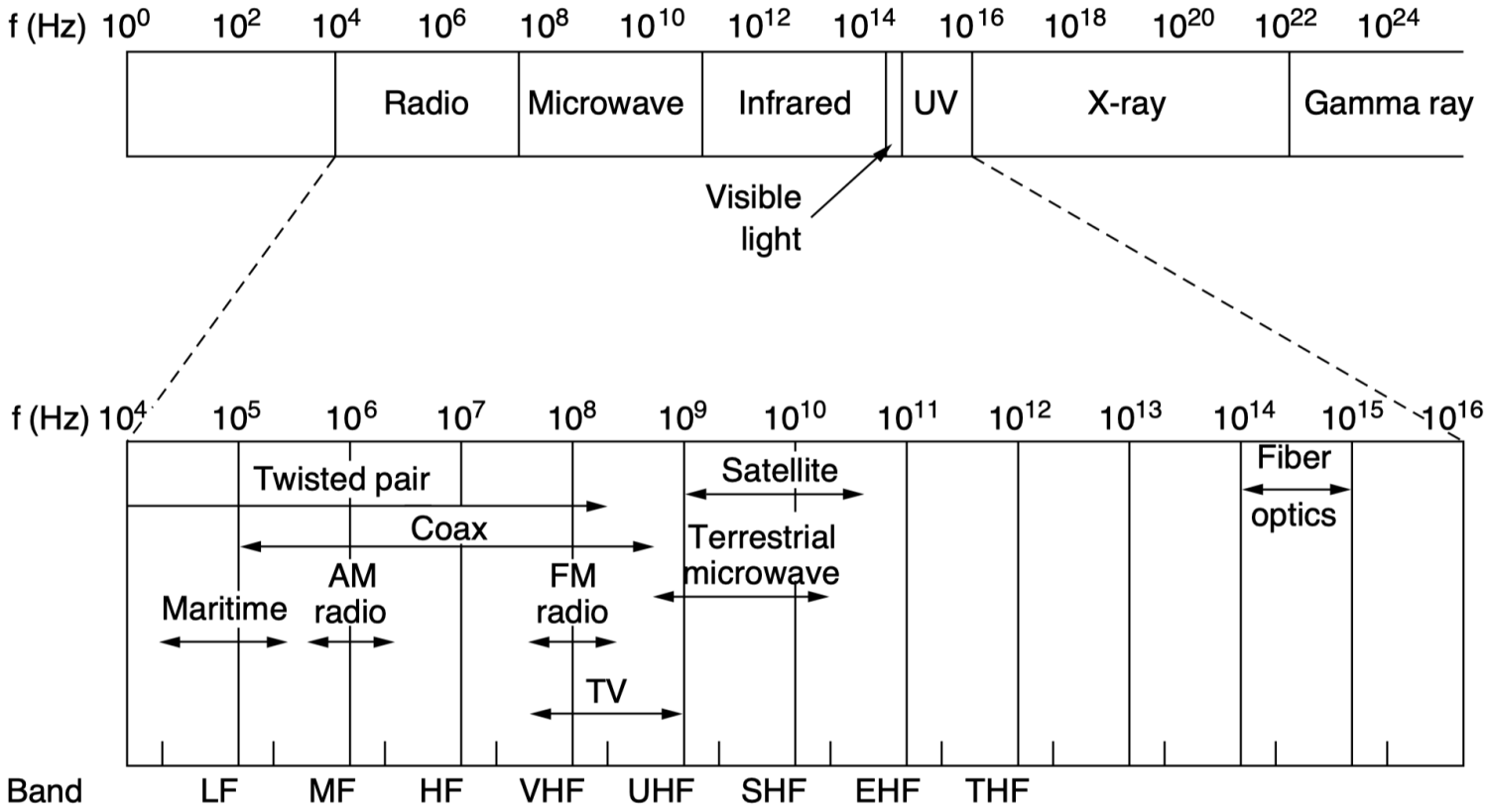


- Simple link
  - Only one fixed direction at all times; not common



Electromagnetic Spectrum

- The transmission signals are actual waveforms that travel through the medium
- Occupies different parts of the spectrum depending on the medium
  - Twisted pair / coax → kHz–MHz–GHz (radio range)
  - Optical fiber → THz (infrared/visible light)
  - Wireless (radio/microwave/infrared) → free-space spectrum bands



The electromagnetic spectrum and its uses for communication.

Guided Transmission Media

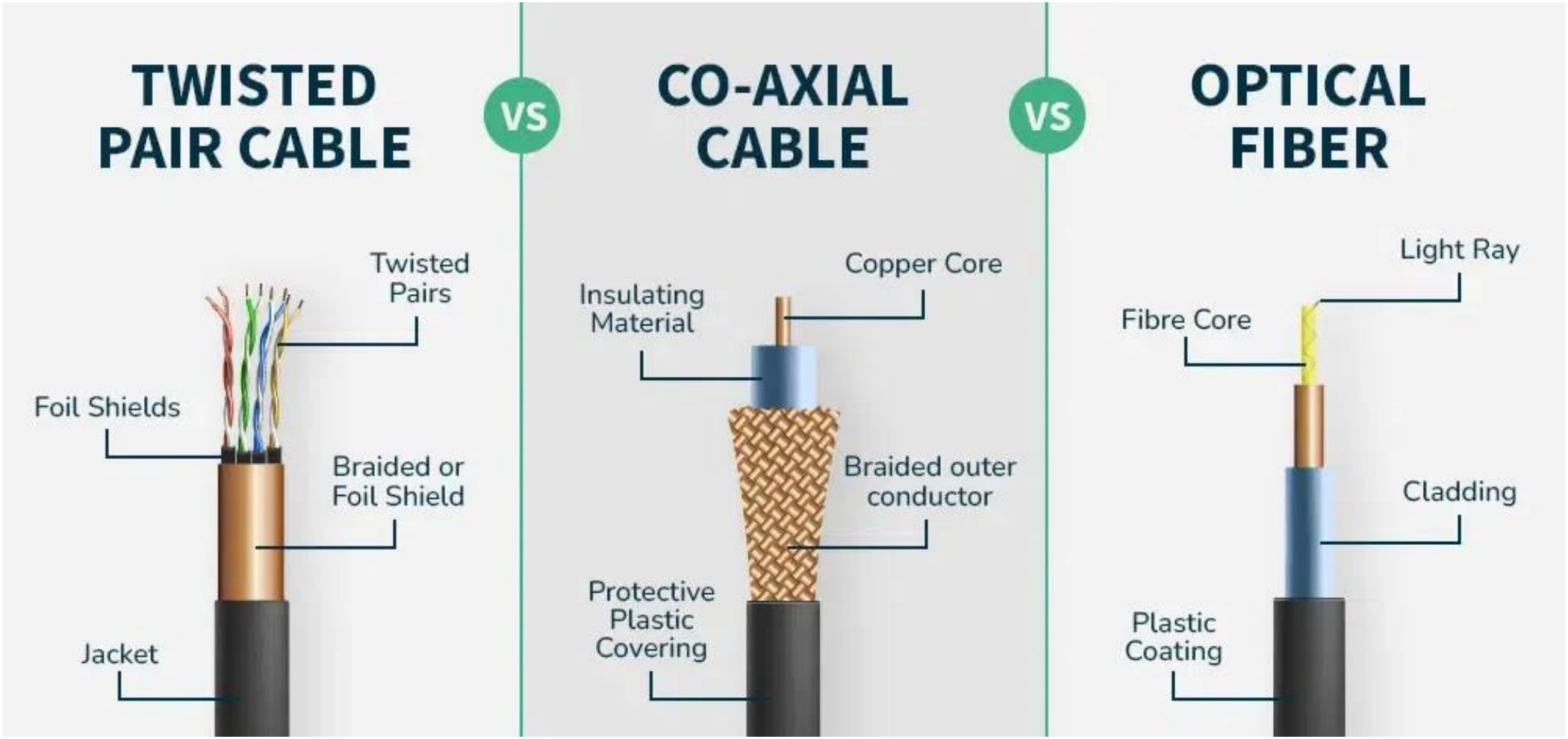
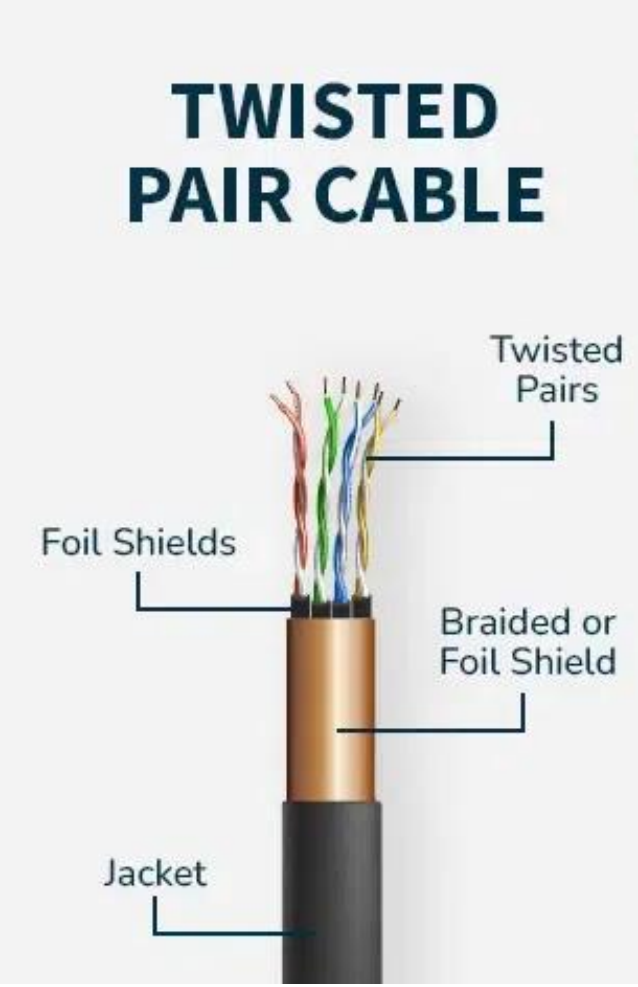


Figure from: https://www.geeksforgeeks.org/computer-networks/difference-between-twisted-pair-cable-co-axial-cable-and-optical-fiber-cable/

Guided Transmission Media

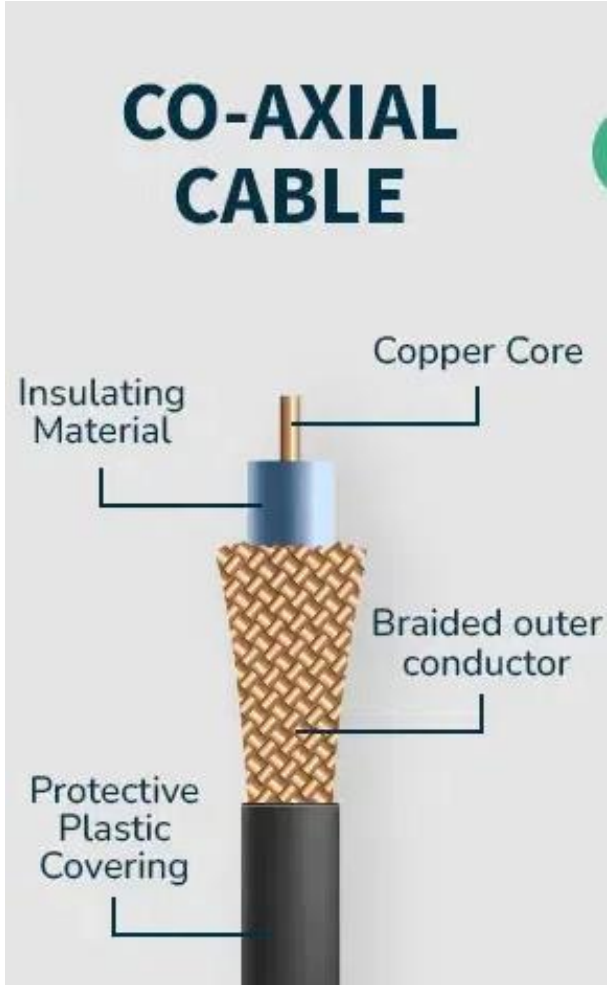


- A twisted pair consists of two insulated copper wires, typically about 1mm thick.
  - More twists per cm leads to less crosstalk and better quality over longer distance
  - Very Common: phone lines, ethernet

Figure from: https://www.geeksforgeeks.org/computer-networks/difference-between-twisted-pair-cable-co-axial-cable-and-optical-fiber-cable/

Guided Transmission Media

- A good combination of high bandwidth and excellent noise immunity
  - Used to be in telecom for long-distance lines (replaced by fiber optics), but still widely used in cable TV



A coaxial cable consists of a stiff copper wire as the core, surrounded by an insulating material.

The insulator is encased by a cylindrical conductor, often as a closely woven braided mesh.

The outer conductor is covered in a protective plastic sheath.

Figure from: https://www.geeksforgeeks.org/computer-networks/difference-between-twisted-pair-cable-co-axial-cable-and-optical-fiber-cable/

Guided Transmission Media

- Fiber-optic cables are similar to coax, except without the braid.
  - At the center is the glass core through which the light propagates.
  - The core is surrounded by a glass cladding with a lower index of refraction than the core, to keep all the light in the core.
  - Next comes a thin plastic jacket to protect the cladding.

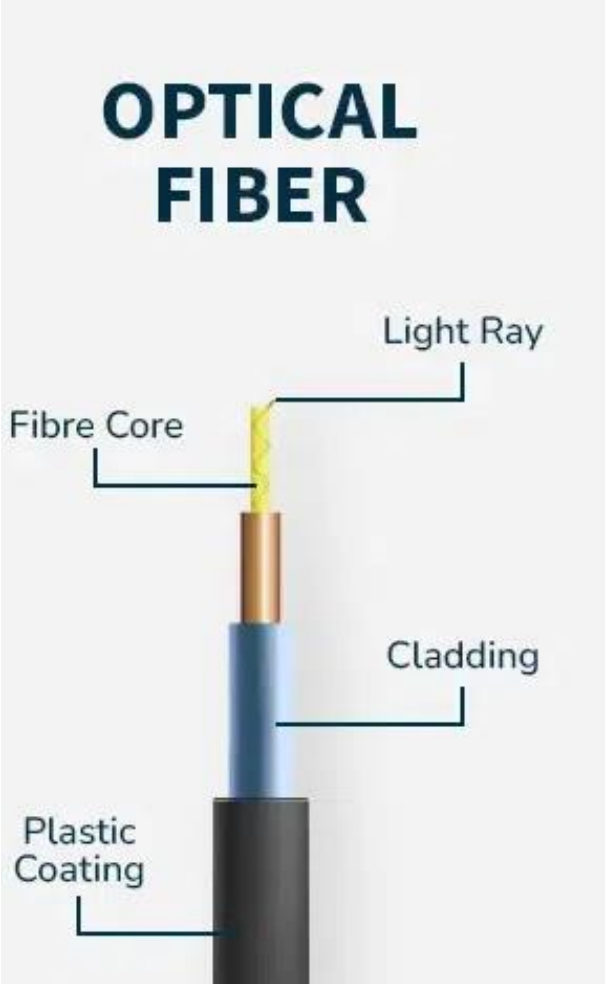


Figure from: https://www.geeksforgeeks.org/computer-networks/difference-between-twisted-pair-cable-co-axial-cable-and-optical-fiber-cable/

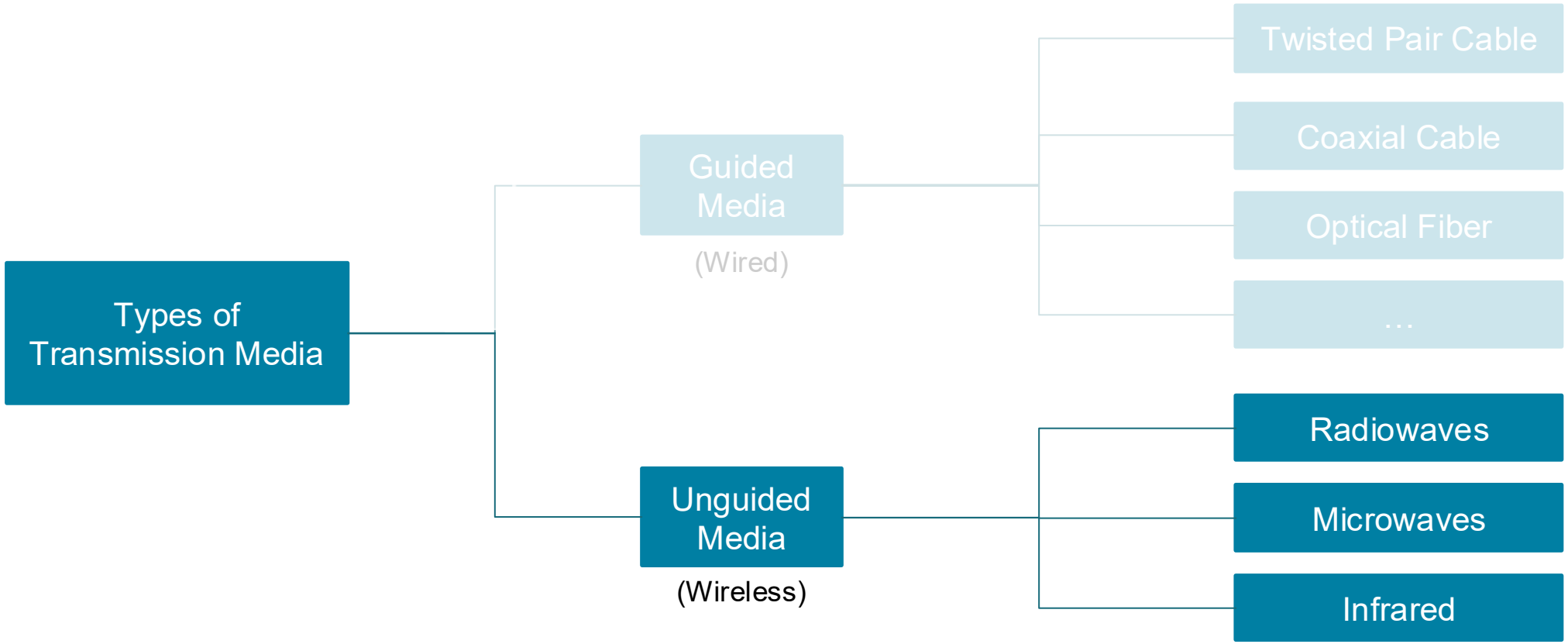
Guided Transmission Media

Name	Twisted Pair	Coaxial Cable	Optic Fiber
Each is used in order physical connect network devices			
Material Length	100m	500m	10 km – 12 km
Speed	10Mbs – 100Mbs	10Mbs – 100Mbs	10Mbs – 100Gbs
Cost	Cheapest	Chep	Expensive
Advantages	Price, easy to install, widely available and used	Less susceptible to EMI interferences, can carry several signals	Security, size, distance length, no EMI, high bandwidth, low errors
Disadvantages	Distance, susceptible to EMI	Harder to install, limited upgrade path, failure may affect many users	Expensive, fragile, requires special equipment to install and terminate

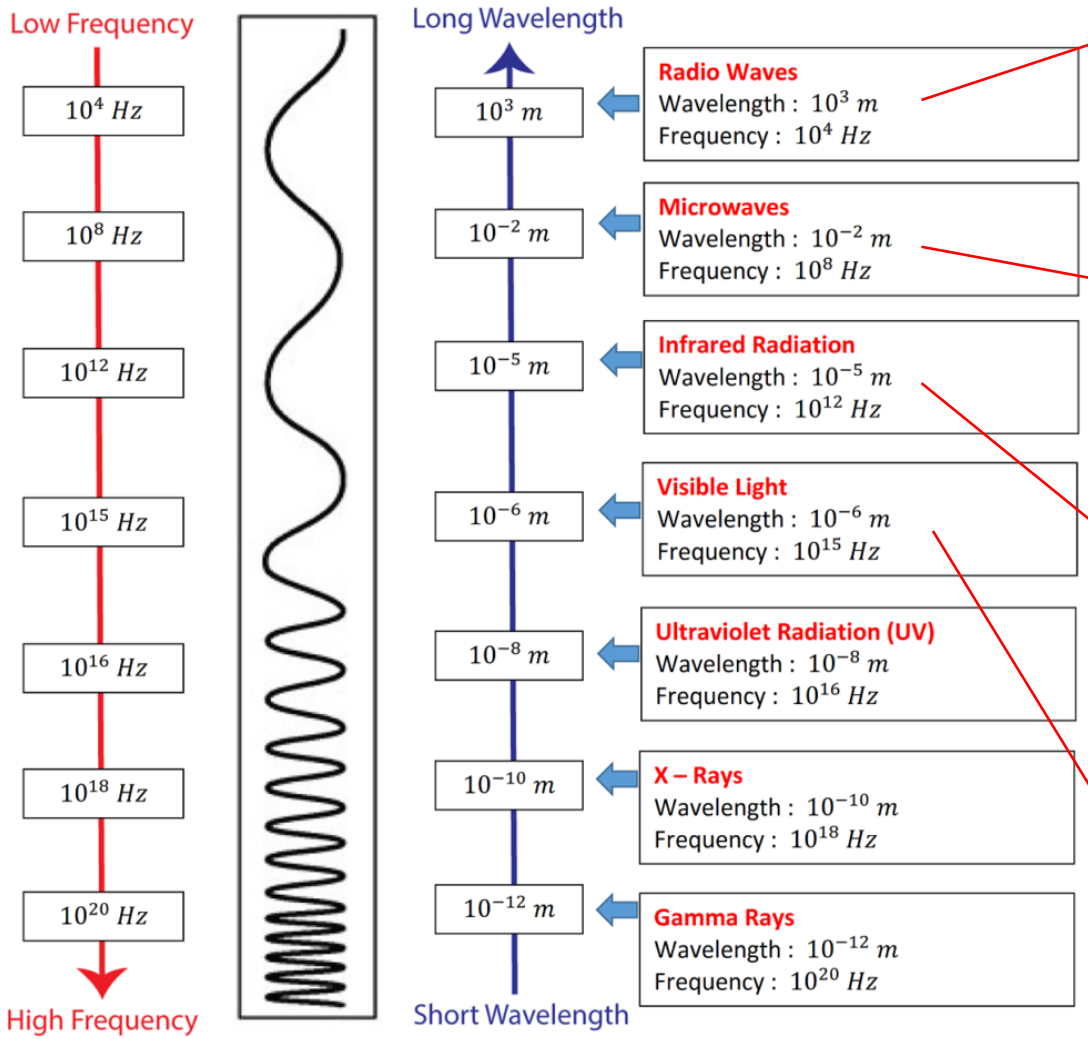
EMI: When electrical signals from one device interfere with the signals in another device

Table from: https://i.ytimg.com/vi/0rFZtCovx28/hq720.jpg?sqp=-oaymwE7CK4FEIIDSFryq4qpAy0IARUAAAAAGAElAADIQj0AgKJD8AEB-AH-CYAC0AWKAgwIABABGGUgVihXMA8=&rs=AOn4CLBjjLvNZ6Z6PBRmqmrazrnwVC1wUg

Transmission media



Wireless Transmission



- Radio transmission
  - Omnidirectional waves, easy to generate, travel long distances, penetrate buildings
  - e.g., cellular network, WiFi
- Microwave transmission
  - Directional waves requiring repeaters, high bandwidth, do not penetrate buildings, but penetrate atmosphere
  - e.g., Satellites, radar
- Infrared transmission
  - Unguided waves used for short-range communication, relatively directional, cheap, easy to build, do not penetrate solid walls
  - e.g., Projectors remote control
- Light transmission
  - Unguided optical communication
  - e.g., home fiber network (Quantum fiber)

Figure from: https://igcsezone.com/3-3-electromagnetic-spectrum/

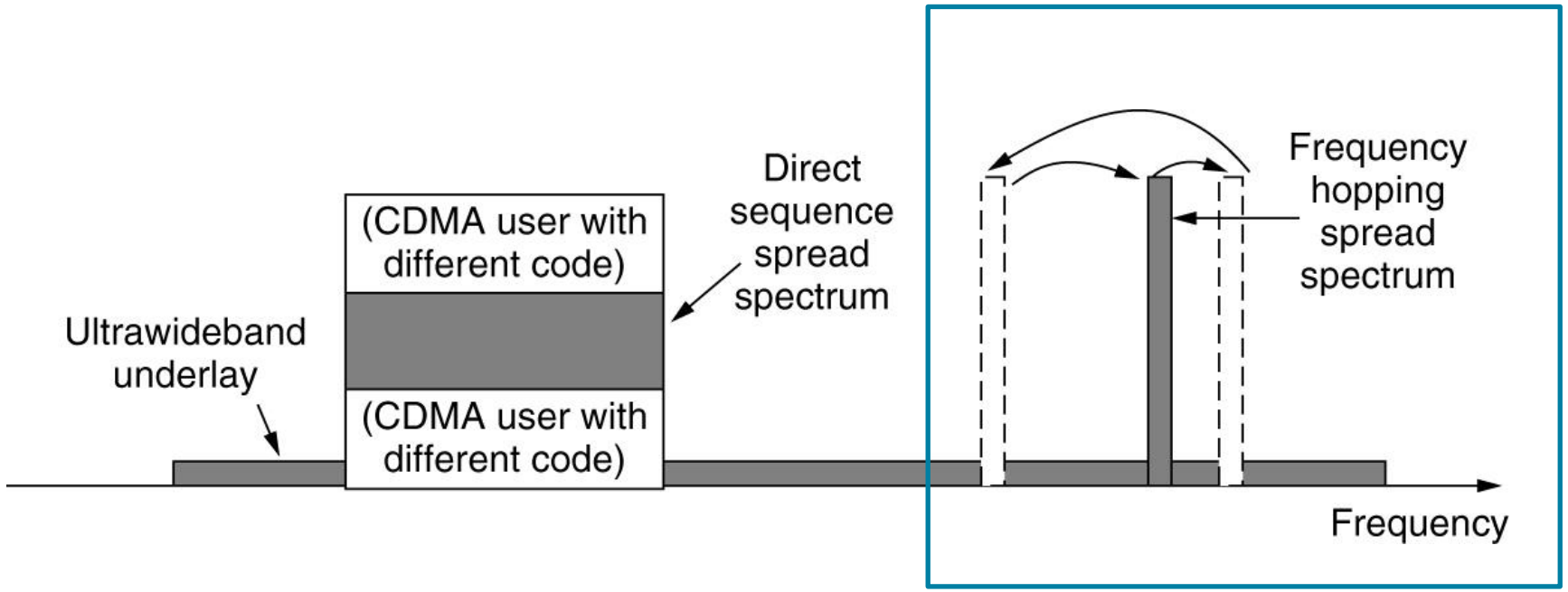
Wireless Transmission Methods

- Frequency hopping spread spectrum
  - Transmitter hops from frequency-to-frequency hundreds of times per second
  - e.g., Bluetooth classic, some military radios
- Direct sequence spread spectrum
  - Code sequence spreads data signal over wider frequency band
  - e.g., GPS signals, Wi-Fi (802.11b)
- Ultra-wideband communication
  - Communication sends a series of low-energy rapid pulses, varying their carrier frequencies to communicate information
  - e.g., Apple AirTag

Wireless Transmission

Frequency Hopping Spread Spectrum

In frequency hopping spread spectrum, a transmitter hops from frequency to frequency hundreds of times per second. It is popular for military communication because it makes transmissions hard to detect and next to impossible to jam.

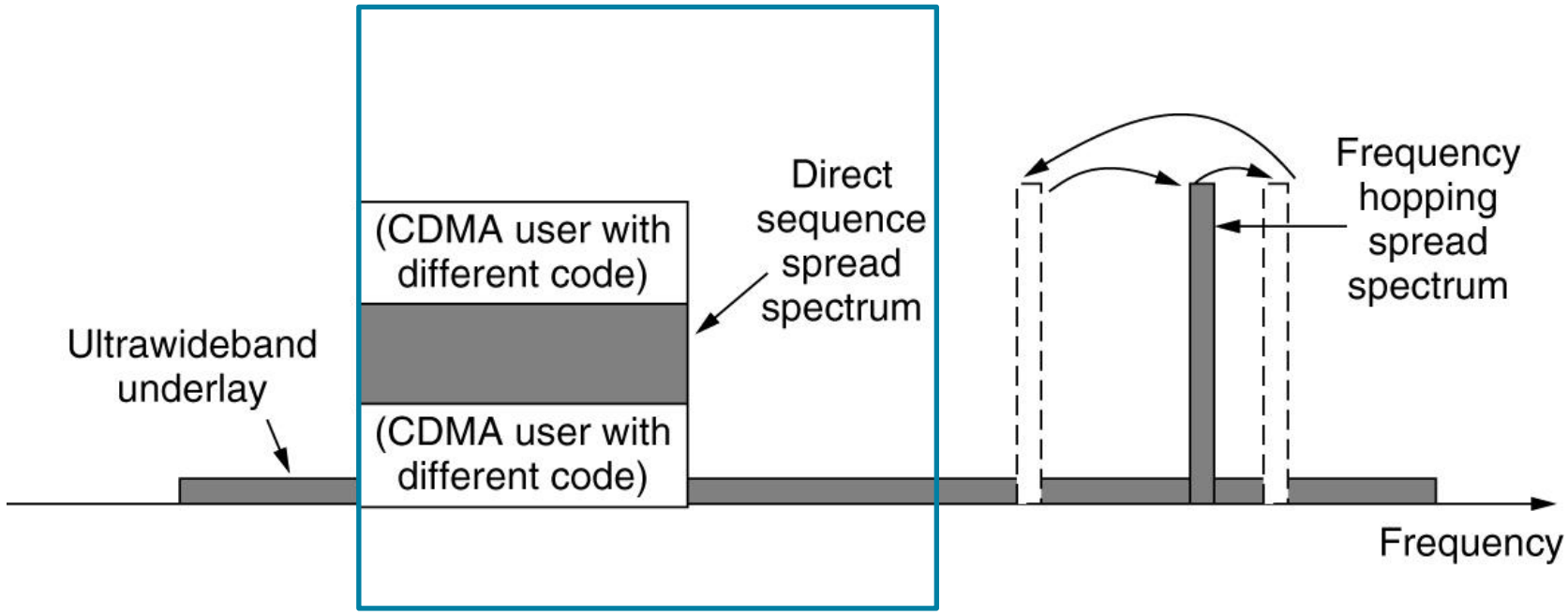


Wireless Transmission

Direct Sequence Spread Spectrum

Direct sequence spread spectrum uses a code sequence to spread the data signal over a wider frequency band. It is widely used commercially as a spectrally efficient way to let multiple signals share the same frequency band.

- In contrast with frequency hopping
- Forms the basis of 3G mobile phone networks and is also used in GPS

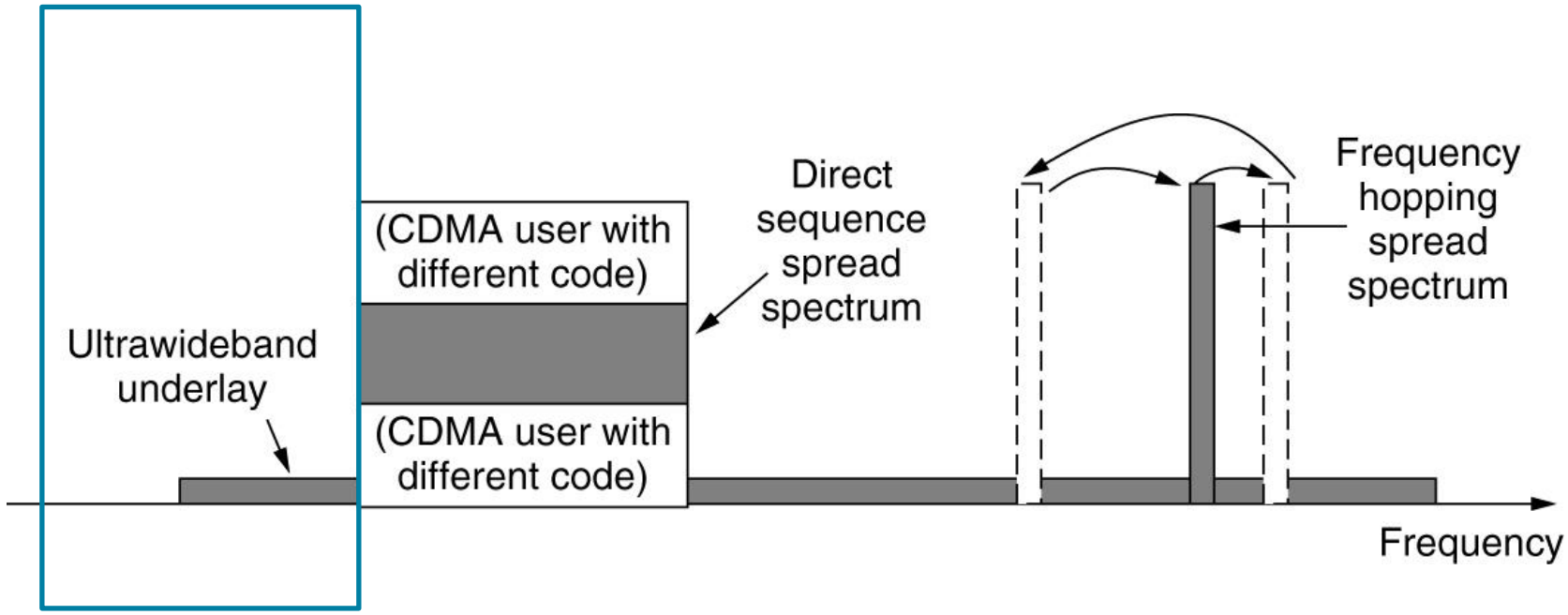


Wireless Transmission

Ultra-WideBand communication

UWB (Ultra-WideBand) is defined as signals that have a bandwidth of at least 500 MHz or at least 20% of the center frequency of their frequency band.

- It has the potential to communicate at several hundred megabits per second
- It is popular for short-distance indoor applications, as well as precision radar imaging and location-tracking technologies.



So far…

- Transmission media
  - Link terminology
  - Electromagnetic spectrums
  - Guided media: twisted pairs, coaxial cable, fiber optics…
  - Unguided media transmission techniques: frequency hopping spread spectrum, direct sequence spread spectrum, ultra-wideband communication

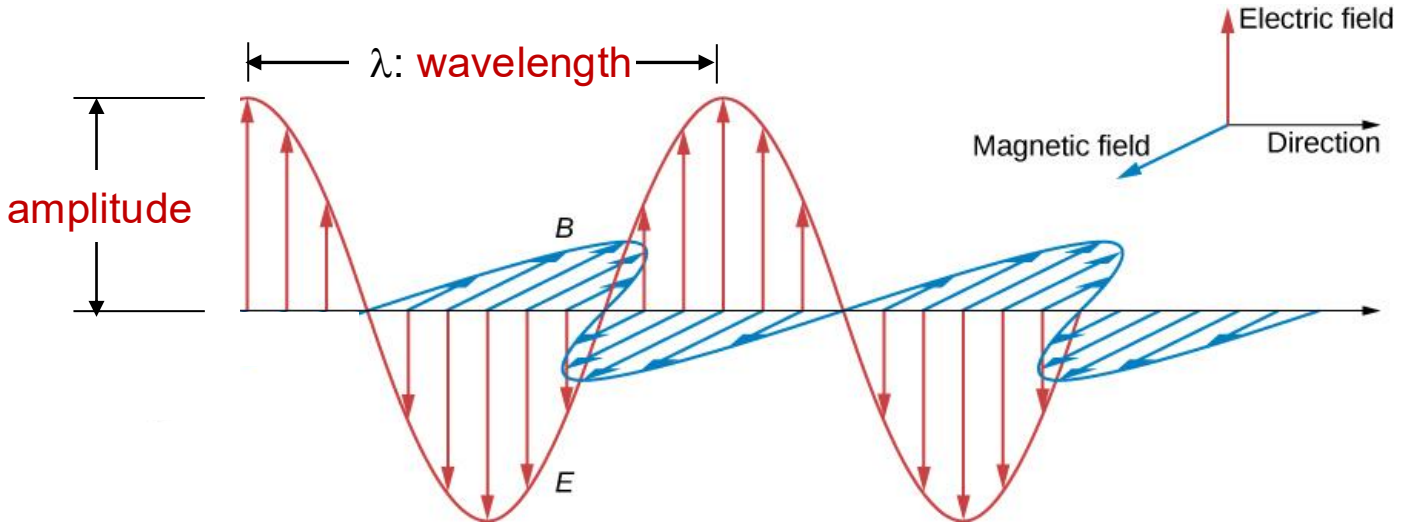
Next

- Three kinds of transmission media
- From waveforms to bits
- Examples of communication systems
  - Wired LANs: Ethernet
  - Wireless access network

From Waveforms to Bits

- Physical design goal: send a string of bits from the transmitter to the receiver over an analog channel
- These waveforms are called symbols

Electromagnetic waves



wave propagation:

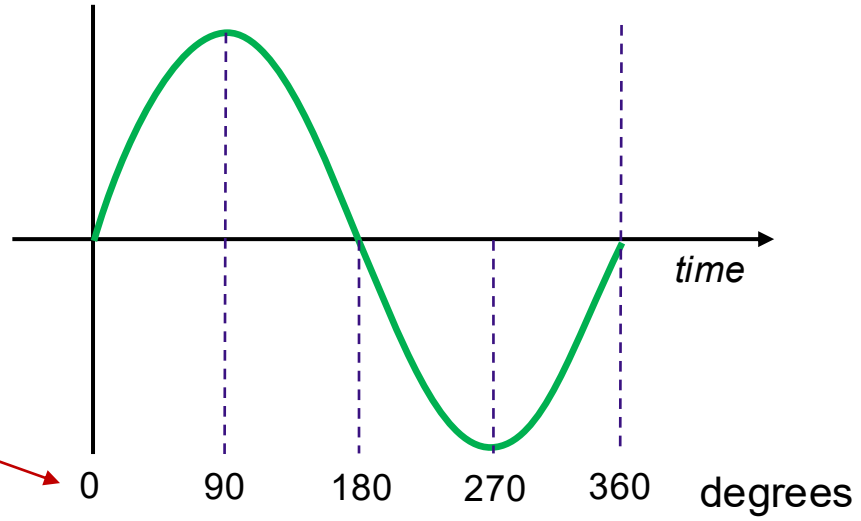
Electromagnetic wave has:

- wavelength (λ)
- frequency: speed of light / wavelength = c/λ
- directionality (of propagation)
- time-varying amplitude

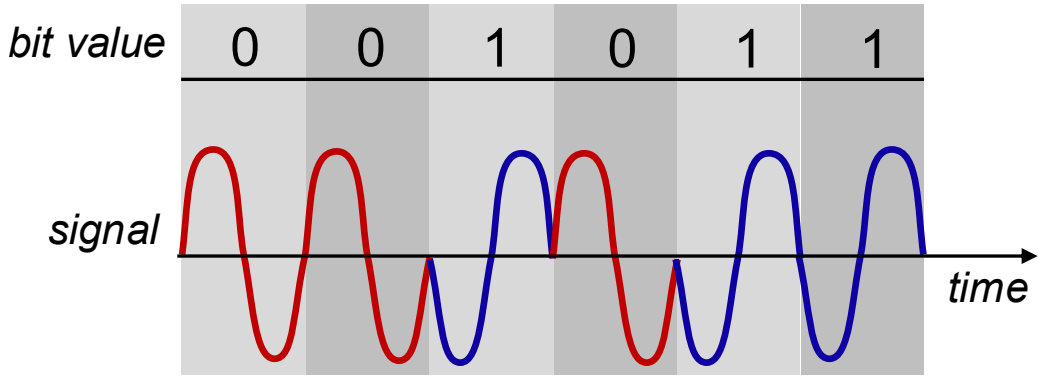
Phase

The phase of a periodic signal, represents the fraction of the period covered up until time t

- often measured in angular units (0 to 360)



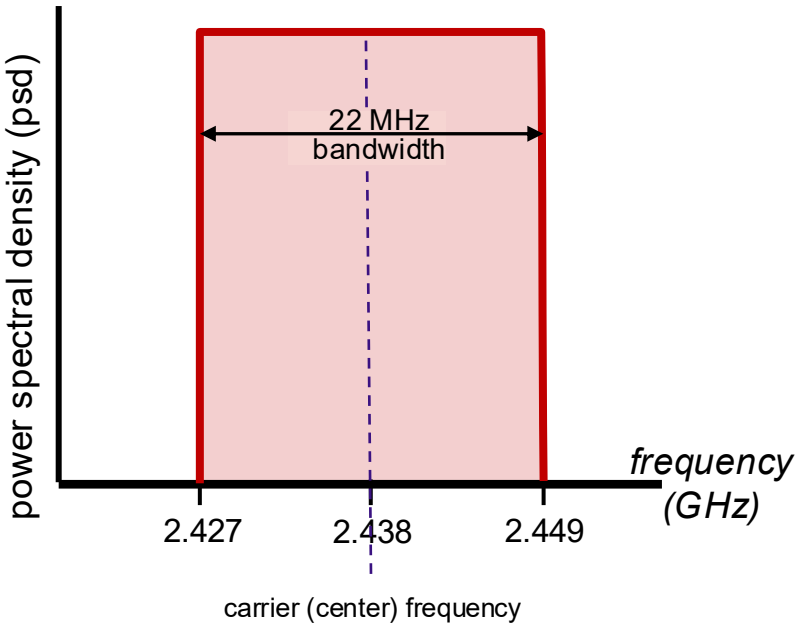
we can code information into signal by changing signal's phase (keeping frequency the same!)



Bandwidth

Bandwidth: width (measured in Hz) of range of frequencies use by radio signal

- radio frequency usage characterized by power spectral density (psd of zero means no signal power at that frequency)
- bandwidth = “band” + “width” (width of frequency band used)



Radio signal with 22 MHz bandwidth, evenly spread between 2.427, 2.429 GHz. This 22 MHz bandwidth channel corresponds to channel 6 in WiFi network)

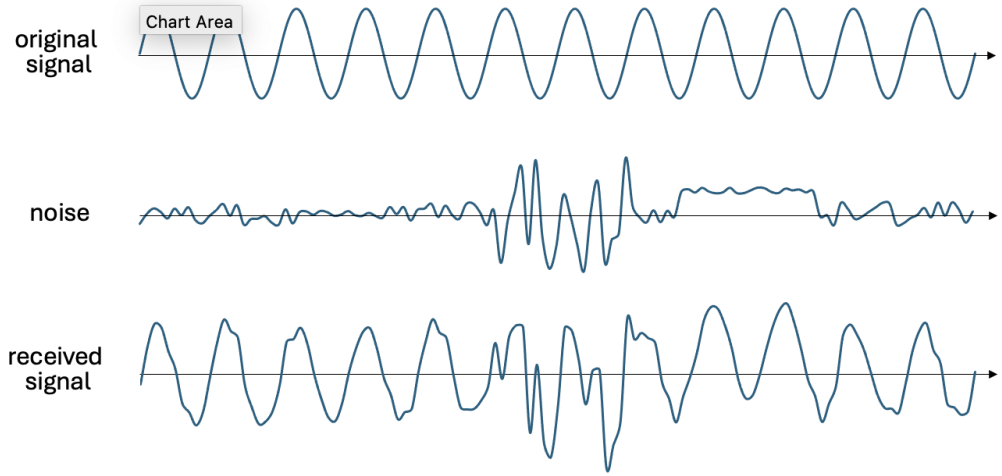
two meanings/usage of “bandwidth”

Radio signal “bandwidth” different from link “bandwidth” (maximum transmission rate) term used by network engineers!

Signals and Noise

- interference: other transmitters/EM radiators in the same frequency band
  - hundreds of consumer devices operate in unlicensed 2.4 GHz band (aka: Industrial, Scientific, and Medical band): WiFi, Bluetooth, Zigbee, satellite TV, microwave ovens, garage-door openers, baby monitors, cordless phones, wireless mics/speakers, radio-controlled drones and toys, amateur radio, ...

- thermal and electronic noise in receiver:
  - natural thermal variations, imperfections in electronics



Original signal, noise, and noisy received signal

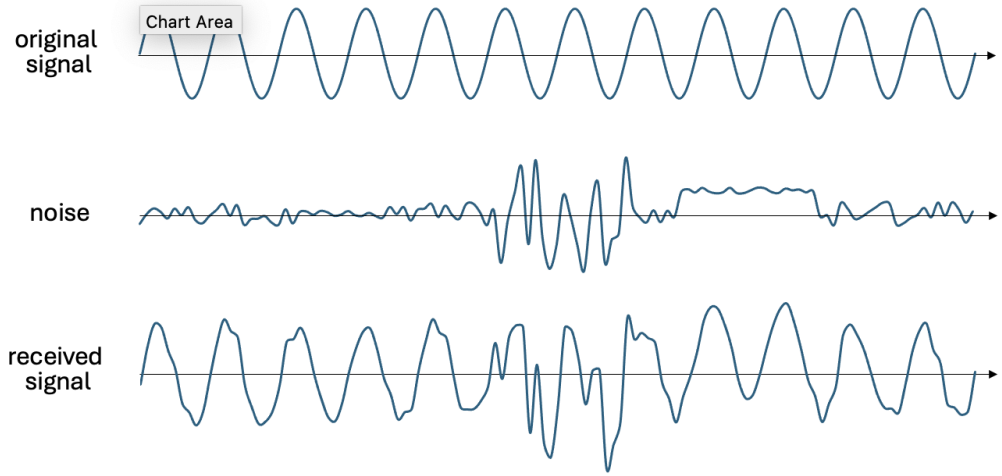
Signal to Noise Ratio (SNR)

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

- fundamental measure of channel "quality"

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

- SNR of 0 implies equal signal and noise
- high (or low) SNR: easy (or hard) to extract signal from signal+noise
- Typical ranges for current radios:
  - lower limit for cellular: -10 to -6 dB
  - lower limit for WiFi: 20dB



Original signal, noise, and noisy received signal

Channel Capacity

Shannon capacity (of a communication channel): maximum rate at which data can be transmitted, given bandwidth, SNR constraints

$$C = B \cdot \log_2 \left(1 + \frac{\text{received signal power}}{\text{noise power}} \right)$$

where:

- C is capacity (bits/sec)
- B is bandwidth (in Hz)
- power measured linearly (e.g., in mW)

Observations:

- C scales linearly with B (for constant SNR)
- high SNR: C scales logarithmically: *little value in increasing SNR beyond a certain point*
- Shannon: classic 1948 paper

From Waveforms to Bits

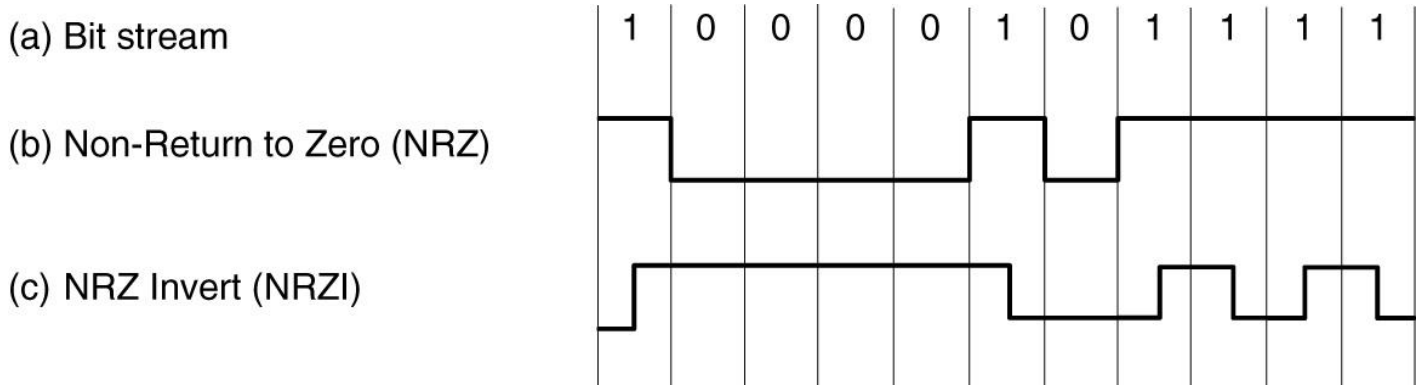
- Digital modulation
  - Map digital bits to analog waveforms able to travel over the analog channel
    - Baseband transmission
    - Passband transmission

- Multiplexing
  - Allows multiple signals to share the same transmission medium by separating them in frequency or time.
    - Frequency Division Multiplexing (FDM)
    - Time Division Multiplexing (TDM)

Digital Modulation

Baseband Transmission

- Baseband transmission: the process of sending an unmodulated signal over a channel without modification
- Digital data (data bits) is directly converted into digital signals
  - The signal can be analog, like from a phone, or digital, like from a computer.

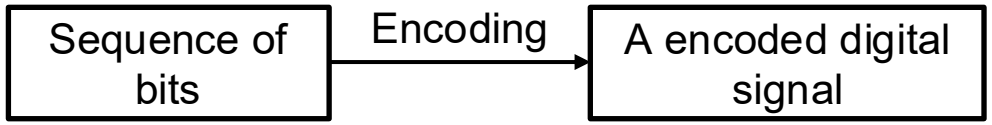


(a) Bits, (b) NRZ, (c) NRZI, (d) Manchester, (e) Bipolar or AMI.

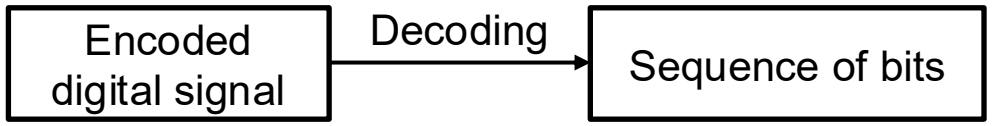
Digital Modulation

Baseband Transmission

- At sender:



- At receiver:



Baseband transmission cannot travel long distances without distortion and cannot support frequency multiplexing

Digital Modulation

Passband Transmission

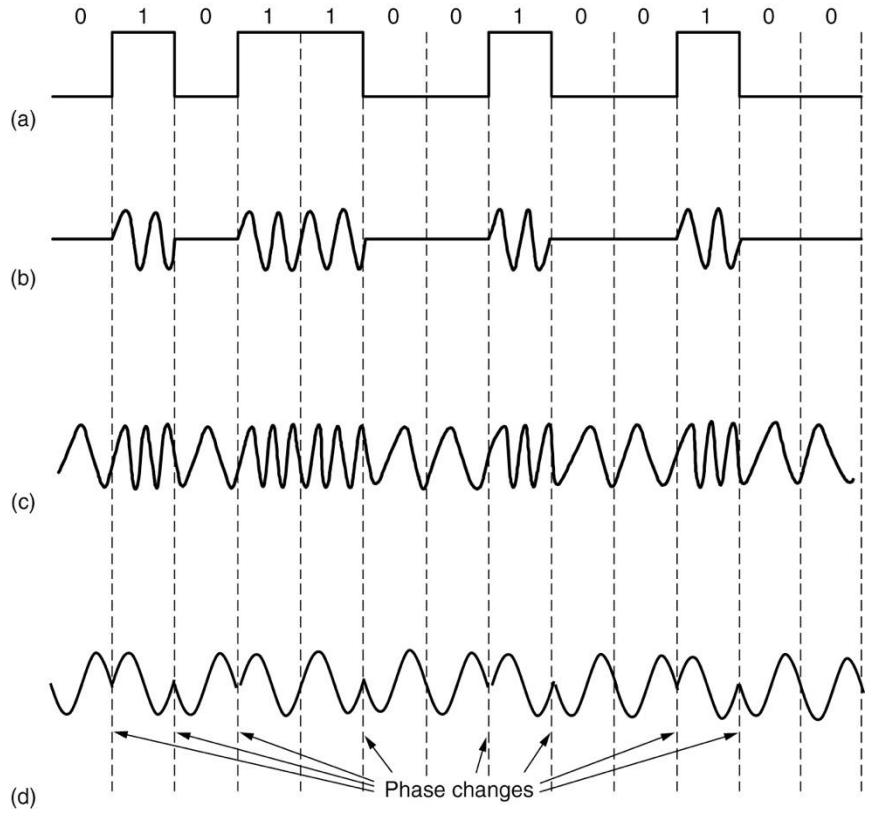
- Passband transmission: the transmission of incoming data steams or baseband signal with the help of modulation
- Two signals are used
  - Modulating signal and
  - Carrier signal

- Modulation is the process by which some characteristics such as amplitude, frequency, and phase, etc., of a carrier signal is varied in accordance to a modulating signal which is also known as information-bearing signal

Digital Modulation

Passband Transmission

- Modulation in the sender section can be divided into:
  - Binary signal
    - raw data: a square wave of 0s and 1s
  - Amplitude shift keying
    - represent bits by changing the amplitude of a carrier wave
    - very sensitive to amplitude noise
  - Frequency shift keying
    - represent bits by changing the frequency of the carrier
    - early modems, some radio links
  - Phase shift keying
    - represent bits by shifting the phase of the carrier wave
    - robust and spectrally efficient
    - basis for advanced methods: Wi-Fi, 4G/5G



(a) A binary signal. (b) Amplitude shift keying. (c) Frequency shift keying. (d) Phase shift keying.

Baseband vs. Passband Transmission

Basis of comparison	Baseband transmission	Passband transmission
Use of modulator and demodulator	x	It uses modulator and demodulator
Frequency of transmission	Uses its own baseband frequencies	A transmission of the signal after shifting the baseband frequencies to some higher frequency range using modulation
Necessity of channel	The baseband signal is transmitted directly	Modulated signal is transmitted through the channel
Preferable frequency	Low	Has a fixed a band of frequencies around the carrier frequency
Preferable distance	Short distance	Long - distance
Noise immunity	It contains a lot of noise because the signal is original	It contains less noise because the signal is modulated
Example	General telephone communication	Satellite and wireless communication

Refer to: https://www.youtube.com/watch?v=Ce-qQ_jB6Dc

So far…

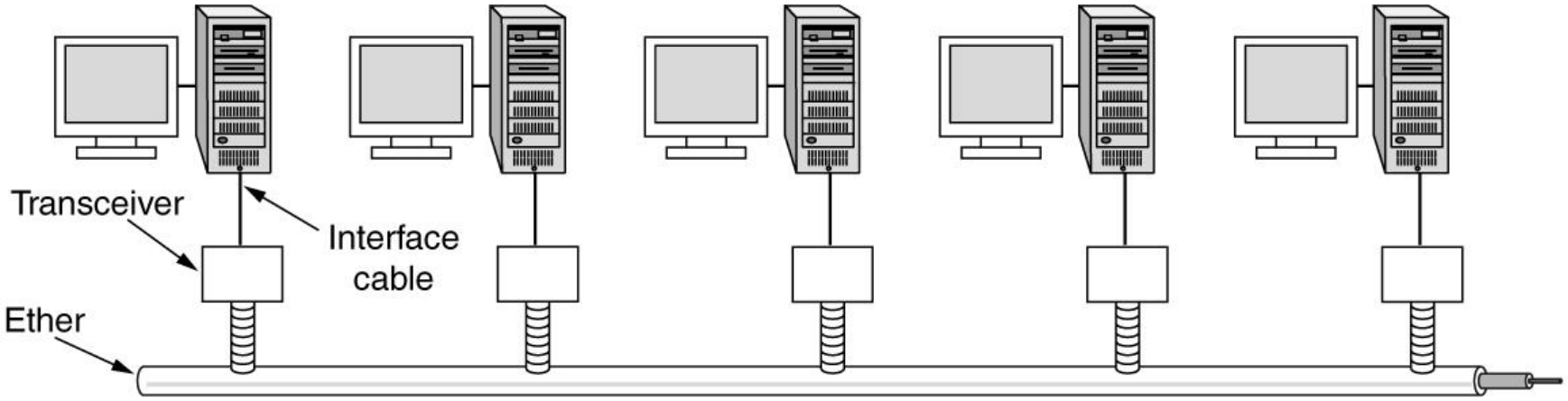
- Transmission media
  - Link terminology
  - Electromagnetic spectrums
  - Guided media: twisted pairs, coaxial cable, fiber optics…
  - Unguided media transmission techniques: frequency hopping spread spectrum, direct sequence spread spectrum, ultra-wideband communication
  - Communication satellites
- From waveforms to bits
  - Maximum data rate of a channel: Shannon's theorem
  - Digital modulation: baseband transmission and passband transmission

Next

- Transmission media
- From waveforms to bits
- Examples of communication systems
  - Wired LANs: Ethernet
  - Wireless access network

Wired LANs: Ethernet

- Classic Ethernet snaked around the building as a single long cable to which all the computers were attached



Architecture of classic Ethernet

Wired LANs: Ethernet

- Ethernet cable is the backbone of the network cabling, connecting various devices such as computers, routers, TVs, tablets, or even PlayStations.

Figure from: https://www.cisco.com/content/dam/cisco-cdc/site/images/legacy/assets/swa/img/anchor-info/what-is-ethernet-628x353.png

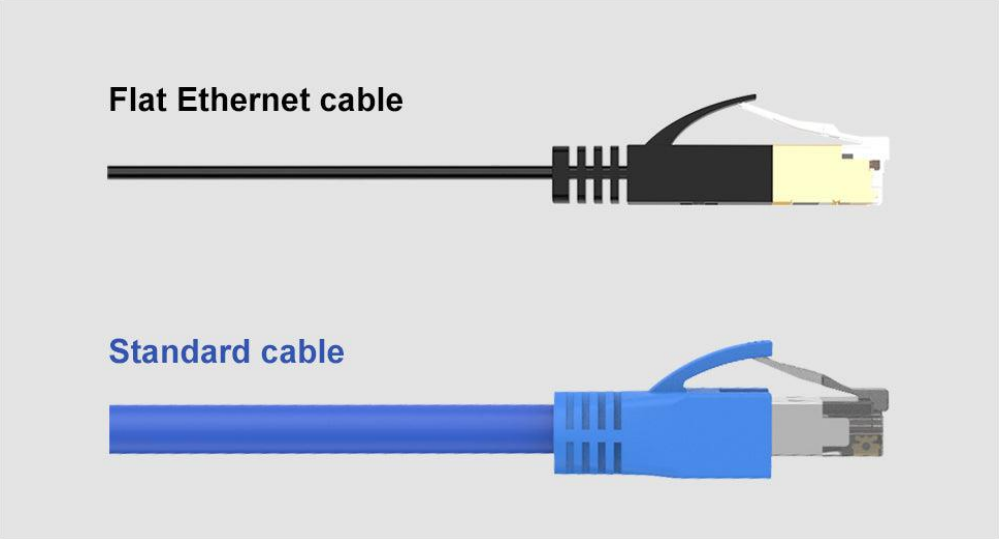
Ethernet Cable Category

Cable Category	Max Speed	Max Length for Highest Performance	Internal Color Code	Physical Differences
Cat5	100 Mbps	100 meters	T568A/B	Basic insulation, no separator
Cat5e	1 Gbps	100 meters	T568A/B	Improved twist ratios, better crosstalk reduction
Cat6	10 Gbps	55 meters (10 Gbps), 100 meters (1 Gbps)	T568A/B	Thicker insulation sometimes includes a spline separator
Cat6a	10 Gbps	100 meters	T568A/B	Heavy shielding, rigid construction, always includes a separator

https://www.smartechcables.com/blog/Ethernet-cable-color-code/

Ethernet Cable Structure

- Eight wires twisted into four pairs and a rip cord



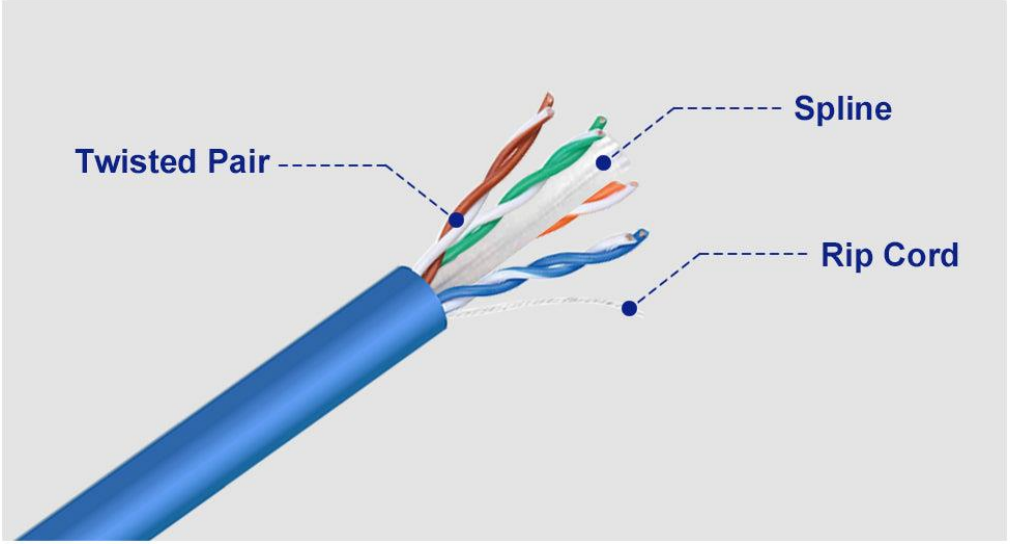


Figure from: https://www.vcelink.com/blogs/focus/ethernet-cable-101

Ethernet Cable Pins

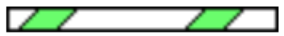
RJ45 Pin #	Wire Color (T568A)	Wire Diagram (T568A)	10Base-T Signal 100Base-TX Signal	1000Base-T Signal
1	White/Green		Transmit+	BI_DA+
2	Green		Transmit-	BI_DA-
3	White/Orange		Receive+	BI_DB+
4	Blue		Unused	BI_DC+
5	White/Blue		Unused	BI_DC-
6	Orange		Receive-	BI_DB-
7	White/Brown		Unused	BI_DD+
8	Brown		Unused	BI_DD-

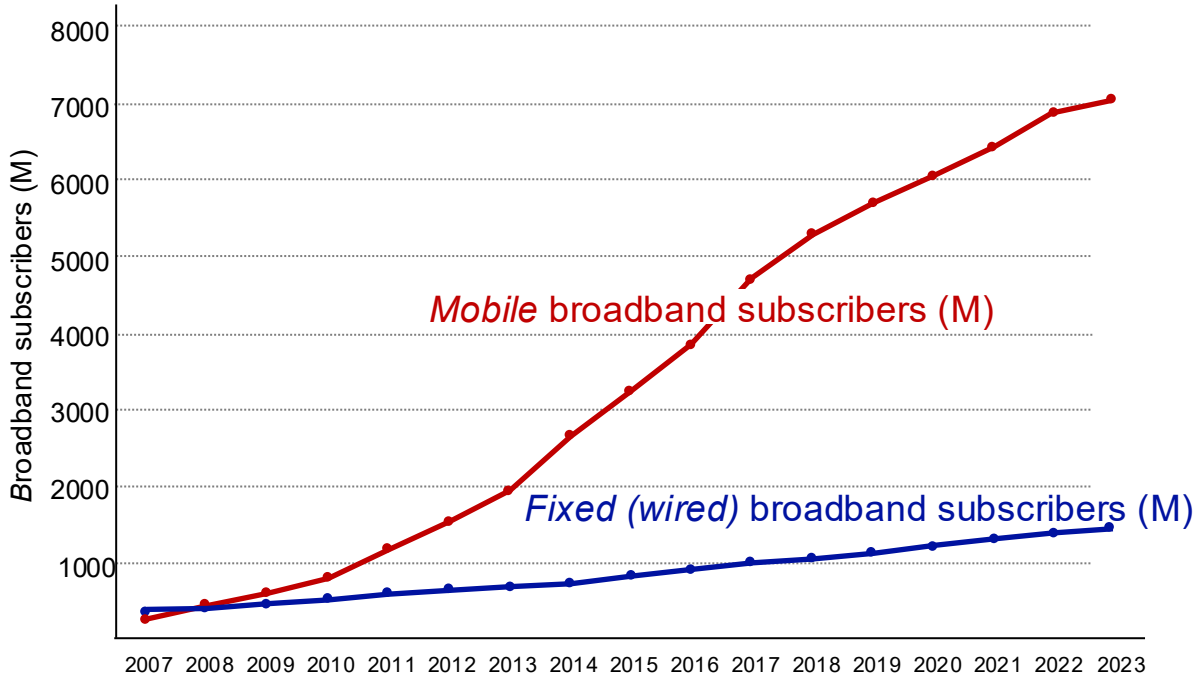
Figure from: https://networkengineering.stackexchange.com/questions/57752/what-do-the-positive-and-negative-transmit-and-receive-pins-mean-on-ethern

Next

- Transmission media
- From waveforms to bits
- Examples of communication systems
  - Wired LANs: Ethernet
  - Wireless access network

Wireless access network: context

- more mobile-broadband-connected (cellular) devices than fixed-broadband-connected devices devices (5-1 in 2019)!
  - wireless connectivity even great when WiFi users considered (80% of broadband homes use WiFi)
  - 60% of Internet traffic from major web sites destinated to mobile device



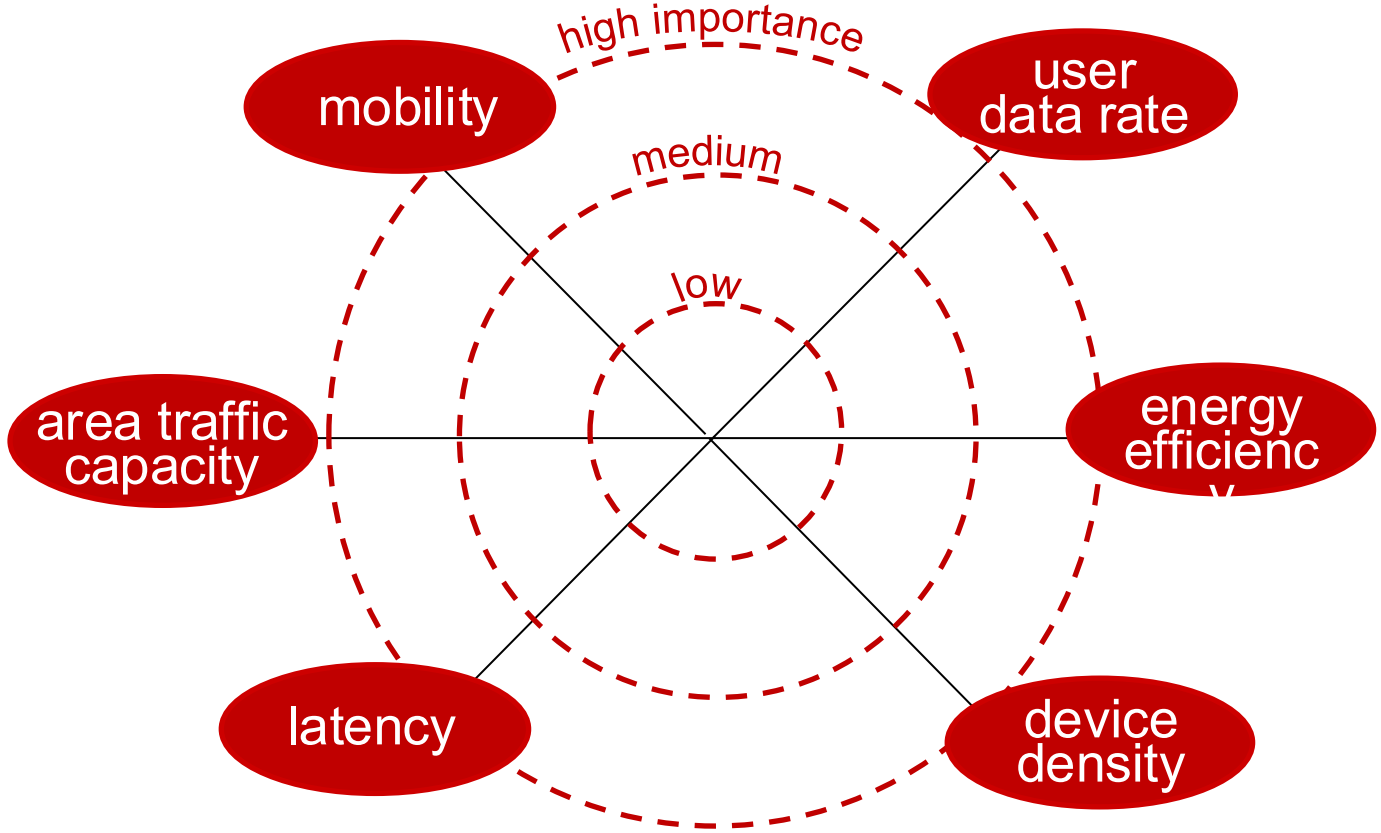
Data source: www.statista.com (1/25)

Wireless applications their needs

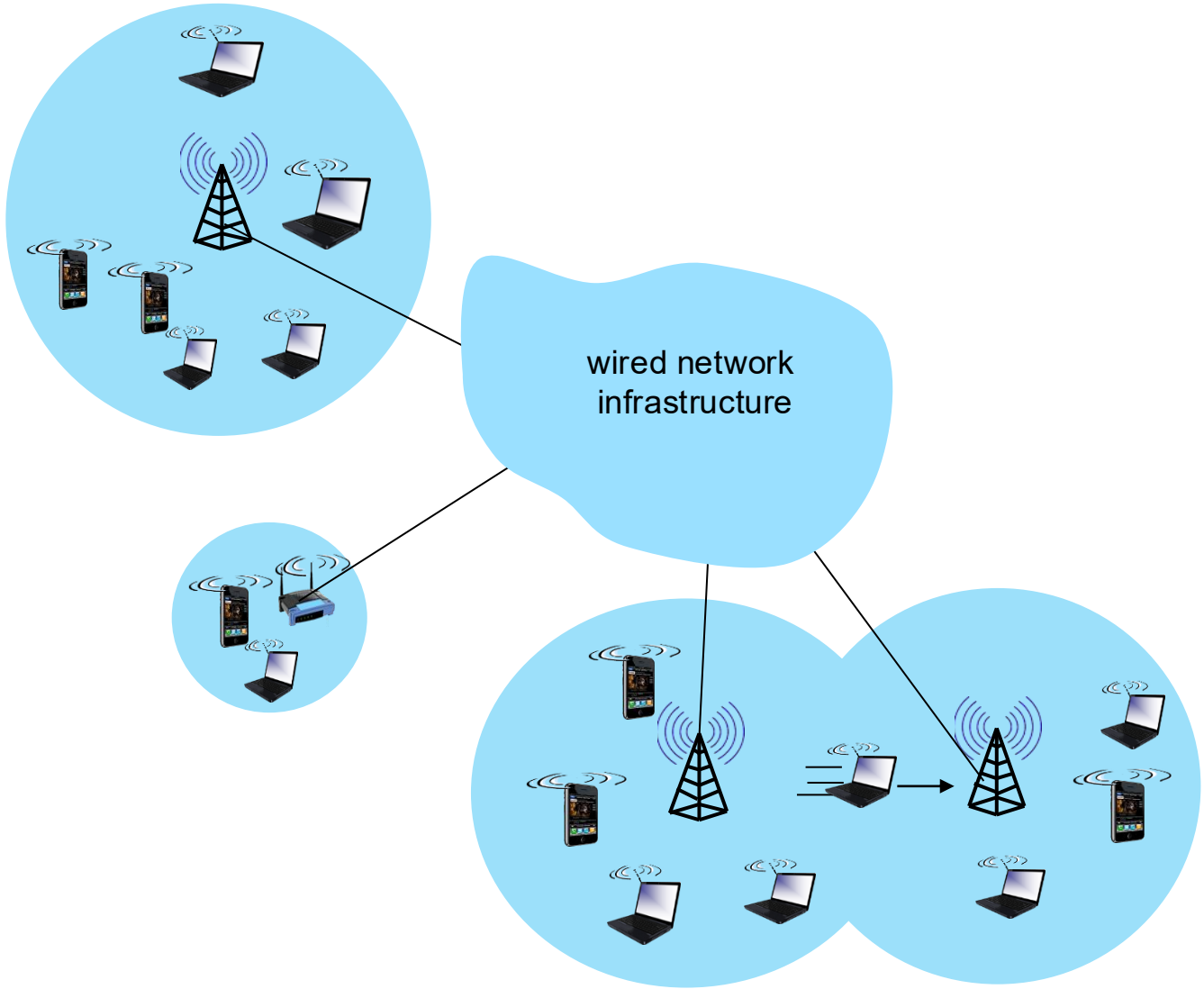
Six application areas :

- Wide-area Mobile Wireless Internet Access
- Local-area Mobile Wireless Internet Access
- Fixed Wireless Internet Access
- Satellite Networks for Internet Access and Sensing
- Cable replacement
- Internet of Things (IoT)

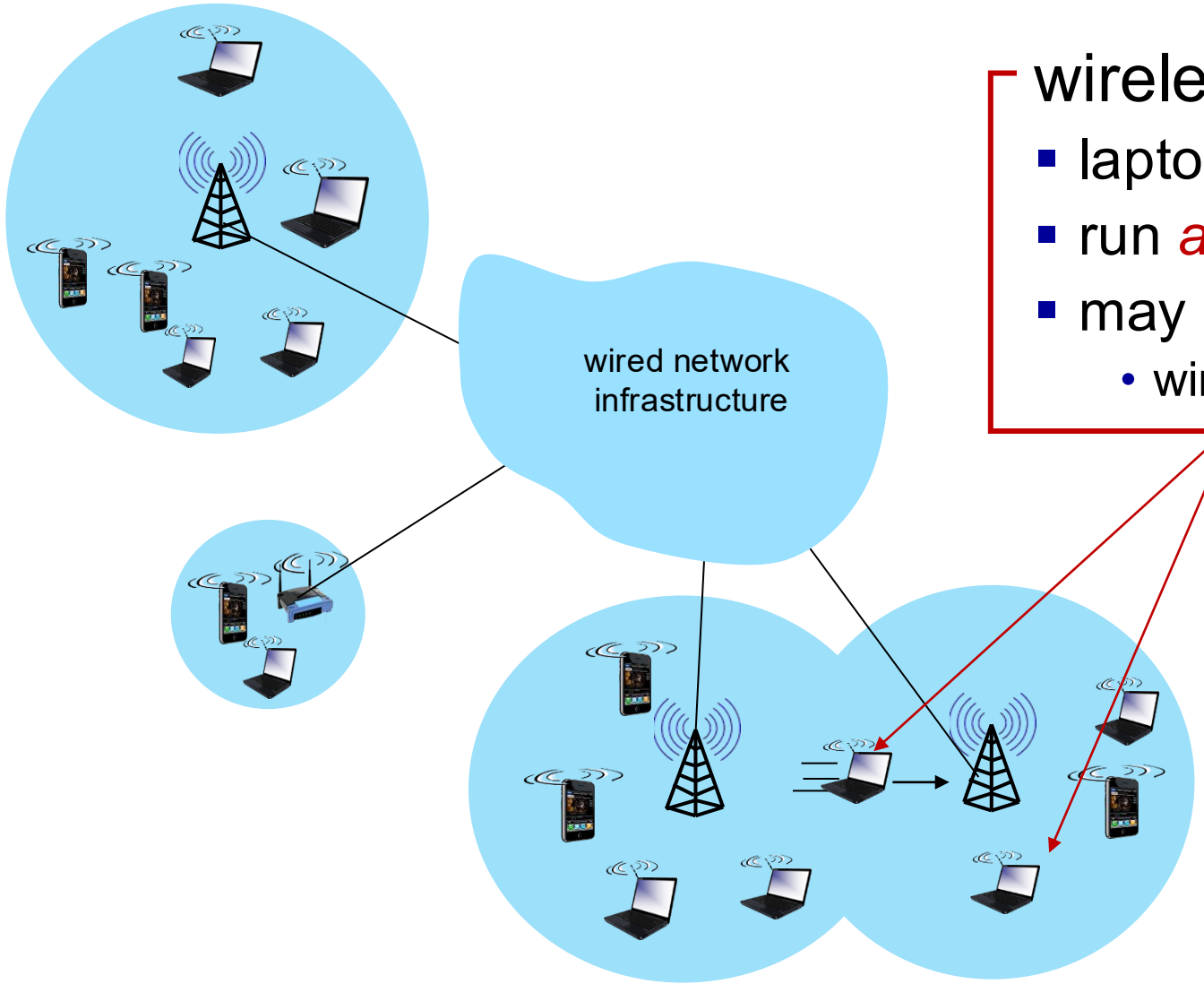
Application needs:



Elements of a wireless network



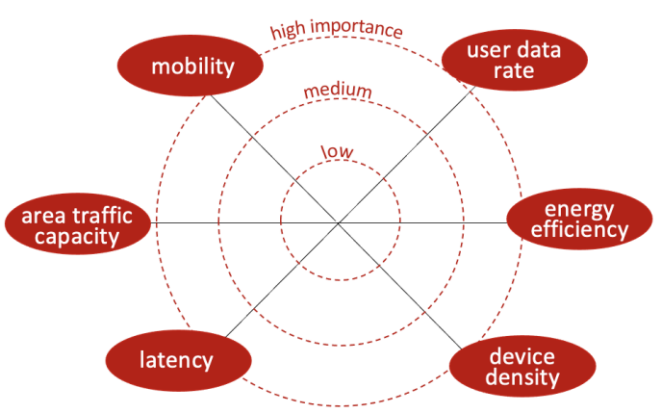
Elements of a wireless network



wireless hosts

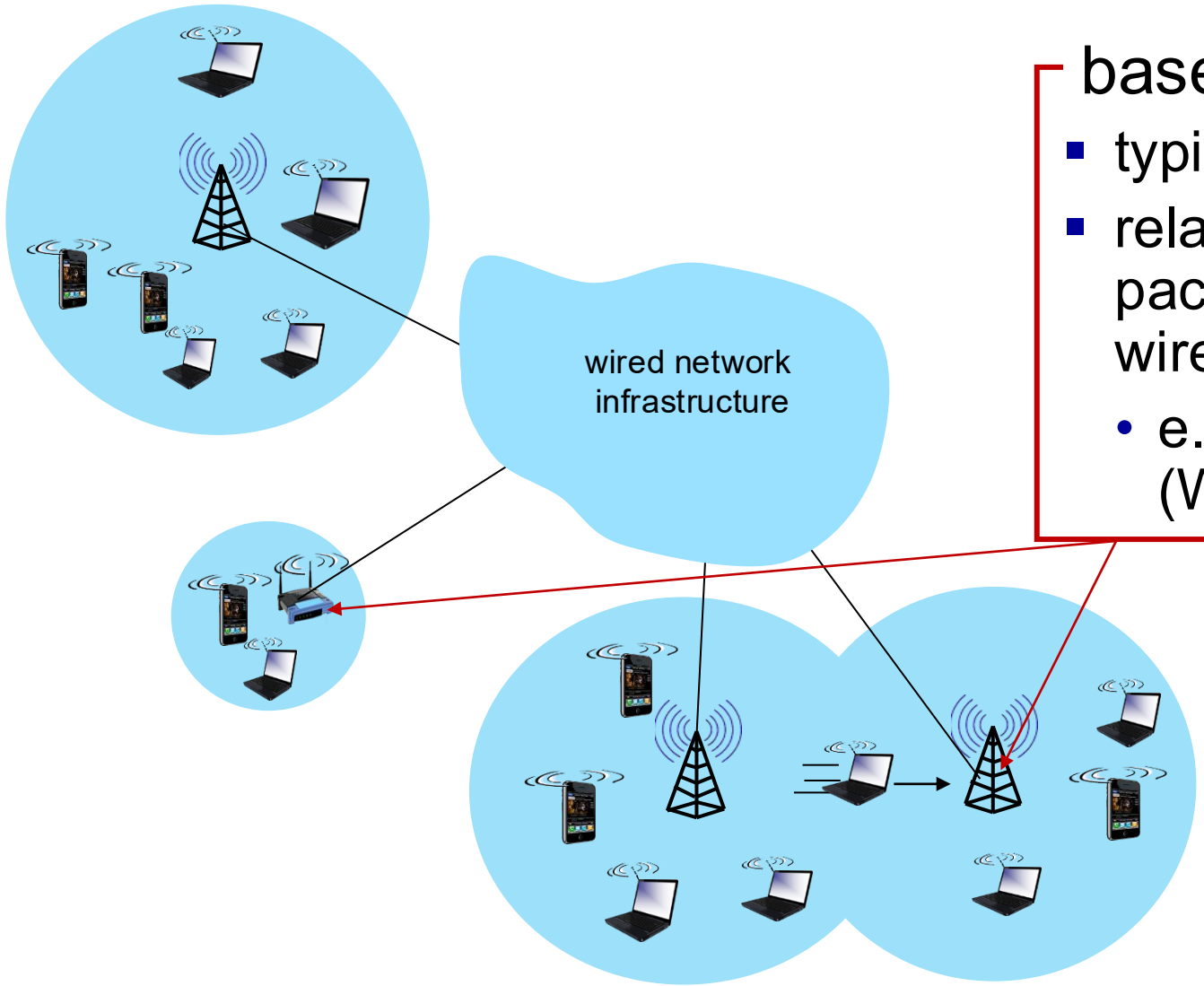
- laptop, smartphone, IoT

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



UCCS

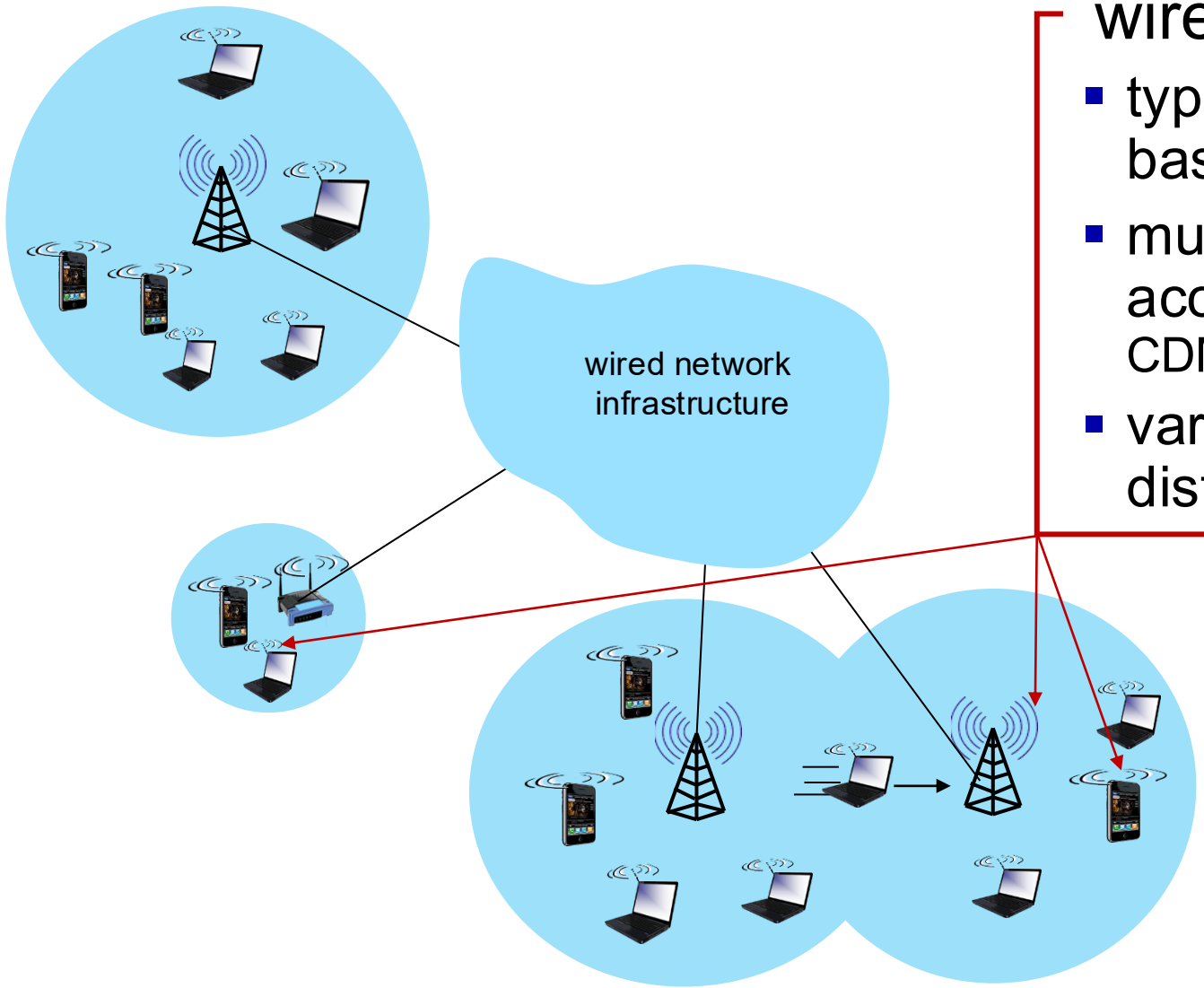
Elements of a wireless network



base station

- typically connected to wired network
- relay - responsible for sending packets between wired network and wireless host(s) in its “area”
  - e.g., 4G/5G cell towers, 802.11 (WiFi) access points (APs)

Elements of a wireless network



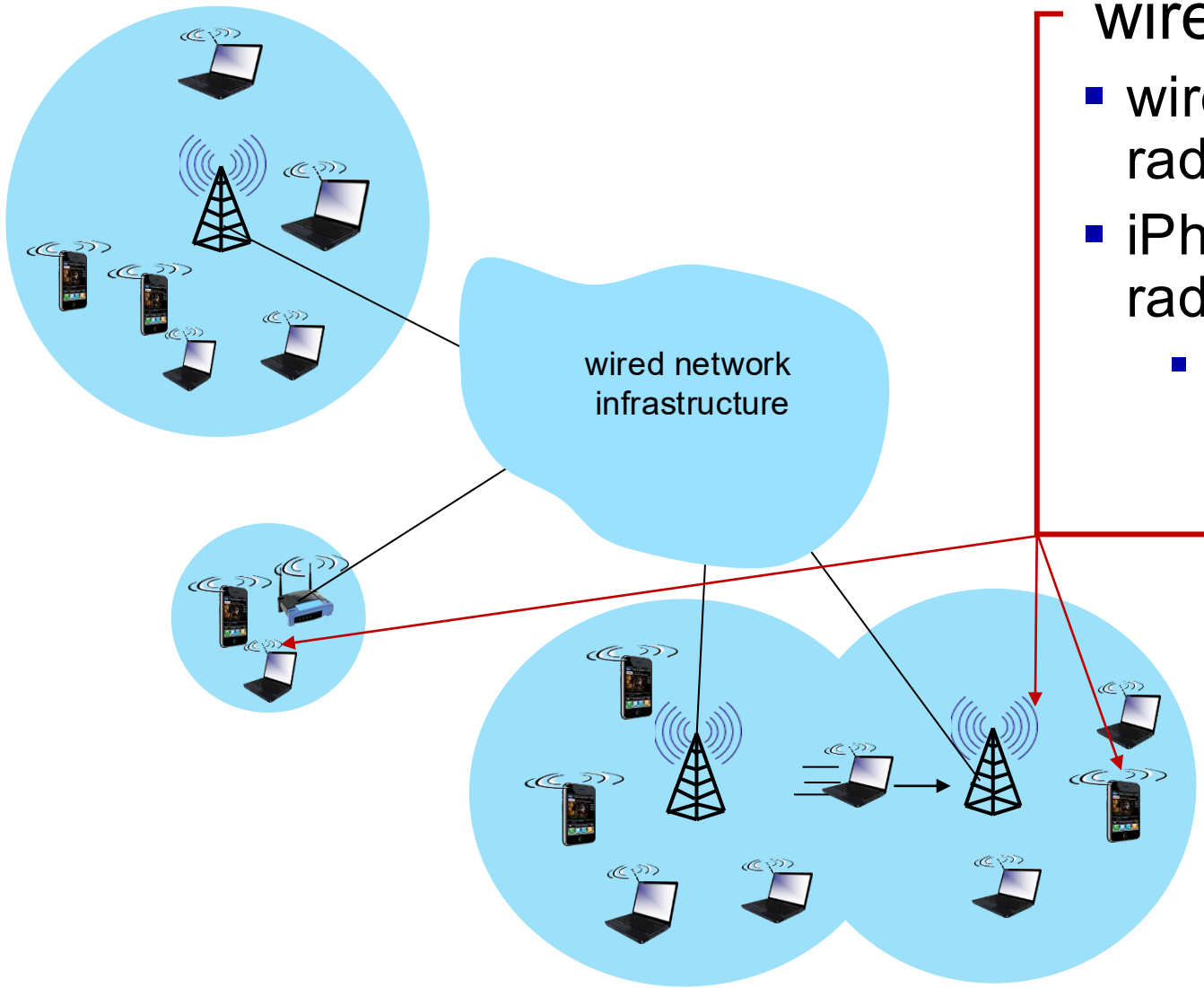
wireless link

- typically used to connect device(s) to base station, also used as backbone link
- multiple access protocol coordinates link access (random access, FDMA, TDMA, CDMA, polling)
- various transmission rates and distances, frequency bands

Ad hoc networks: not all wireless networks are connected into a larger network

UCCS

Elements of a wireless network



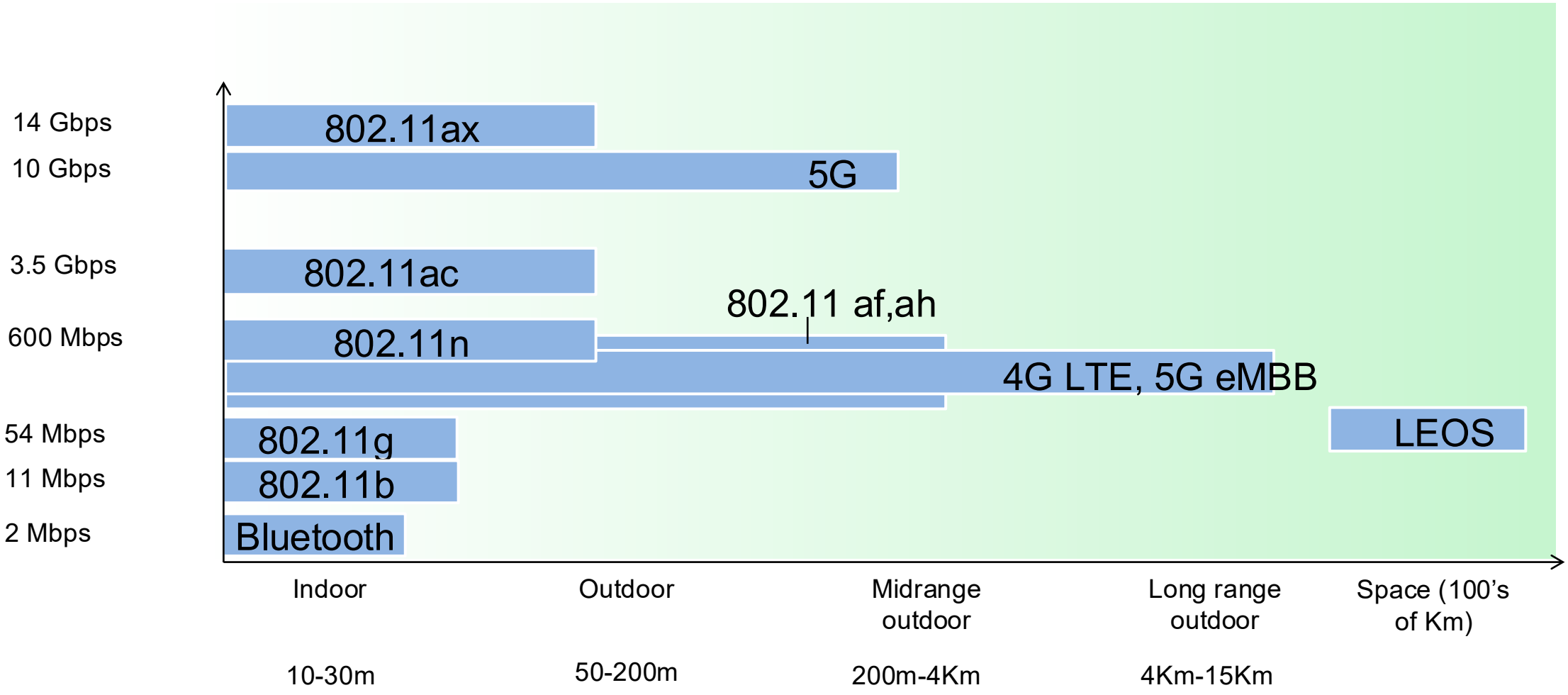
wireless device radio

- wireless device has different radios for different networks
- iPhone16: has ~11 different radios, many antennae
  - 5 different cellular radios, WiFi, Bluetooth, UWB, satellite NFC, GPS

Ad hoc networks: not all wireless networks are connected into a larger network

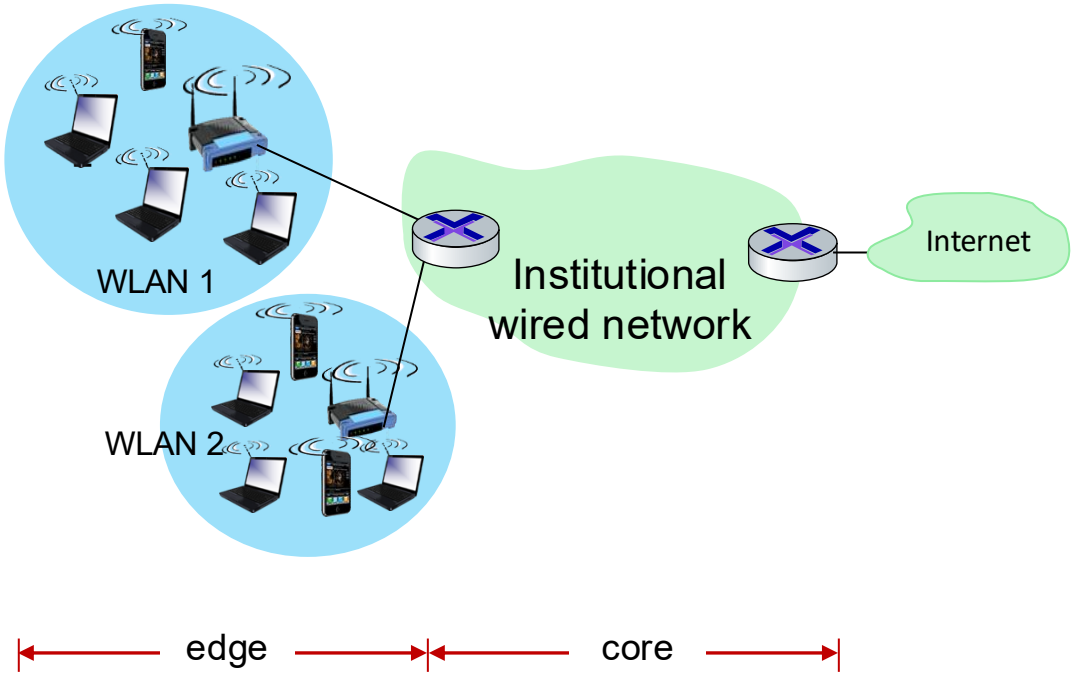
UCCS

Characteristics of selected wireless links

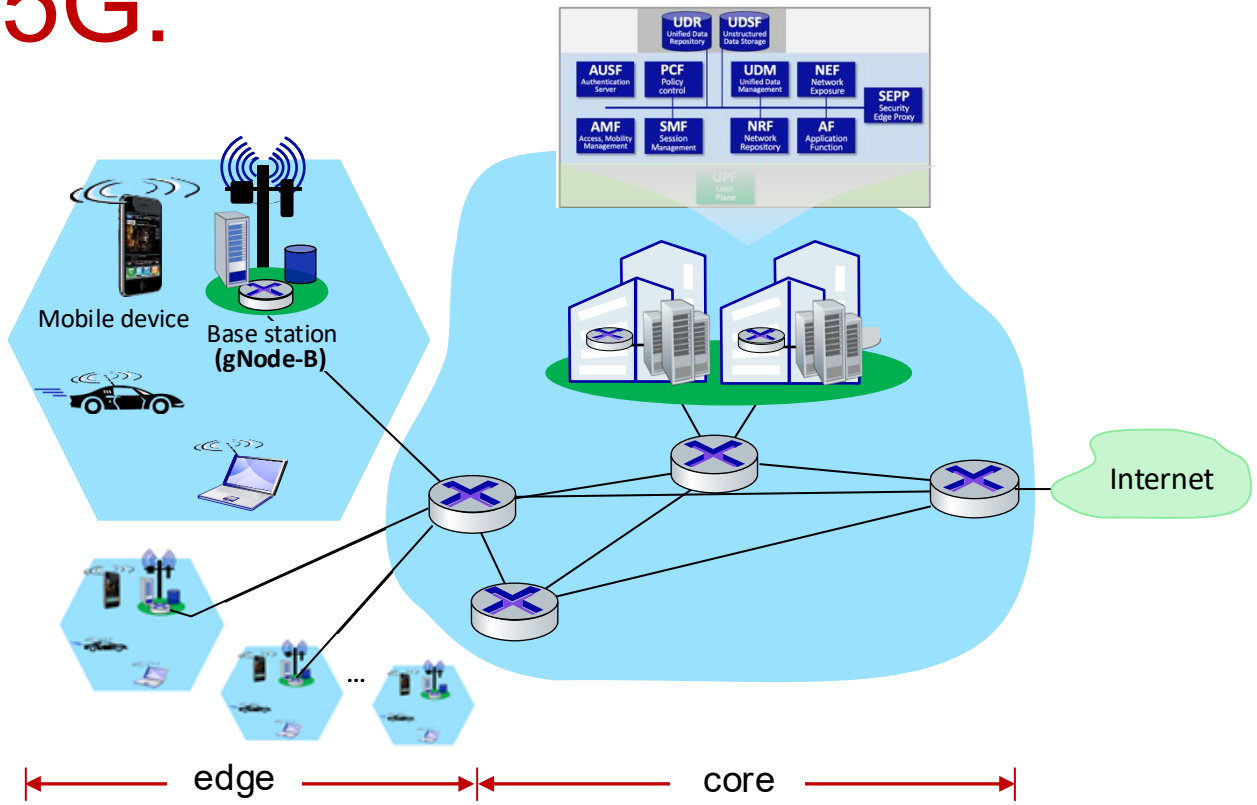


Wireless networks: edge and core networks

WiFi:



5G:



Wireless radio spectrum:

- radio spectrum: national asset, owned by the nation
- national government determine how spectrum is used "locally"
- different spectrum use types:

licensed:

- dedicated use, typically by one "owner" (e.g., cellular carrier such as AT&T, Verizon)
- often allocated by spectrum auction

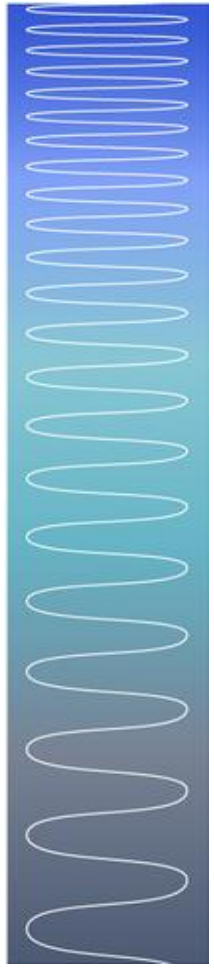
shared:

- spectrum dynamically shared among users
- "incumbent" may get preferential access, others "back off"

unlicensed:

- open (free) for anyone to use, conforming to rules (e.g., power transmission levels)
- 2.4GHz and 5 Ghz WiFi
- 3.5GHz "Private 5G" (aka CBRS)

WiFi spectrum bands



6 GHz range
- most recently added
- more than 250 configurable/selectable WiFi channels of different transmission rates

802.11 ax/be

5 GHz range
- more than 150(configurable/selectable WiFi channels) of different transmission rates

802.11 a/h/n/ac/ax

2.4 GHz
- Divided into 11-14 channels, depending on country

802.11 b/g/n/ax

- other 802.11 WiFi spectrum bands, but not in widespread use

5G spectrum: three spectrum bands*

* No single, well-accepted ranges for "low", "mid" and "high"

High band frequencies: 25–66 GHz range (aka mmwave)

- 26 GHz, 40 GHz, 50 GHz, 66 GHz bands popular
- short distances (< mile), high speeds (<3 Gbps)
- line of sight transmission: poor penetration of trees, buildings, ...

Mid-band frequencies: 1 - 6 GHz ranges

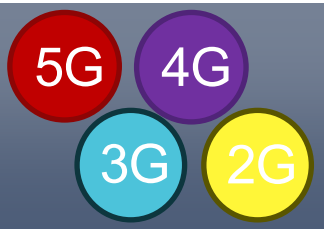
- balance distances (~5 miles ?) and transmission rates (100–900 Mbps)
- 1.8, 3.3 GHz to 3.8 GHz, 6 GHz bands popular

3.4 - 6 GHz

1-2.6 GHz

Low band frequencies: (< 1 GHz range)

- covers longer distances (10's of miles), but at lower speeds (50–250 Mbps)



UCCS

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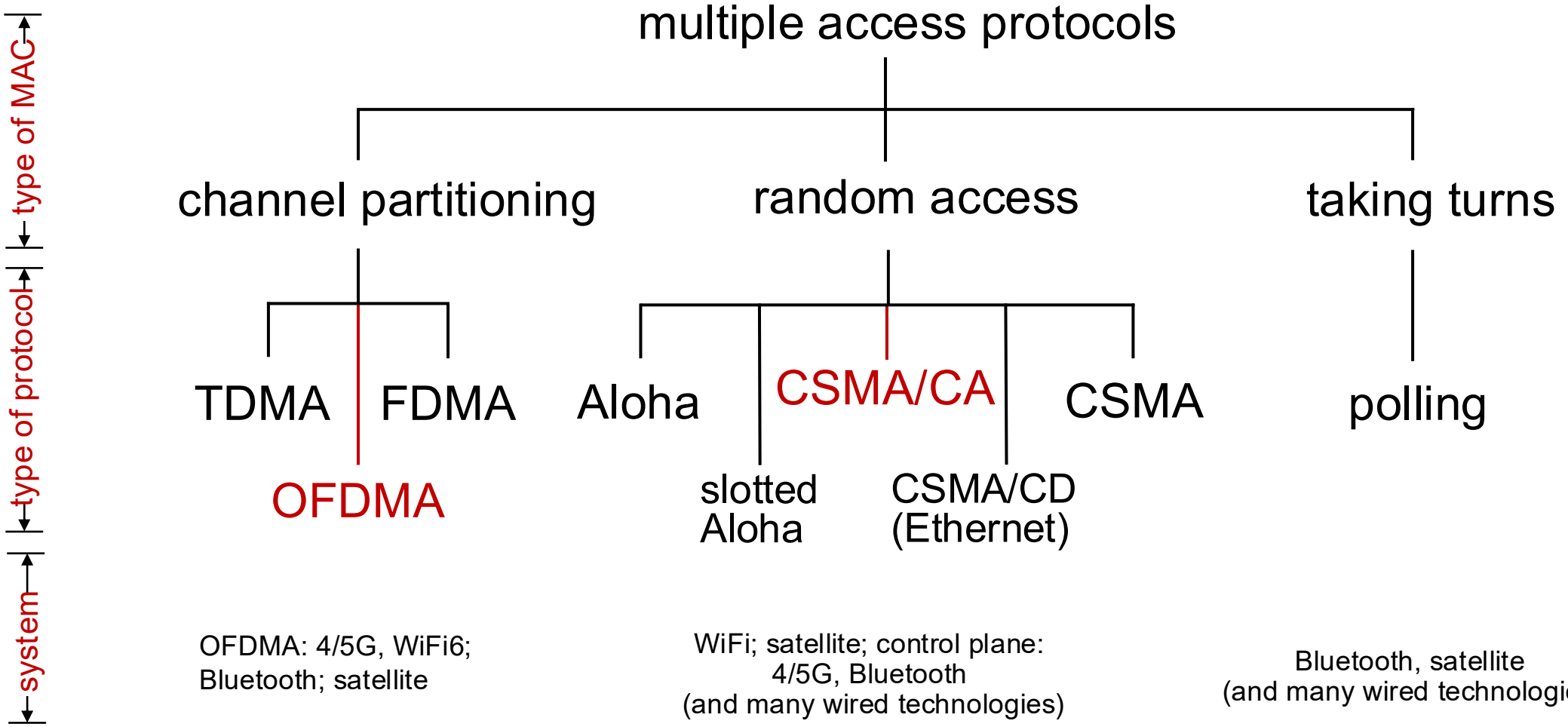
  - Wireless access network
    - Sharing a wireless access channel: OFDMA, CSMA/CA
    - WiFi wireless LAN
    - Cellular networks
    - Satellite, Bluetooth, IoT wireless networks

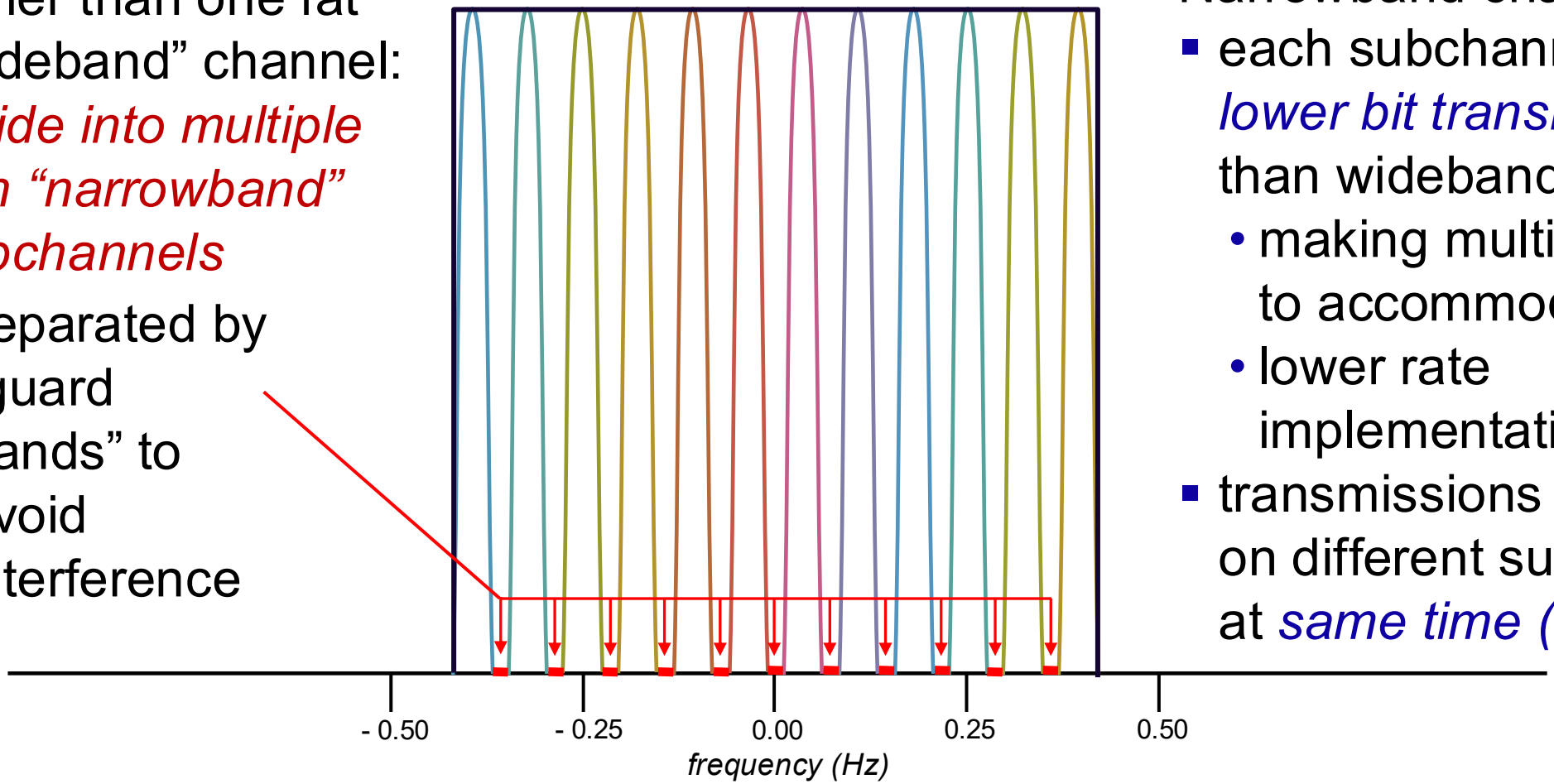
Recall: MAC protocols



FDM: Frequency Division Multiplexing

rather than one fat "wideband" channel: *divide into multiple thin "narrowband" subchannels*

- separated by "guard bands" to avoid interference

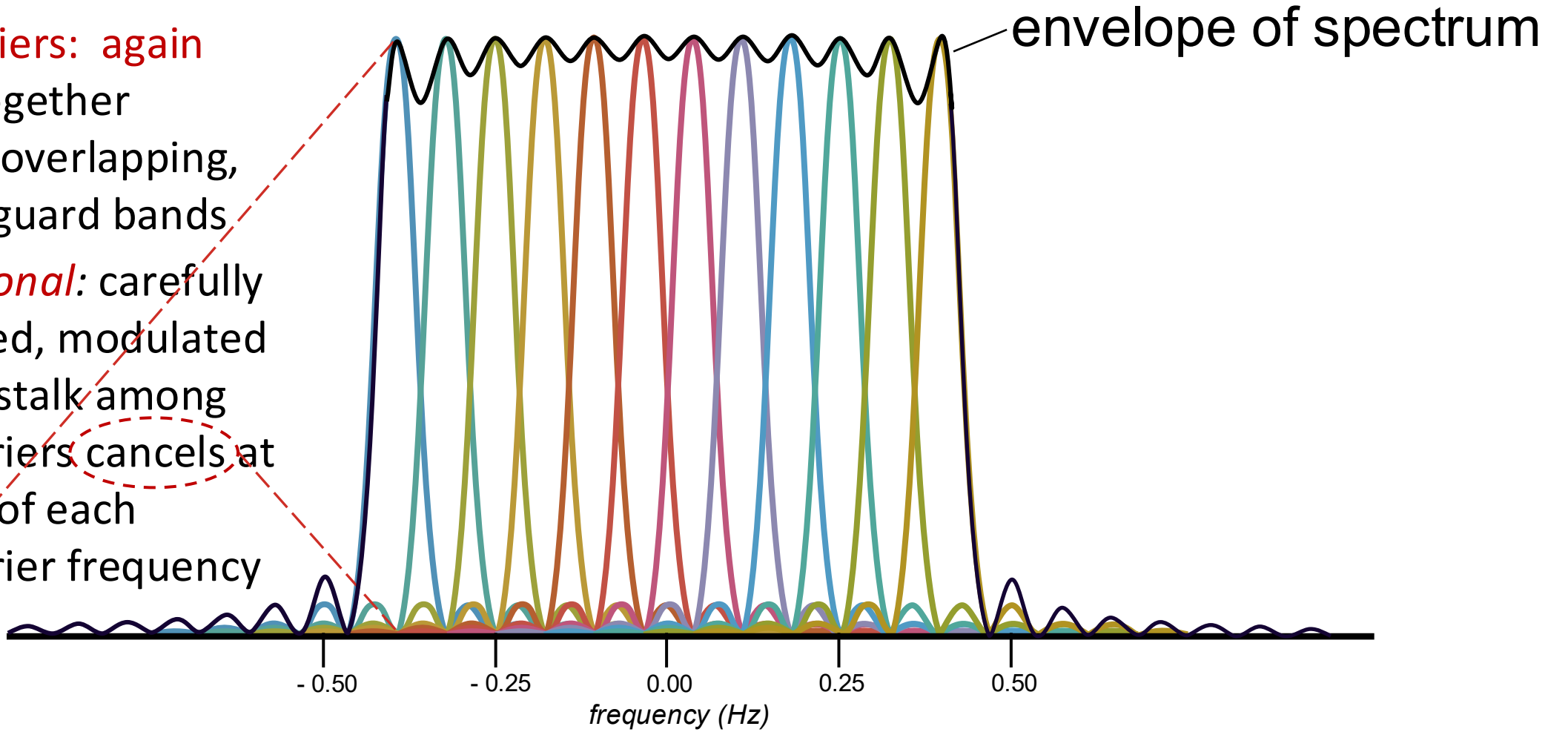


Narrowband channels:

- each subchannel has *lower bit transmission rate* than wideband channel:
  - making multipath easier to accommodate
  - lower rate implementations easier
- transmissions can happen on different subchannels at *same time (in parallel)*

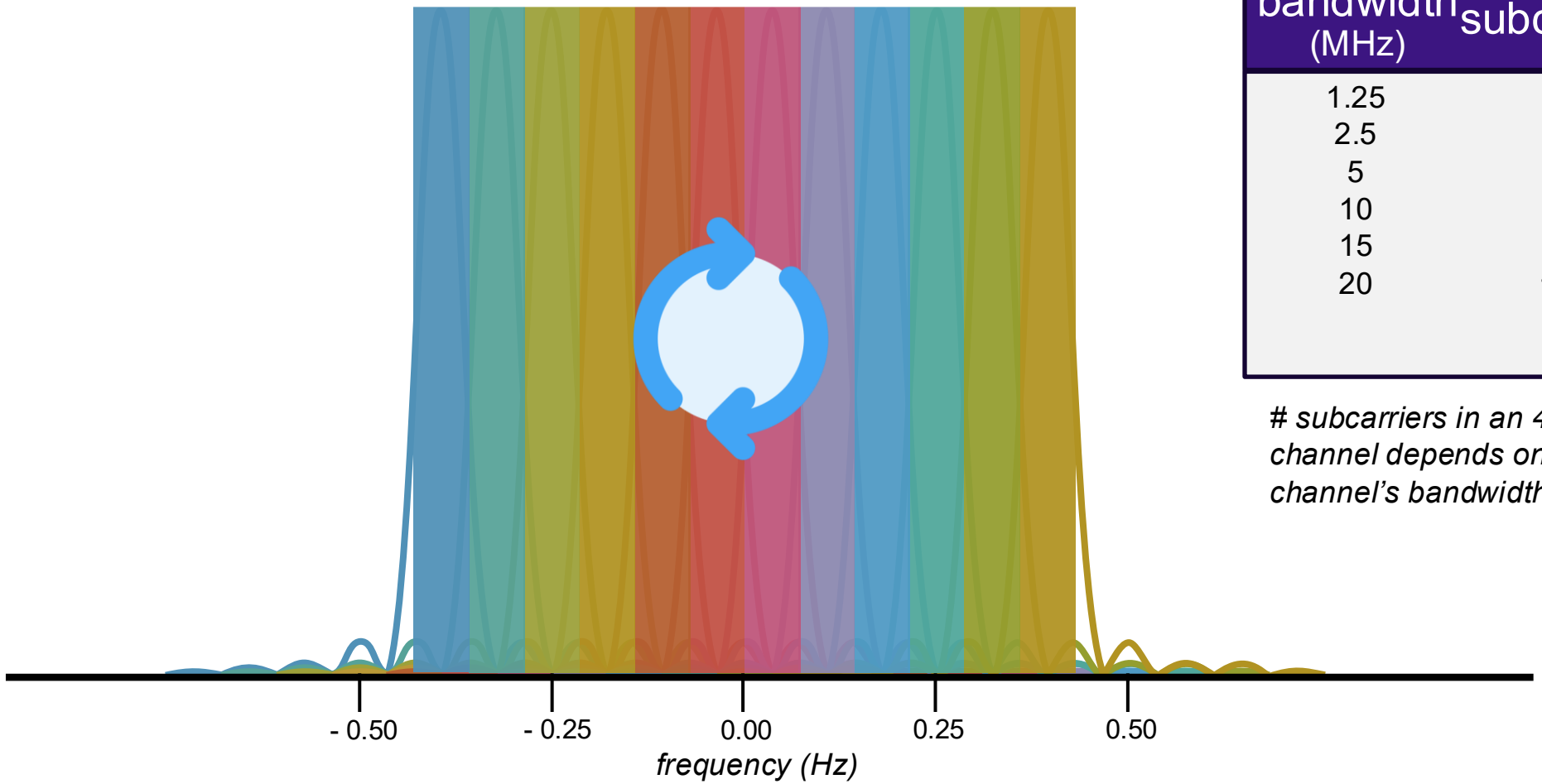
OFDM: *Orthogonal* FDM

- subcarriers: again close together
- slightly overlapping, but no guard bands
- *orthogonal:* carefully designed, modulated so crosstalk among subcarriers cancels at center of each subcarrier frequency



OFDM: Subcarriers

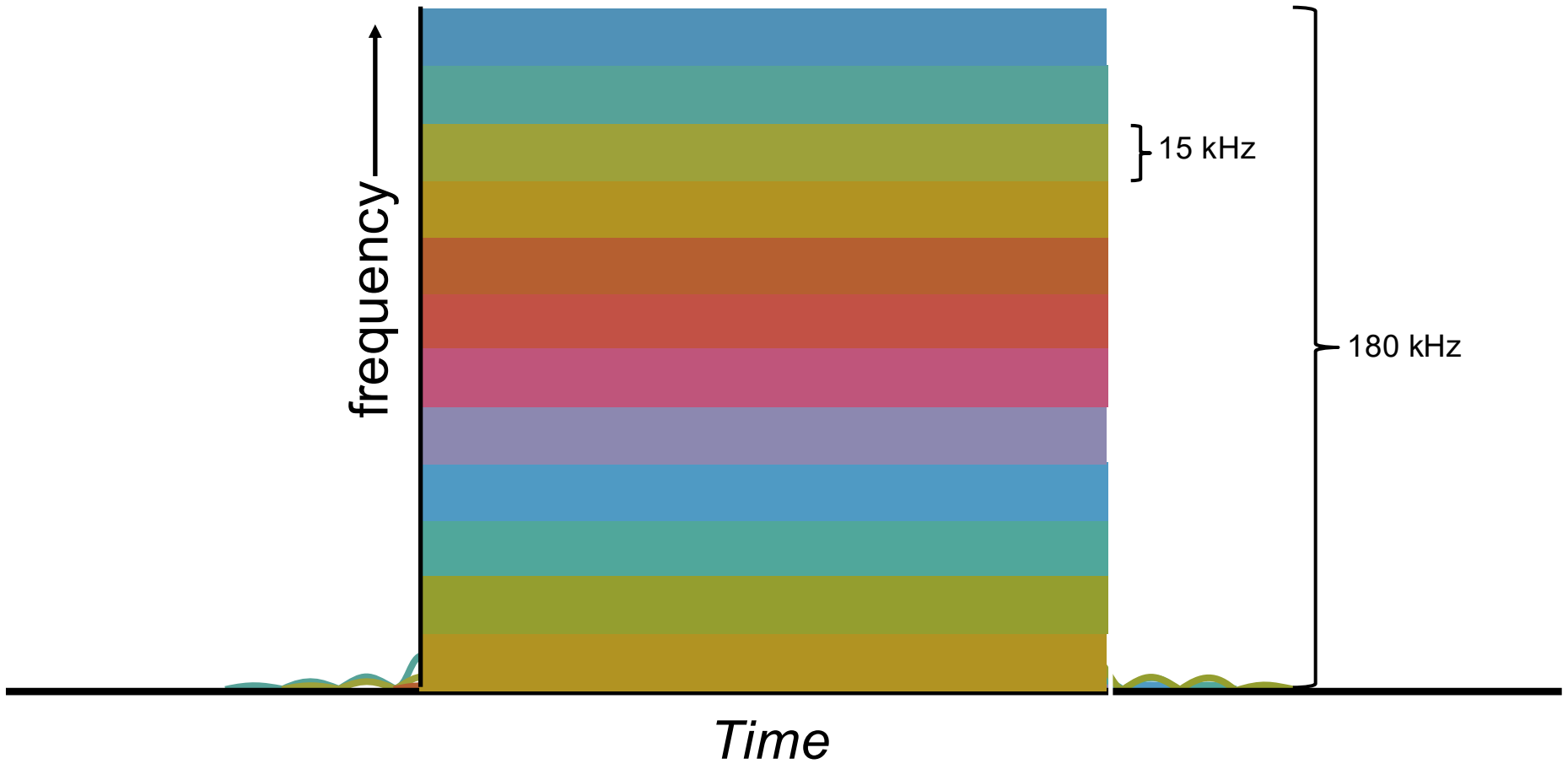
Wireless Jargon:
"carrier" ~ "channel"
"subcarrier" ~ "subchannel"



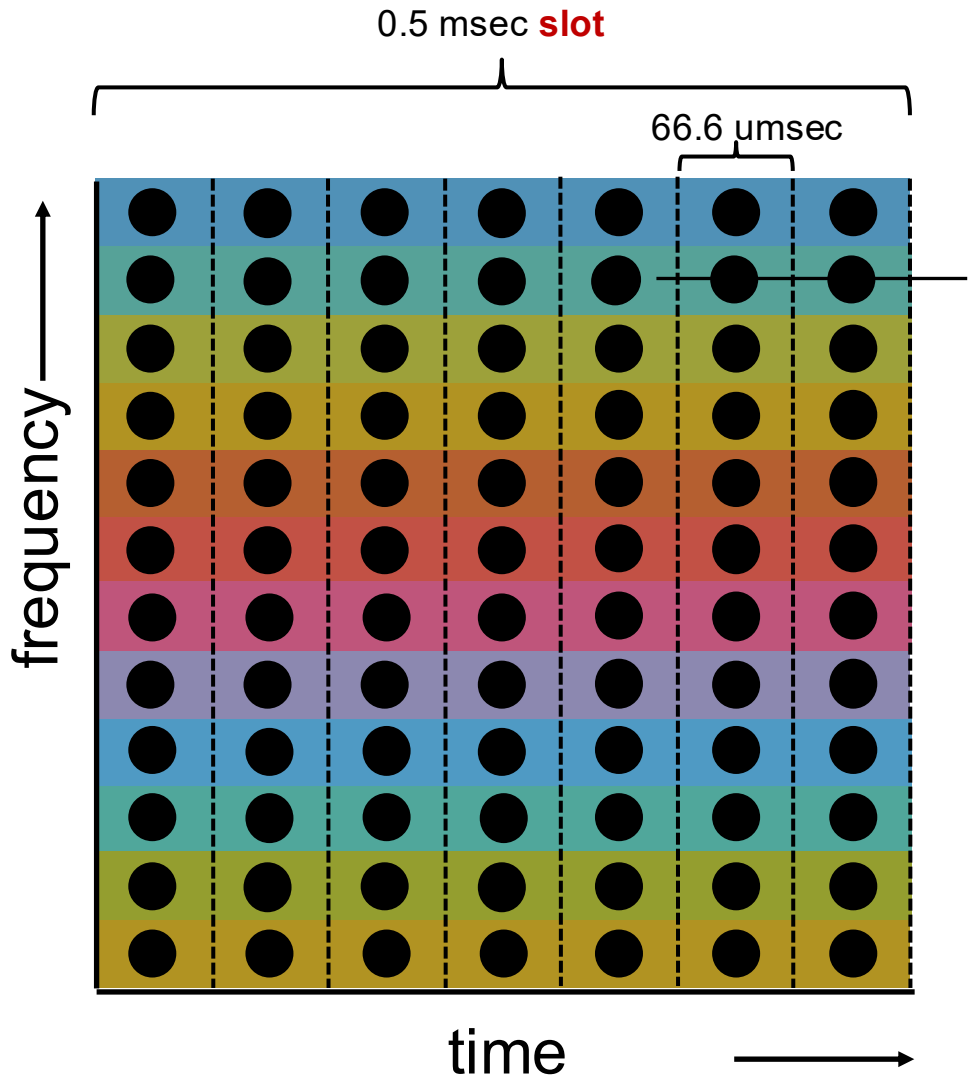
Channel bandwidth (MHz)	Number of subcarriers
1.25	76
2.5	150
5	300
10	600
15	900
20	1200

 # subcarriers in an 4G / 5G channel depends on channel's bandwidth

OFDMA: subcarriers, time



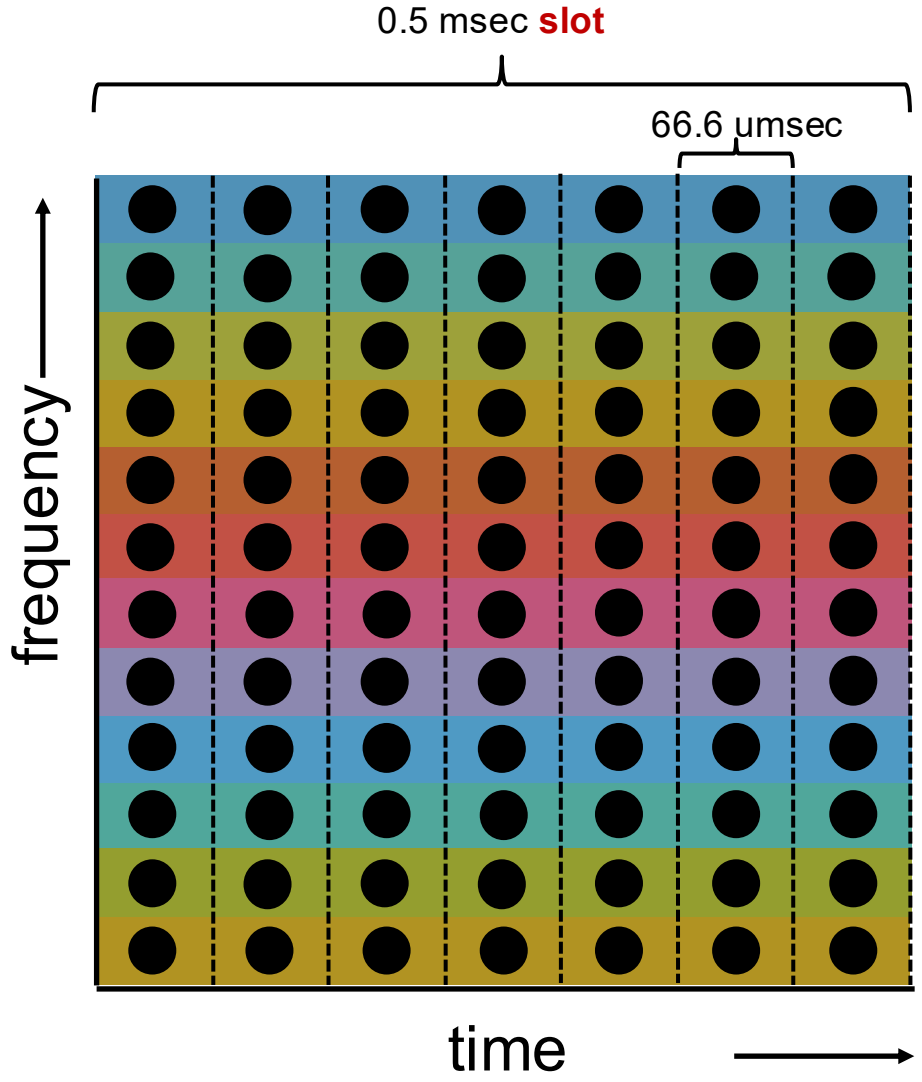
OFDMA: symbols



one “symbol” can be transmitted per 66.6 usec (4G) at given subcarrier frequency

- *number of bits (between 2-8) in symbol depends on modulation technique* chosen (which depends on channel quality)

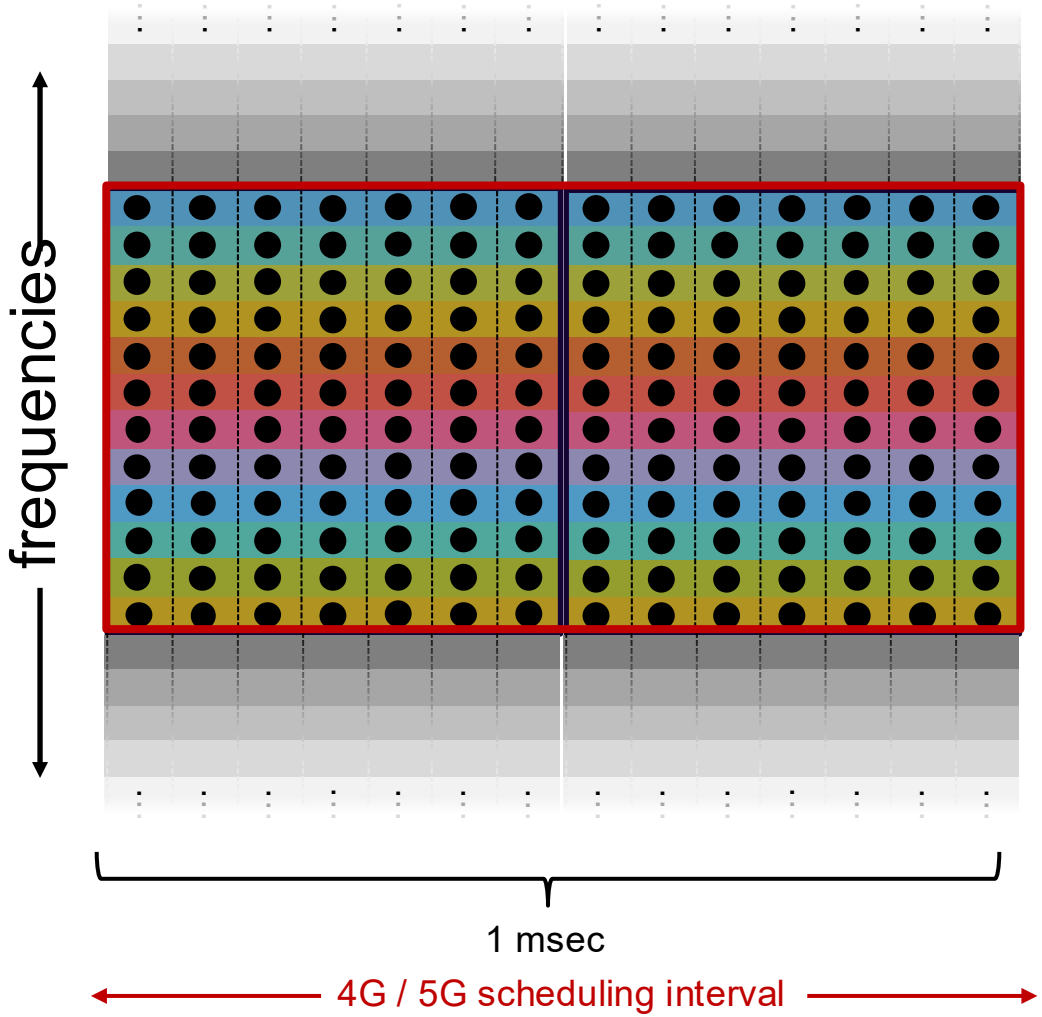
OFDMA: resource blocks



resource block (RB):

- symbols grouped into resource blocks
- 84 symbols (7 symbols/slot over 12 subcarriers) in 4G
- *smallest unit of data that can be sent to (assigned to) a user*

OFDMA: resource blocks



Base station decides which RBs get assigned (over all frequencies) to which devices at 1 msec intervals

From 4G LTE to 5G New Radio (NR)

Commonalities, differences:

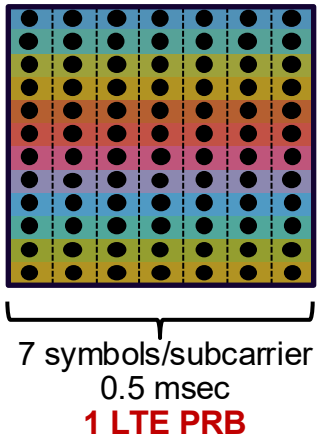
4G, 5G both use OFDMA

- Subcarrier bandwidths:
  - 4G: 15 kHz
  - 5G: 15, 30, 60, 120 kHz
- Max carrier bandwidth:
  - 4G: 20 MHz
  - 5G: 100 MHz

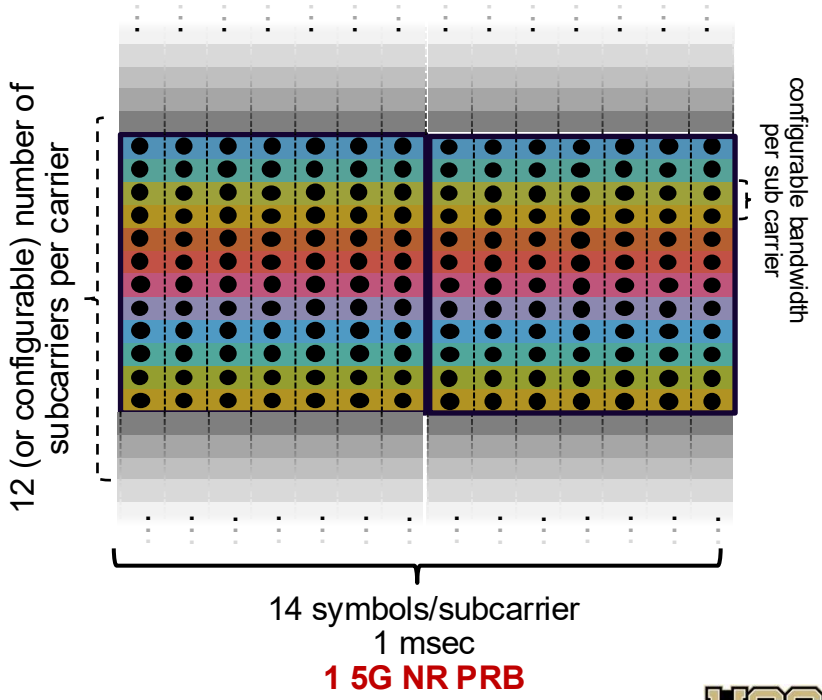
4G, 5G: resource blocks (RB)

- smallest scheduling unit of transmission to device

4G

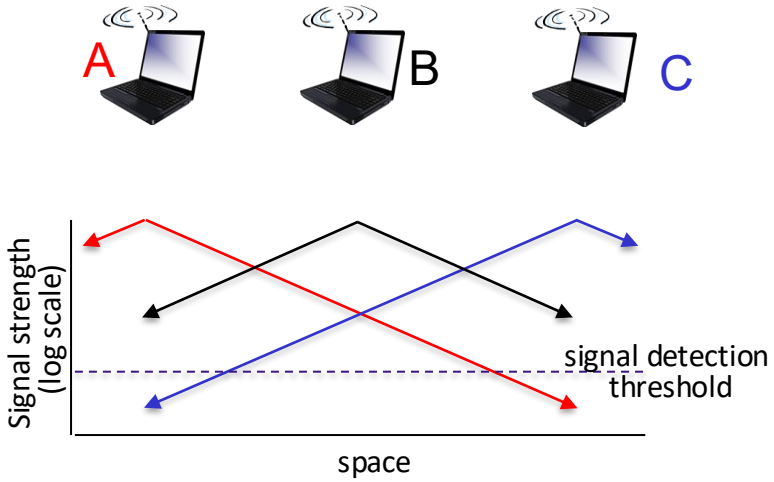


5G



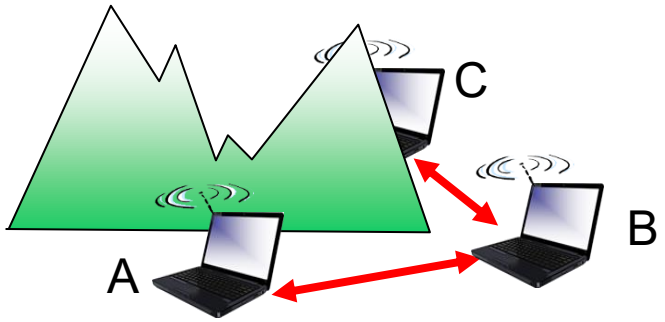
CSMA/CA: addressing the “hidden terminals” problem

Path loss causes “hidden terminals”



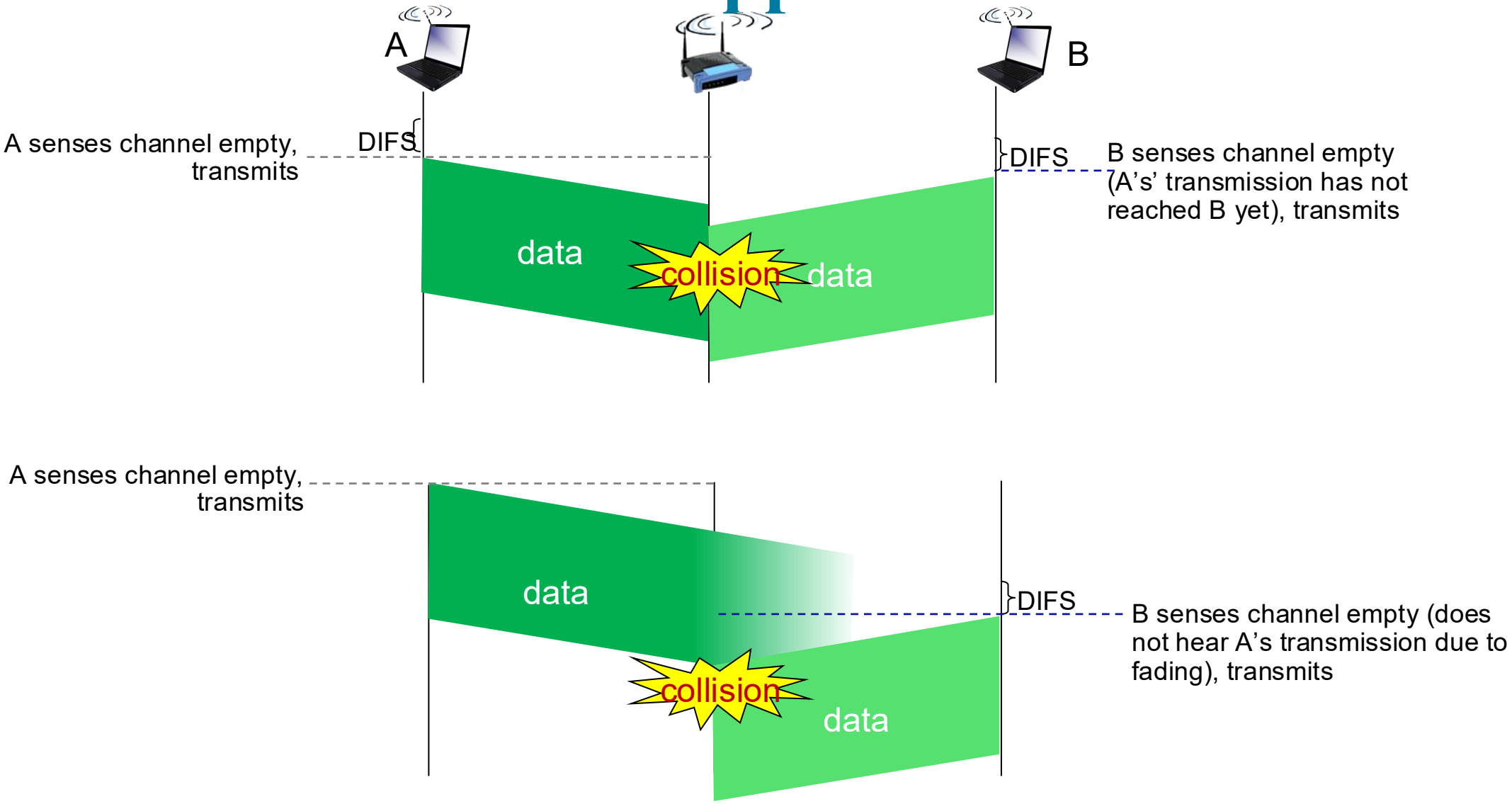
- B, A hear each other
- B, C hear each other
- A, C can not hear each other interfering at B

Objects cause ”hidden terminals”



- 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

CSMA/CA: collisions happen



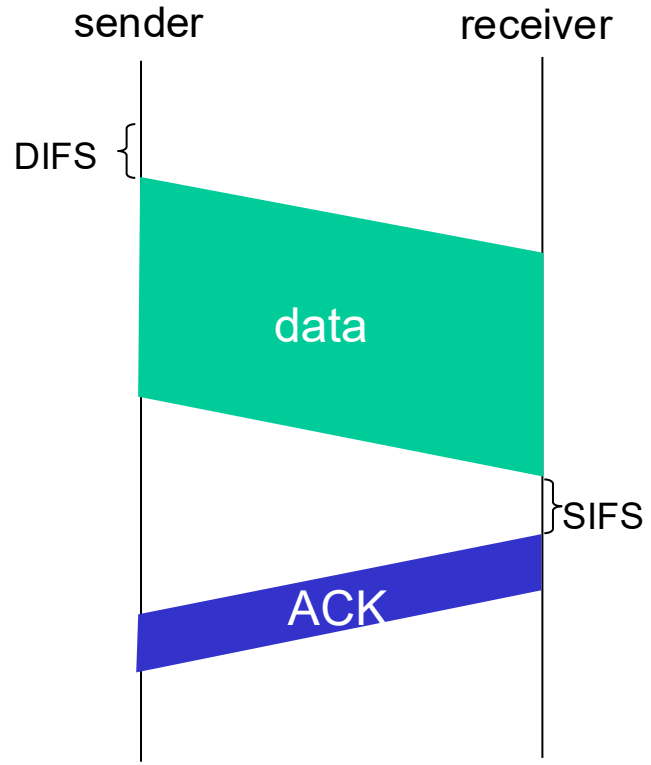
IEEE 802.11 MAC Protocol: CSMA/CA

802.11 sender

1 if sense channel idle for **DIFS** then
  transmit *entire* frame (no collision detection)

2 if sense channel busy then
  start random backoff time
  timer counts down while channel idle
  transmit when timer expires

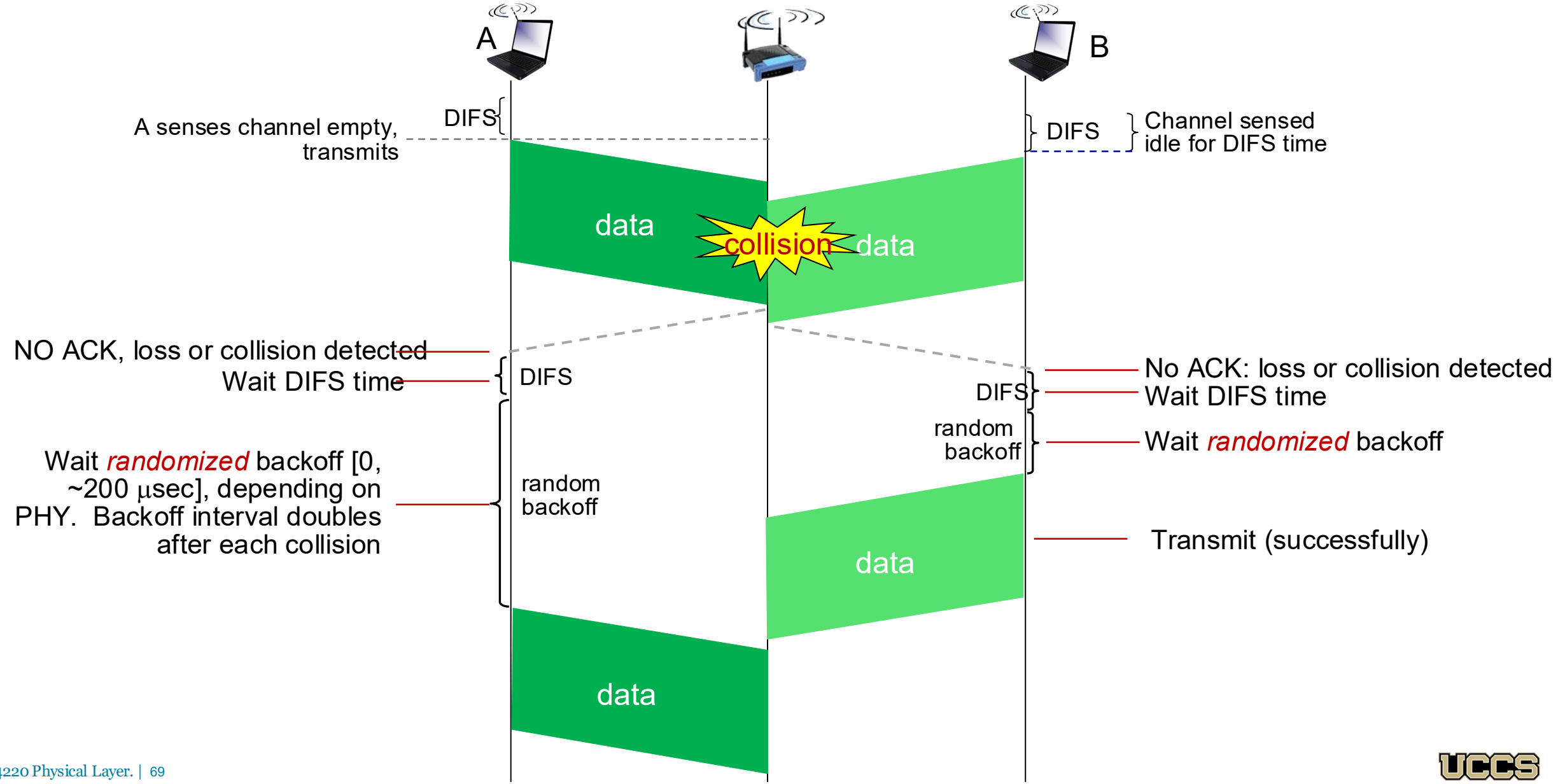
3. if no ACK, increase random backoff interval, repeat 2 (see next slide)



802.11 receiver

if frame received OK
  return ACK after **SIFS** (ACK needed due to hidden terminal problem)

CSMA/CA: randomization after collision

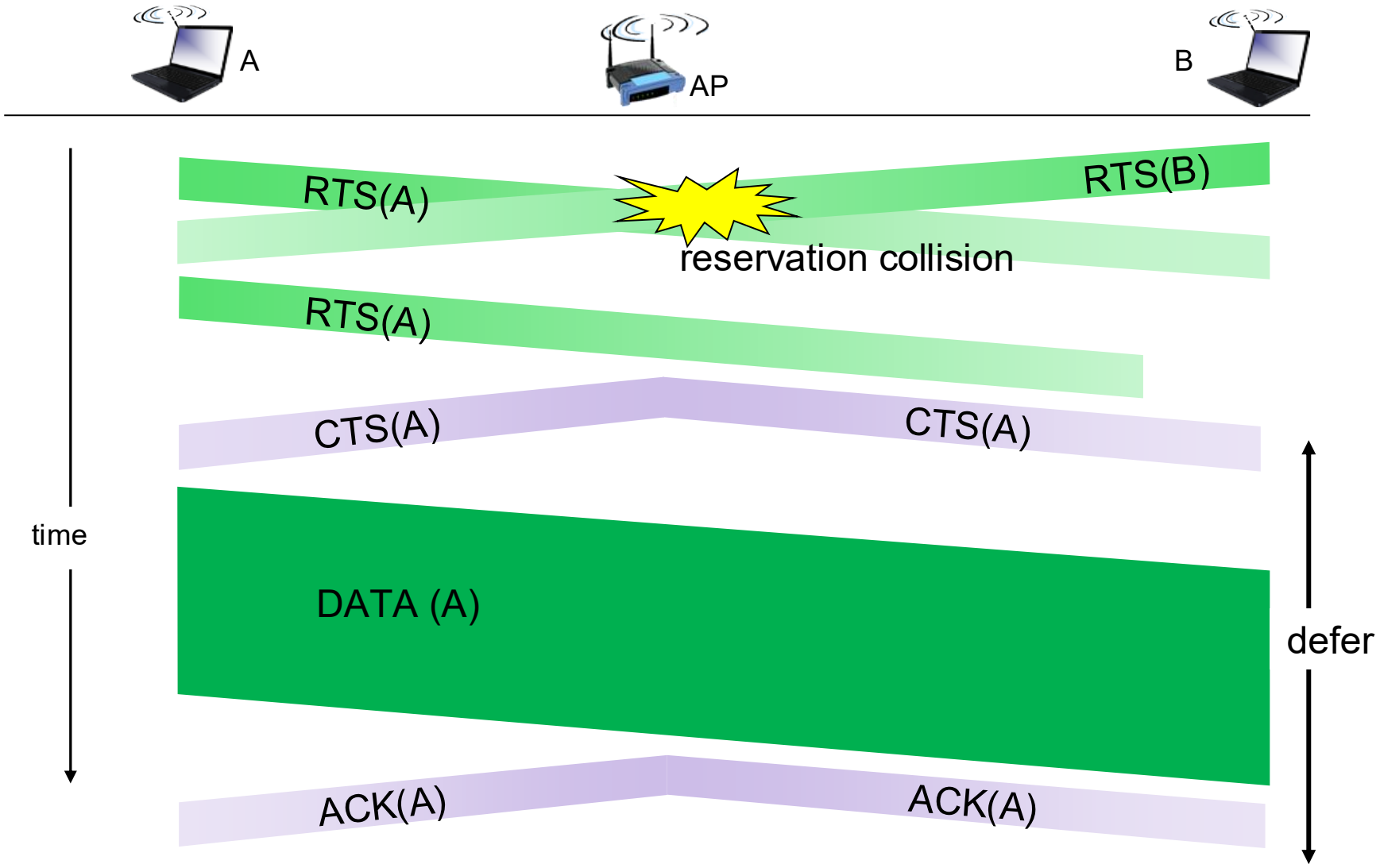


Avoiding collisions: using RTS/CTS

idea: sender "reserves" channel use for data frames using small reservation packets

- sender first transmits *small* request-to-send (RTS) packet to BS using CSMA
  - RTSs may still collide with each other (but they're short)
  - contains duration for following data transmission
- BS broadcasts clear-to-send (CTS) packet in response to RTS
  - contains duration for following data transmission
- RTS and/or CTS heard by all nodes
  - All nodes except transmitter defer transmissions
  - transmits data frame

Collision Avoidance: RTS-CTS exchange



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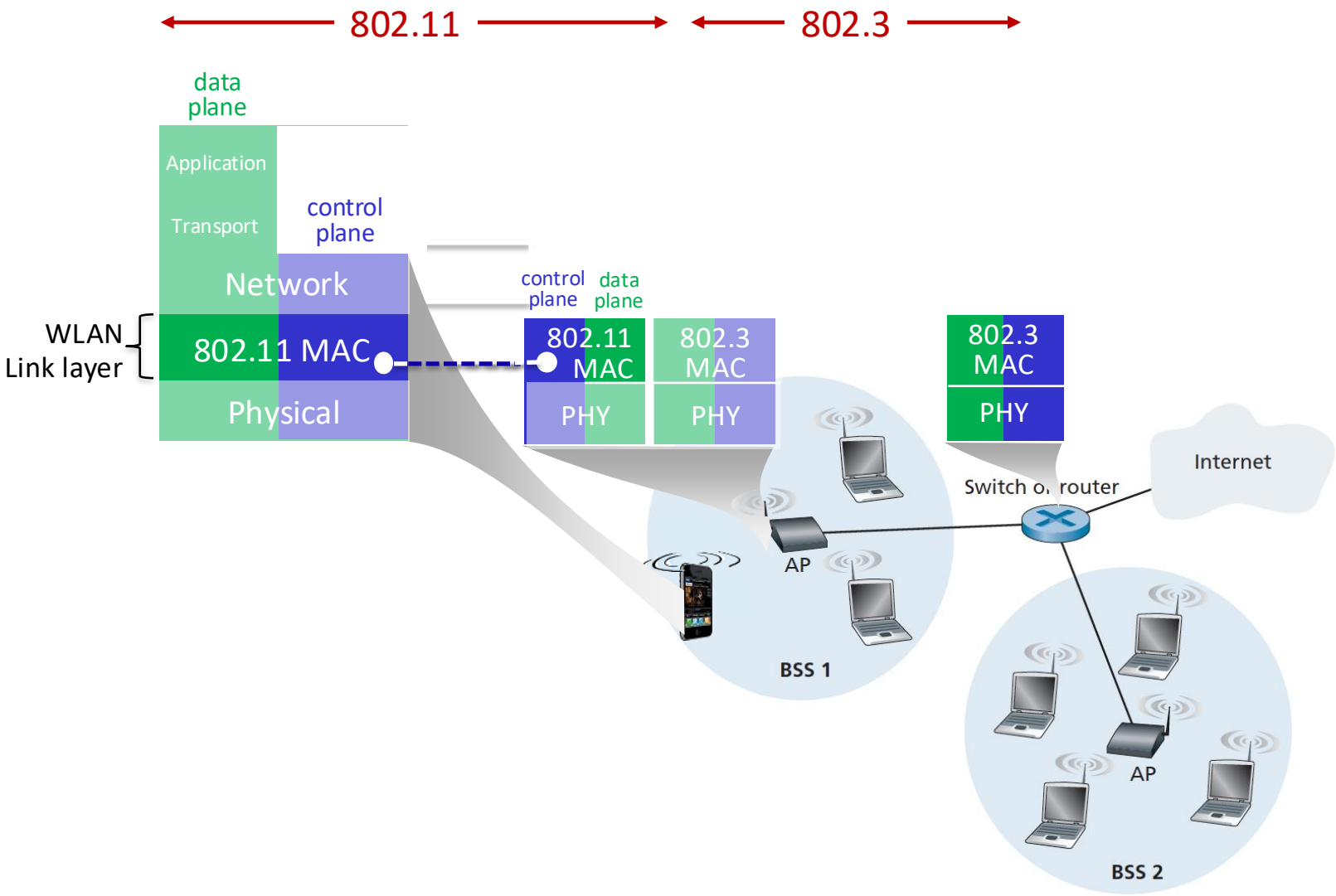
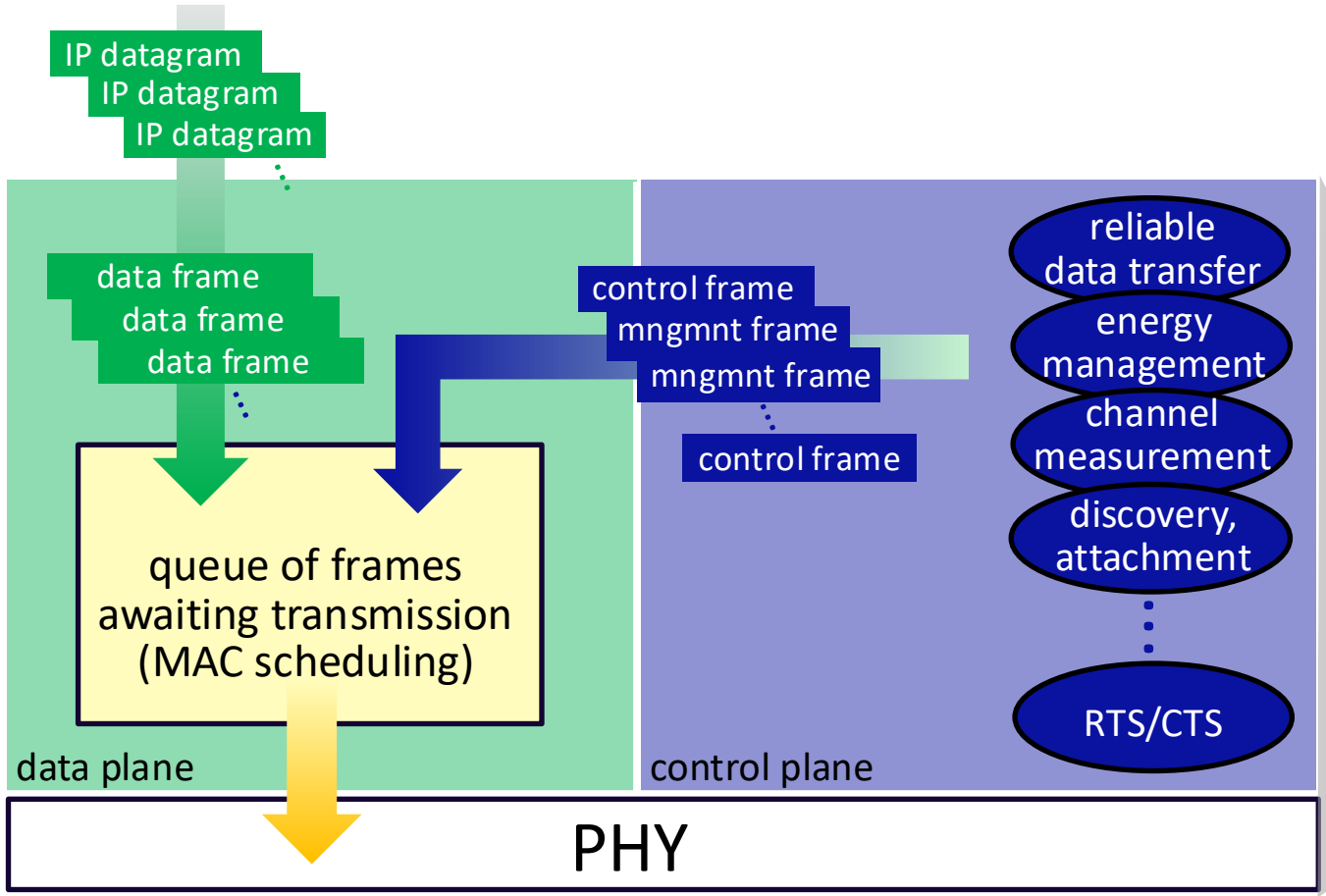
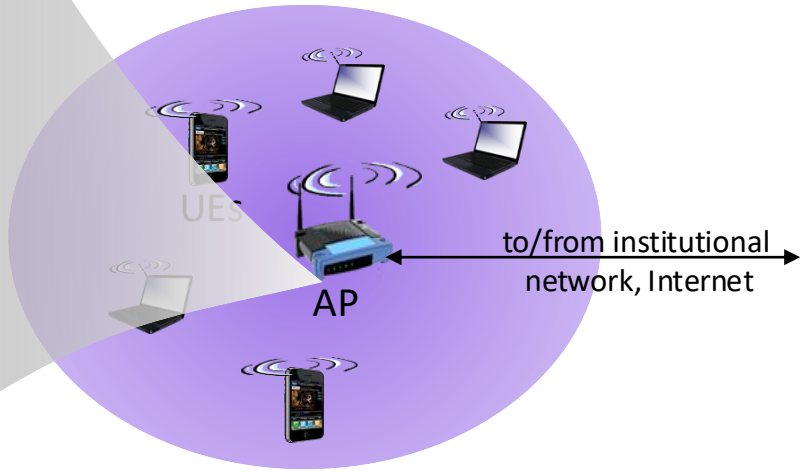
802.11 wireless link layer



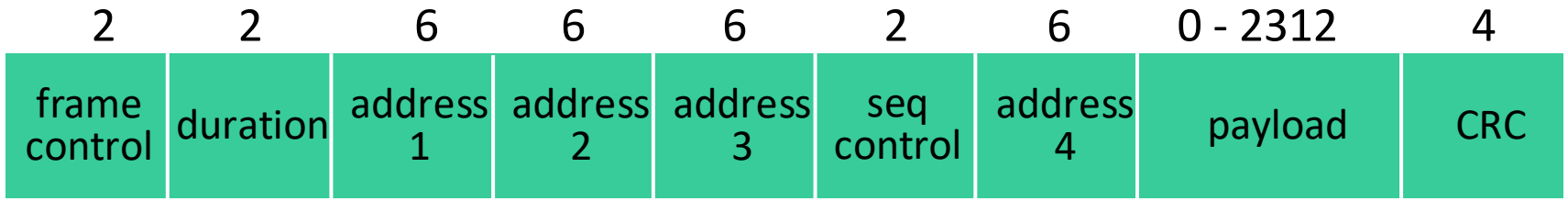
802.11 downlink (AP-to-device) frame flow



- data frames: containing IP datagrams
- Control, management frames



802.11 frame: addressing



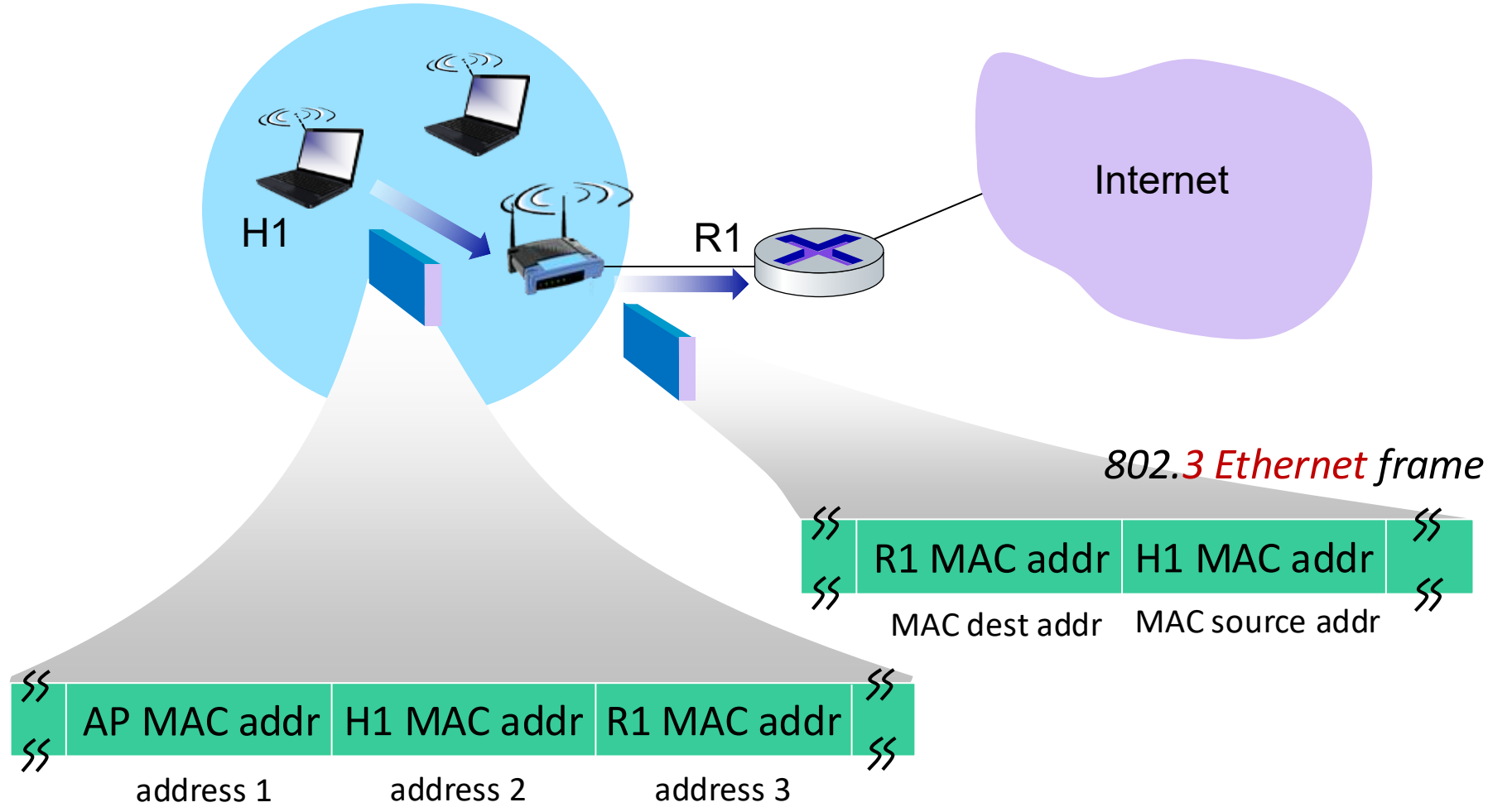
Address 1: MAC address of wireless host or AP to receive this frame

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

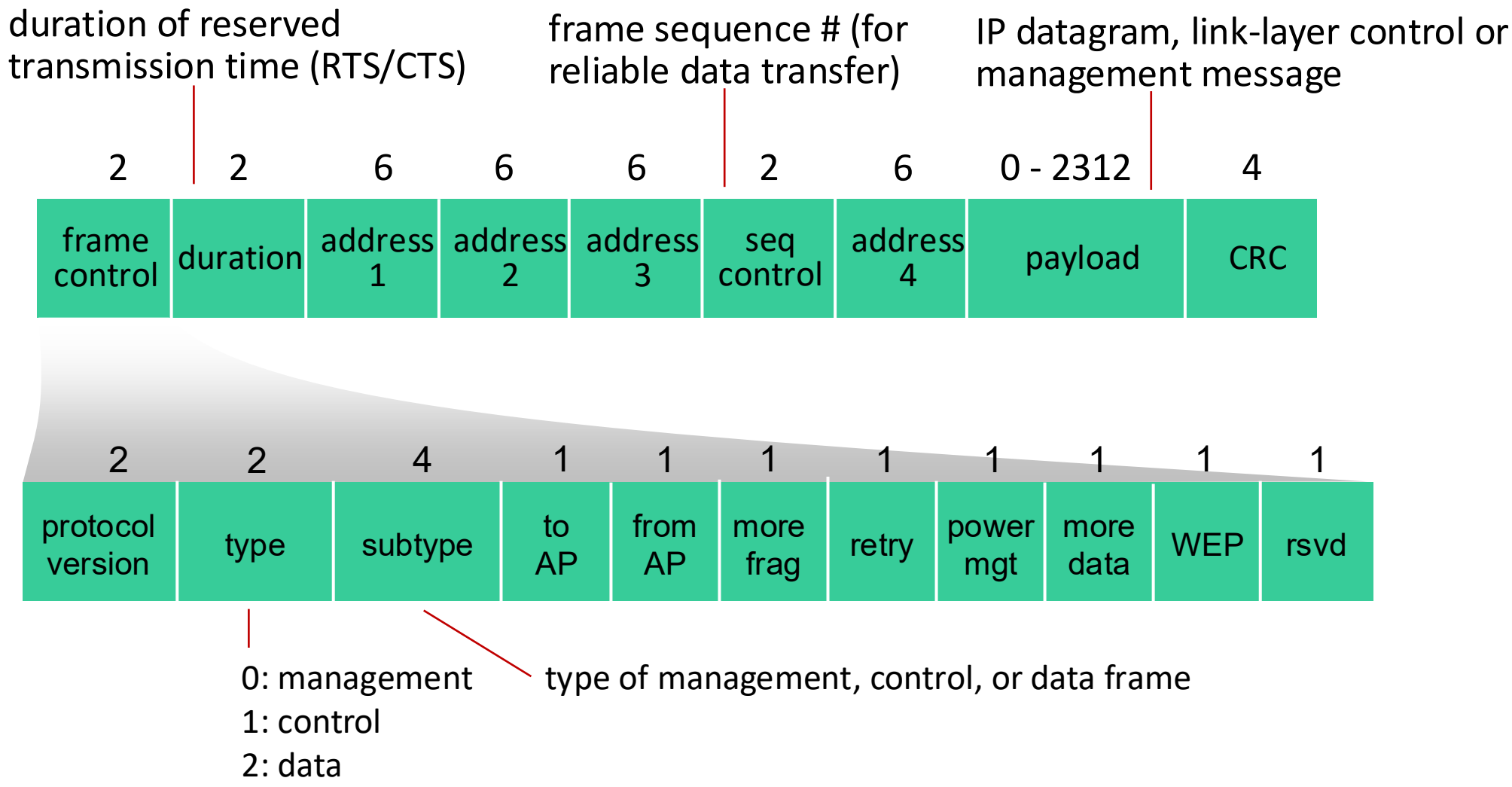
Address 3: MAC address of router interface to which AP is attached

Address 4: used only in ad hoc mode

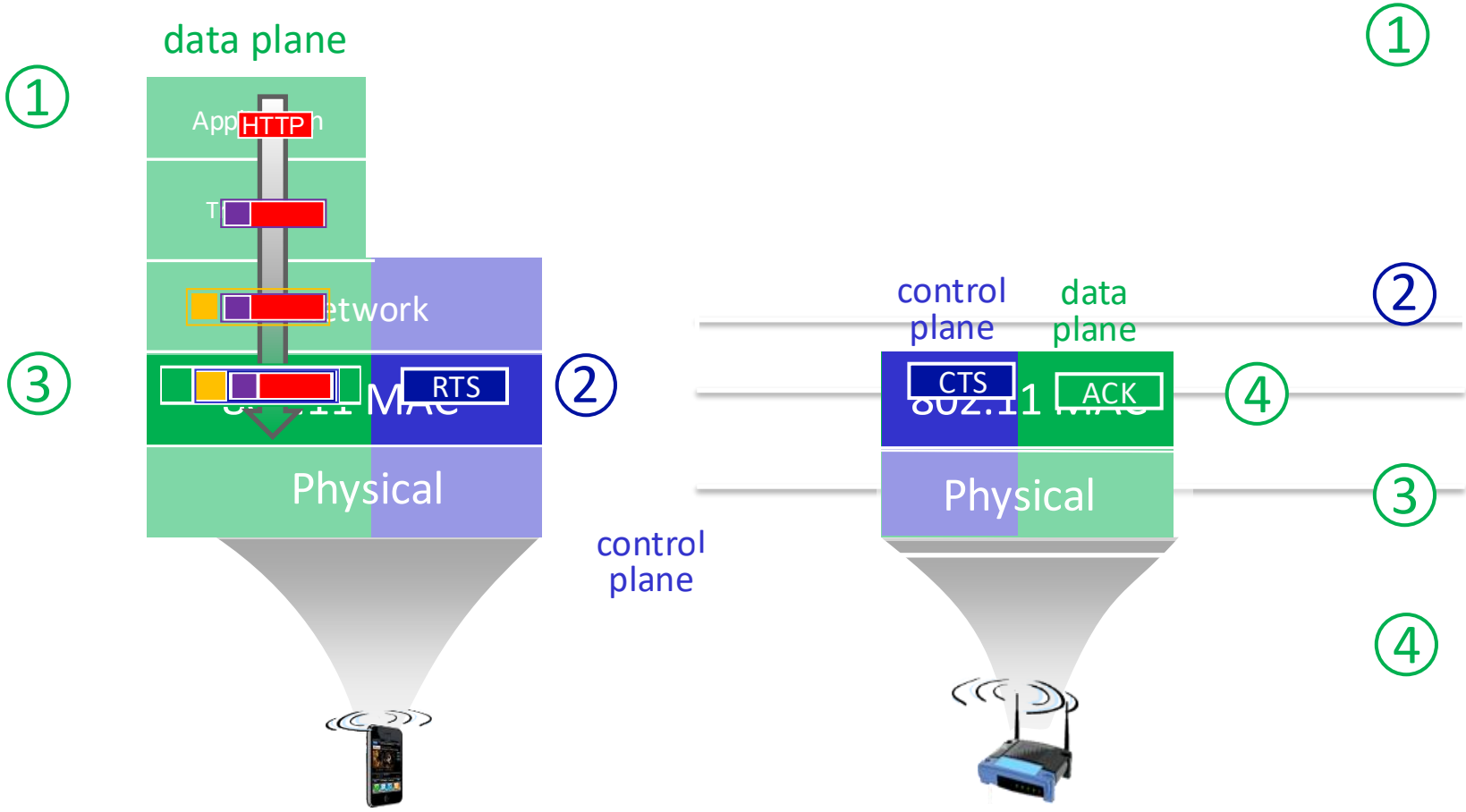
802.11 frame: addressing



802.11 frame


duration of reserved transmission time (RTS/CTS)
frame sequence # (for reliable data transfer)
IP datagram, link-layer control or management message
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
2
2
4
1
1
1
1
1
1
1
1
protocol version
type
subtype
to AP
from AP
more frag
retry
power mgt
more data
WEP
rsvd
0: management
1: control
2: data
type of management, control, or data frame

Retrospective: "A day in the life"* (WiFi)



1. HTTP/3 request in UDP segment, in IP datagram, into 802.11 frame. Enter, wait, MAC frame scheduling queue
2. Device sends RTS control frame (using CSMA/CA); AP responds with CTS.
3. Device sends DATA frame to AP. Buffers DATA frame
4. AP responds with ACK, device removes transmitted frame

AP can now forward frame to router

*https://gaia.cs.umass.edu/kurose_ross/videos/6/

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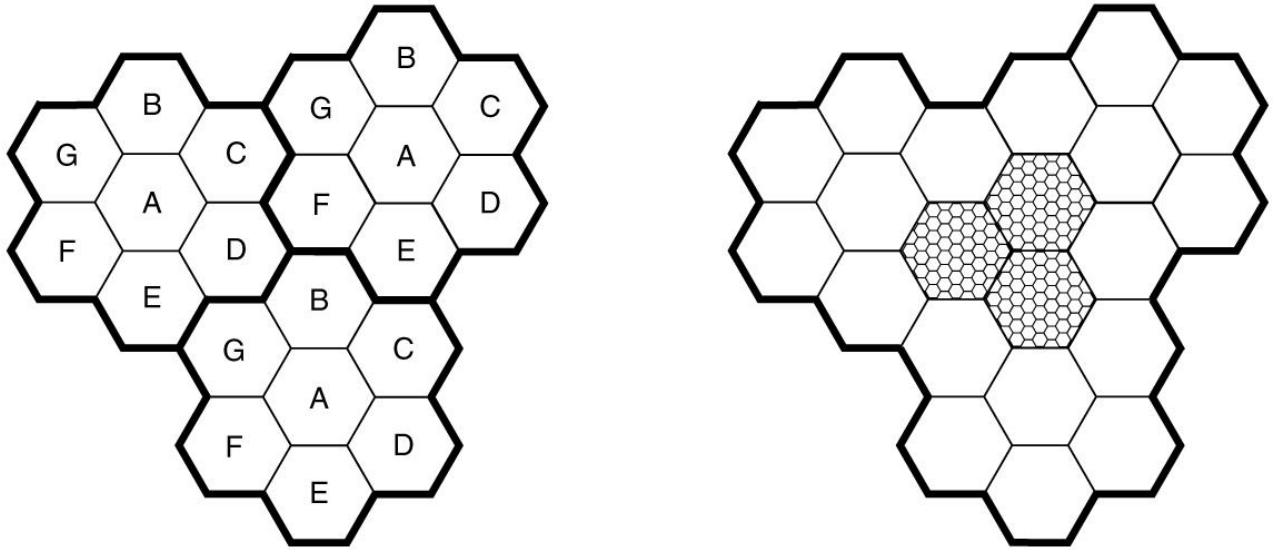
Cellular Networks

- Mobile phone distinct generations
- Using radio transmission
- The initial three generations: 1G, 2G, 3G
  - Provided analog voice, digital voice, and both digital voice and data (Internet, email, etc.) respectively
- 4G technology adds capabilities
  - Physical layer transmission techniques and IP-based femtocells
  - 4G is based on packet switching only (no circuit switching)
- 5G being rolled out now
  - Supports up to 20 Gbps transmissions and denser deployments
  - Focus on reducing network latency

Common Concepts: Cells, Handoff, Paging

Cells: a geographic region

- Each cell uses some set of frequencies not used by any of its neighbors
- The power can be reduced and the overloaded cells split into smaller microcells to permit more frequency reuse



(a) Frequencies are not reused in adjacent cells. (b) To add more users, smaller cells can be used.

Common Concepts: Cells, Handoff, Paging

- Handoff:
  - When a mobile telephone physically leaves a cell, its base station notices the telephone's signal fading away and then asks all the surrounding base stations how much power they are getting from it
  - When the answers come back, the base station then transfers ownership to the cell getting the strongest signal; under most conditions that is the cell where the telephone is now located
  - The telephone is then informed of its new boss, and if a call is in progress, it is asked to switch to a new channel (because the old one is not reused in any of the adjacent cells)

- Paging
  - Paging channels (base to mobile) alert mobile users to calls for them

Cellular Networks

First-Generation (1G) Technology: Analog Voice

1946 push to talk systems

- This system used a single large transmitter on top of a tall building and had a single channel, used for both sending and receiving.
- To talk, the user had to push a button that enabled the transmitter and disabled the receiver.
- Taxis and police cars often used this technology.

1960 IMTS (Improved Mobile Telephone System)

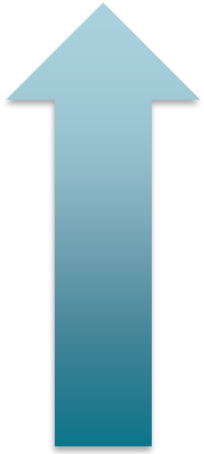
- Two frequencies: one for sending, one for receiving
- The push-to-talk button was no longer needed.
- Since all communication from the mobile telephones went inbound on a different channel than the outbound signals, the mobile users could not hear each other (unlike the push-to-talk system used in older taxis).

1983 AMPS (Advanced Mobile Phone System)

- Analog mobile phone system
- Cells are typically 10 to 20 km across
- Used FDM to separate channels
- 832 full-duplex channels that consist of a pair of simplex channels used (Frequency Division Duplex)
- Each simplex channel is 30 kHz wide
- 832 channels in AMPS are divided into four categories

Cellular Networks

First-Generation (1G) Technology: Analog Voice



Outgoing calls

- Phone switched on, number entered, CALL button hit
- Phone transmits called number and its own identity on the access channel
- Base informs the MSC and MSC looks for a channel for the call

Incoming calls

- Idle phones continuously listen to the paging channel to detect messages directed at them
- Packet sent to base station in the current cell as a broadcast on the paging channel
- The called phone responds on the access channel
- Called phone switches to channel and starts ringing sound

Cellular Networks

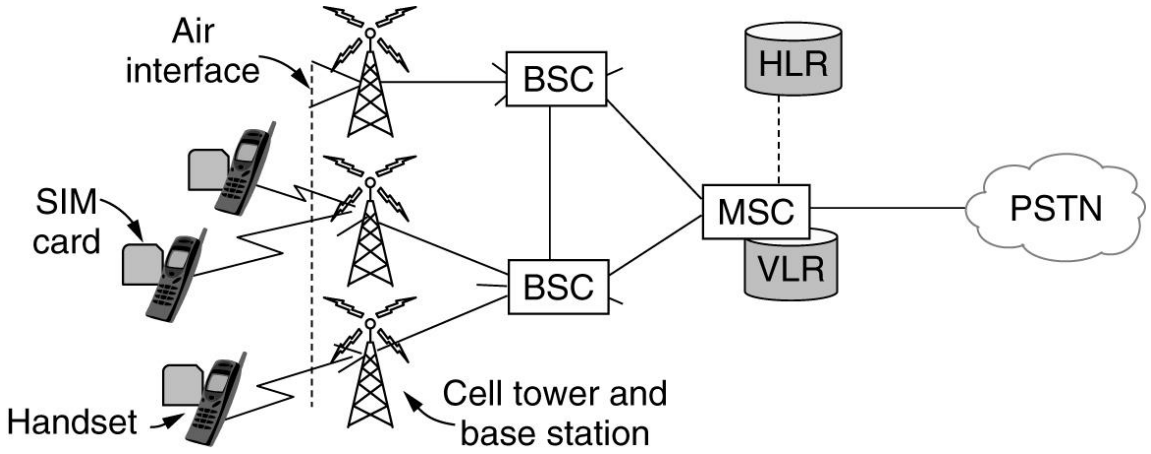
Second-Generation (2G) Technology: Digital Voice

- Digital advantages
  - Provides capacity gains by allowing voice signals to be digitized and compressed
  - Improves security by allowing voice and control signals to be encrypted
  - Deters fraud and eavesdropping, whether from intentional scanning or echoes of other calls due to RF propagation
  - Enables new services such as text messaging
- Three systems developed
  - D-AMPS (Digital Advanced Mobile Phone System)
  - GSM (Global System for Mobile communications)
  - CDMA (Code Division Multiple Access)

Cellular Networks

Second-Generation (2G) Technology: Digital Voice

- GSM: The Global System for Mobile Communications
  - SIM: The mobile itself is now divided into the handset and a removable chip with subscriber and account information called a **SIM** card, short for Subscriber Identity Module
    - SIM card activates the handset and contains secrets that let the mobile and the network identify each other and encrypt conversations
  - The mobile talks to cell base stations over an air interface that we will describe in a moment
    - Each cell base station connects to a BSC (base station controller)

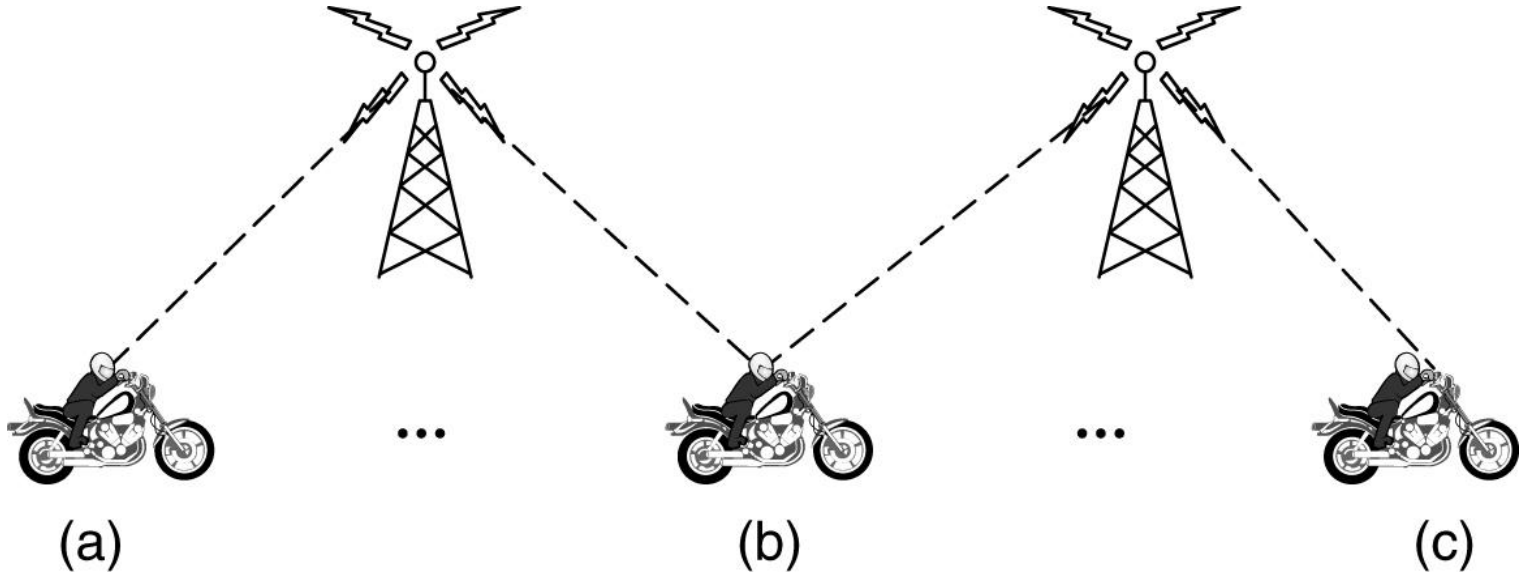


GSM mobile network architecture.

Cellular Networks

Third-Generation (3G) Technology: Digital Voice and Data

- Data traffic began to exceed voice traffic on the fixed network
- Each cell uses the same set of frequencies
- Soft handoff, in which the mobile is acquired by the new base station before the previous one signs off.



Soft handoff (a) before, (b) during, and (c) after.

Cellular Networks

Fourth-Generation (4G) Technology: Packet Switching

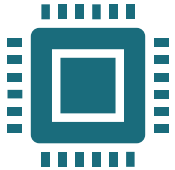
- Also called IMT Advanced
- Based completely on packet-switched technology
- EPC (Evolved Packet Core) allows packet switching
  - Simplified IP network separating voice traffic from the data network
  - Carries both voice and data in IP packets
  - Voice over IP (VoIP) network with resources allocated using the statistical multiplexing approaches
  - The EPC must manage resources in such a way that voice quality remains high in the face of network resources that are shared among many users

Cellular Networks

Fifth-Generation (5G) Technology

Two main factors

Higher data rates and lower latency than 4G technologies



Technology used to increase network capacity

Ultra-densification and offloading

Increased bandwidth with millimeter waves

Increased spectral efficiency through advances in massive MIMO (Multiple-Input Multiple-Output) technology

Network slicing feature

Lets cellular carriers create multiple virtual networks on top of the same shared physical infrastructure

Can devote network portions to specific customer use cases

5G spectrum: three radio spectrum bands*

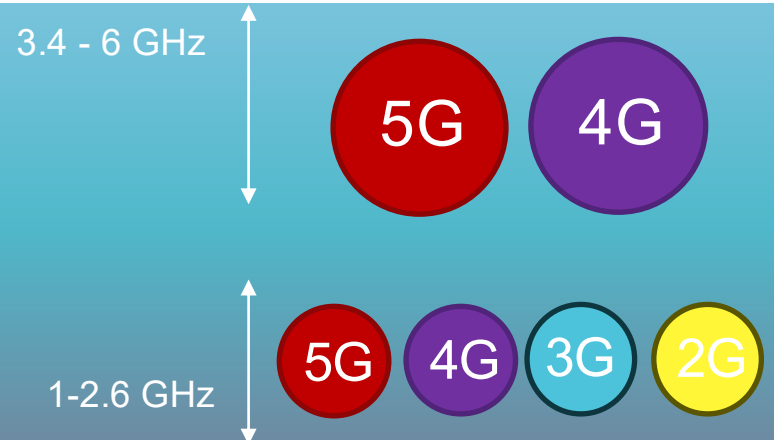
* No single, well-accepted ranges for "low", "mid" and "high"

High band frequencies: 25–66 GHz range (aka mmwave)

- 26 GHz, 40 GHz, 50 GHz, 66 GHz bands popular
- short distances (< mile), high speeds (<3 Gbps)
- line of sight transmission: poor penetration of trees, buildings, ...

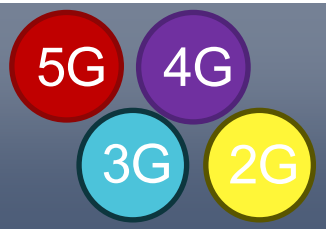
Mid-band frequencies: 1 - 6 GHz ranges

- balance distances (~5 miles ?) and transmission rates (100–900 Mbps)
- 1.8, 3.3 GHz to 3.8 GHz, 6 GHz bands popular



Low band frequencies: (< 1 GHz range)

- covers longer distances (10's of miles), but at lower speeds (50–250 Mbps)



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Next

- Transmission media
- From waveforms to bits
- Examples of communication systems
  - Wired LANs: Ethernet
  - Wireless access network
    - Sharing a wireless access channel: OFDMA, CSMA/CA
    - WiFi wireless LAN
    - Cellular networks
    - Bluetooth, Satellite, IoT wireless networks

Bluetooth (BT) overview

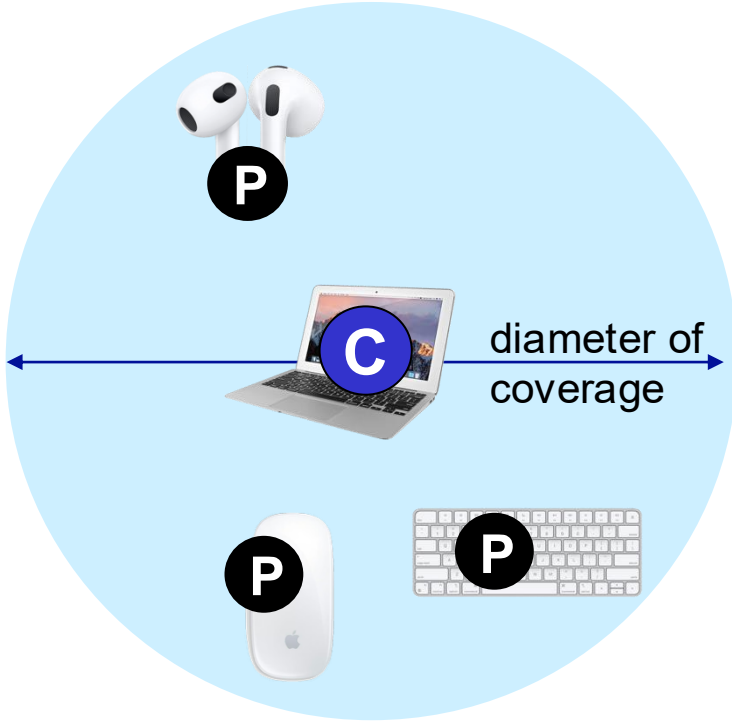
example of *wireless ad hoc network*: devices have no "infrastructure" (e.g., access point, base station) to connect to

- BT devices must find other BT devices, *organize themselves* into a network from scratch!
  - connect devices at link layer, providing channel allocation
  - addressing assignment
  - service discovery
  - application-to-application communication over Bluetooth network
  - security

An entirely new architecture and protocol stack (different from Internet) is needed!

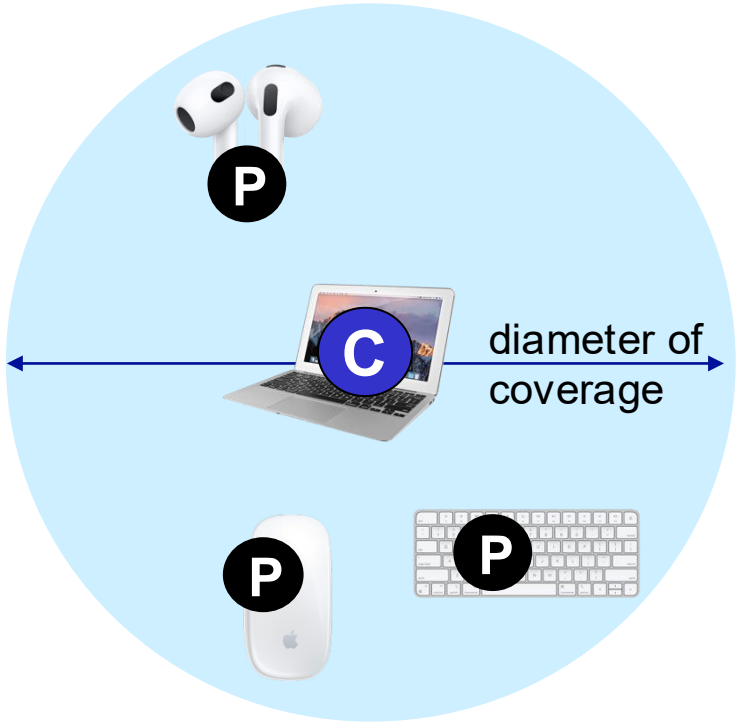
Bluetooth: overview

- Bluetooth network: piconet
- coverage: generally <10 m diameter
- no more than 8 devices per piconet
  - device initially forming network: *central* role
  - up to 7 more devices: *peripheral* role
- *communication only between central and peripheral node*
  - no direct peripheral-to-peripheral communication
- BT device has unique 48-bit address
- Operate in unlicensed ISM band: 2.4 GHz



Bluetooth basics: wireless channel

- operates in 2.4-2.5 GHz ISM radio band
  - Classic BT: 1 MHz bandwidth/channel, 79 channels, 2.1 Mbit network max rate
  - BLE: 2 MHz bandwidth/channel, 40 channels. 3 advertising, 37 data channels
- BT channel: TDM, 625 μsec slot length
- channel access via polling: central device advertises, grants channel access to peripherals in its BT network
- uses frequency hopping (form of "spread spectrum") transmissions

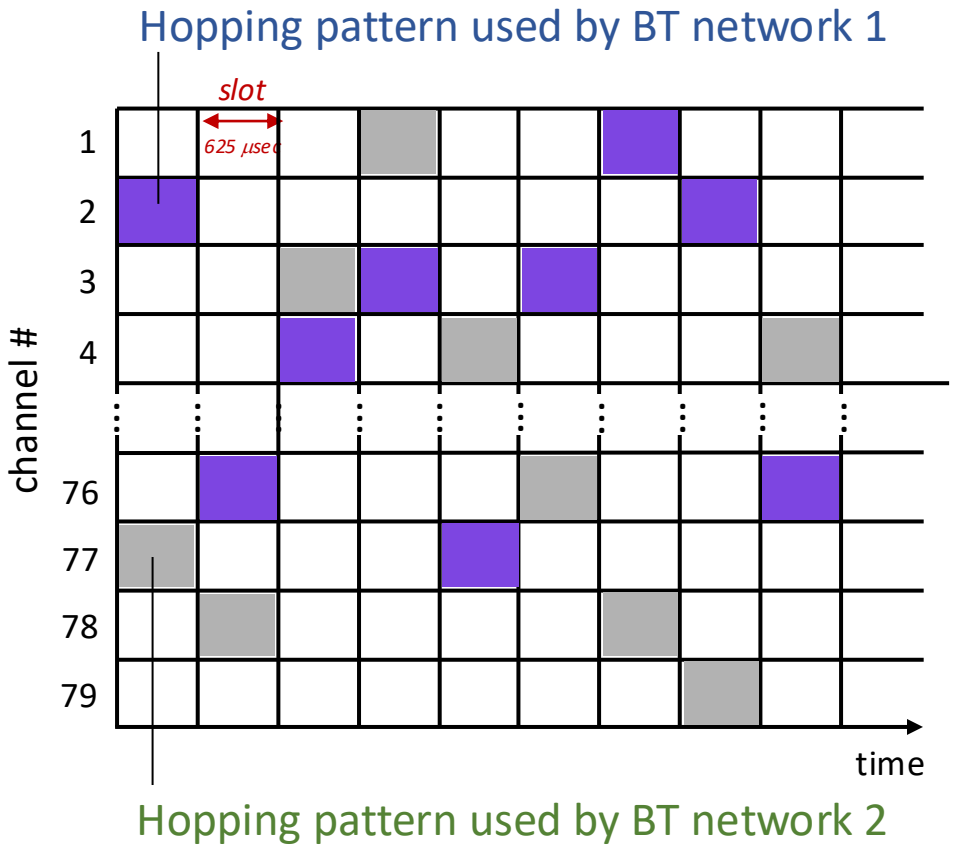


C device with central role

P device with peripheral role

Bluetooth channel: frequency hopping

- senders in BT network "hop" among 79 frequencies/channels
  - transmit on different frequency after each slot
  - hopping pattern known by all BT devices in same piconet
- different BT piconets (with different hop patterns) can exist in same space

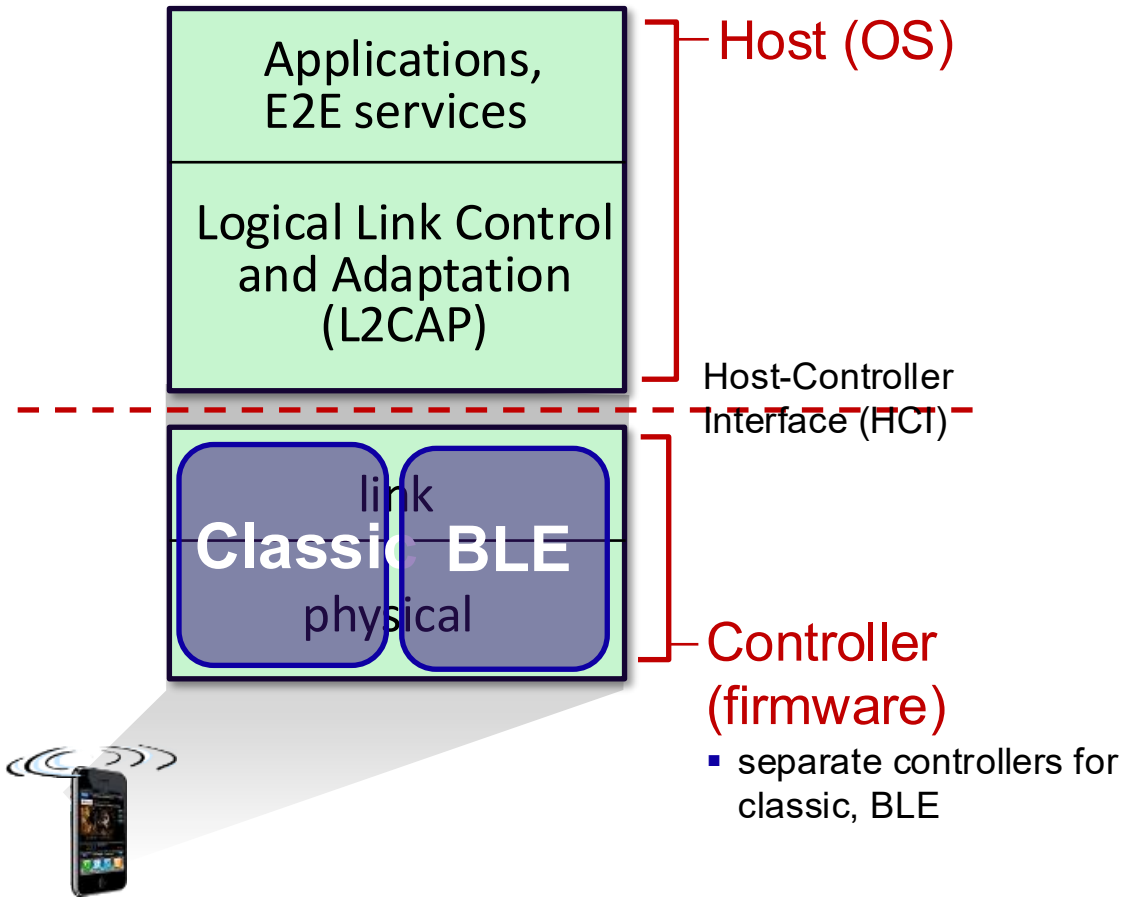


Q: Why hop?

A: minimize effects of interference:

- potentially many interfering transmitters in ISM
- If interfering device uses channel *x*, *x* occurs only occasionally in sequence
- BT frame sent on *x* (not received at receive due to interference), retransmitted on different frequency in next slot

Bluetooth architecture, protocol stack (simplified)

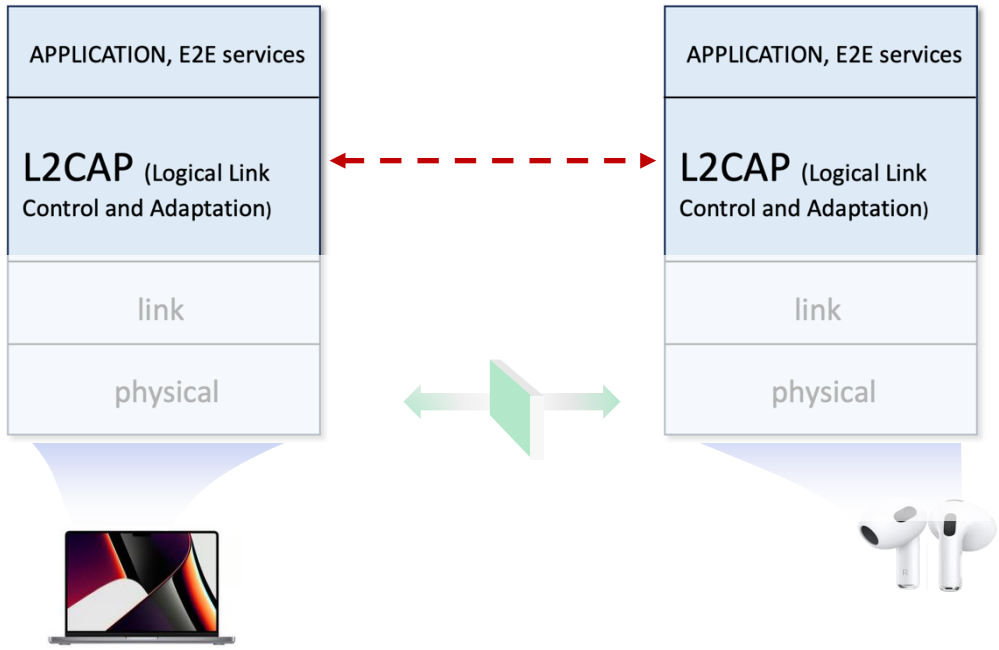


- Bluetooth stack *completely* different from Internet stack!
  - differences reflect BT's special purpose
- no "network," "transport" layer!
  - no routing in Classic BT (BLE adds managed flooding)
- layers not as conceptually well-defined as in Internet, 5G

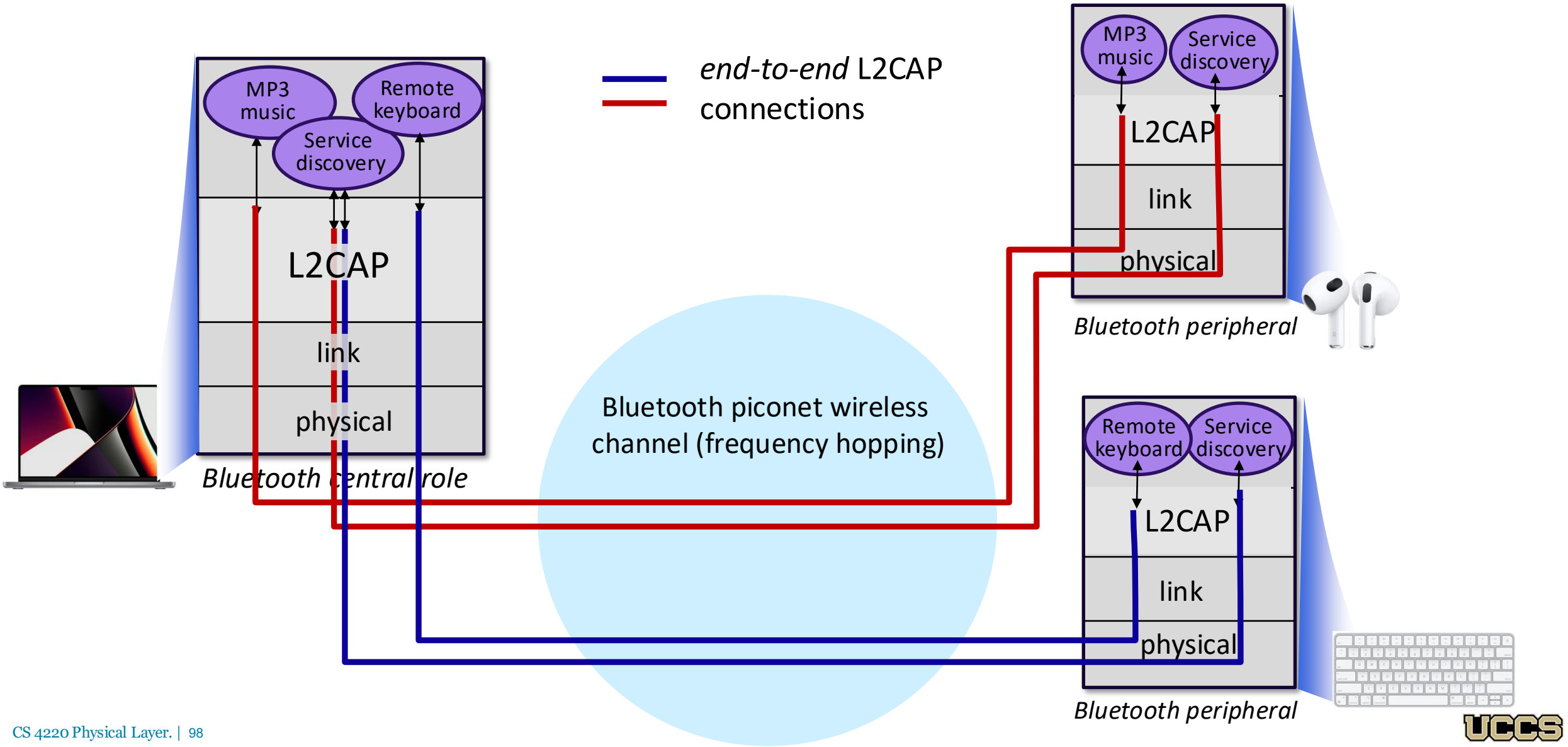
- host, controller structure deeply embedded in architecture

Logical Link Control, Adaptation (L2CAP) layer

- creation, management of end-end L2CAP channels *between two devices*
  - channels for E2E application/user data, or higher-level services
  - reliability, flow control, segmentation
- L2CAP channels types:
  - connection-oriented, asynchronous (ACL)
  - connectionless, asynchronous (ACL)
  - synchronous (eSCO), e.g., for periodic audio app)



Bluetooth piconet and L2CAP connections



Communication Satellites

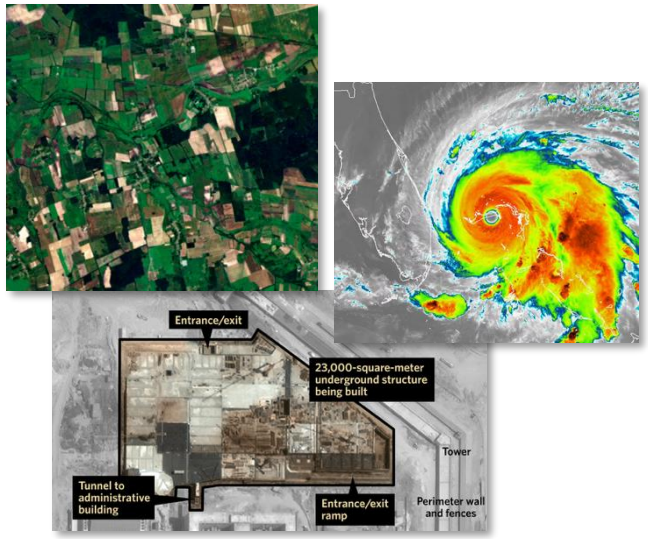
- A satellite is a relay station in space that receives signals from one point on Earth and retransmits them to another.
- Uses microwave frequencies (GHz range).

- Why do we need satellites?
  - Long-distance communication
  - Mobility support
  - Special applications: navigation, earth observation, emergency communication
  - …

Satellite Applications

Sensing:

- environment: weather, land use, various human activity
- resolution: ~m/pixel



Broadcast:

- consumer: Direct to Home TV/video, radio (Dish, SiriusXM)
- business: content to many cable head ends
- GPS
- leverage broadcast: one send reaches many users

dish NETWORK

Internet:

- connectivity to unserved regions, alternative to wired Internet
- low latency over long distances
- access in airplanes

STARLINK

Fly-Fi
CONNECTED BY Viasat

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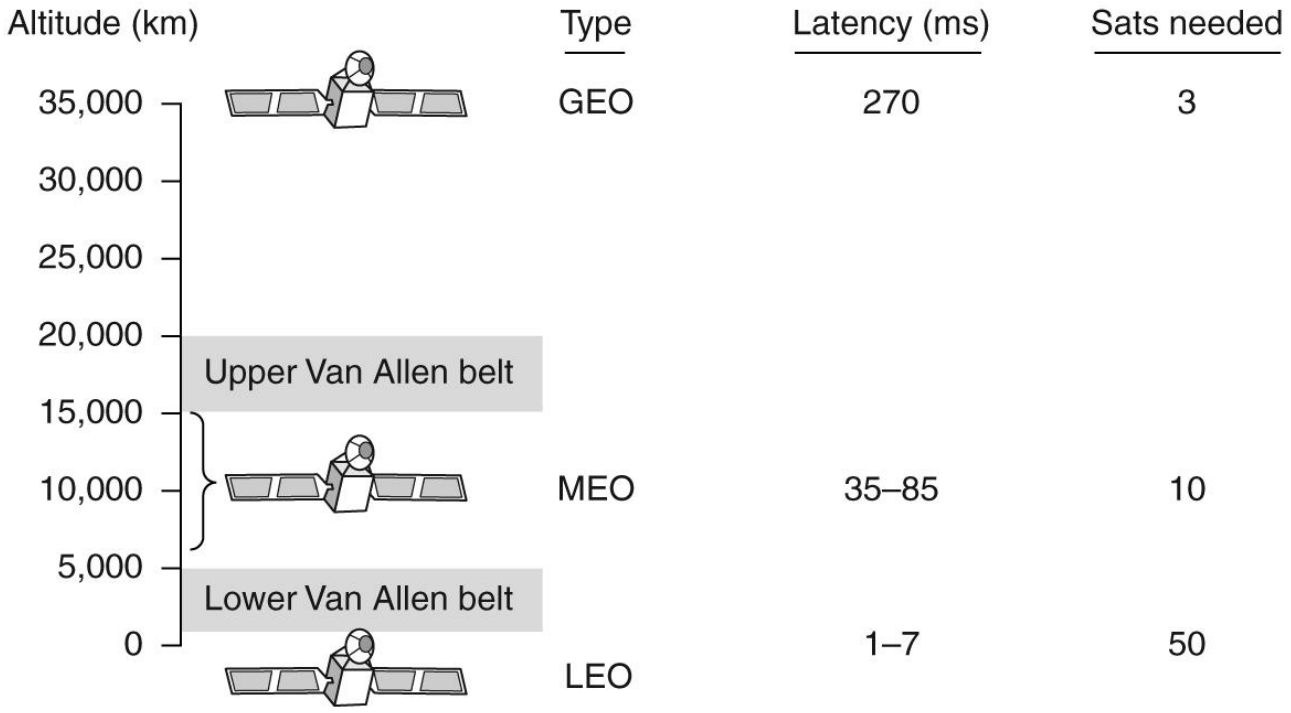
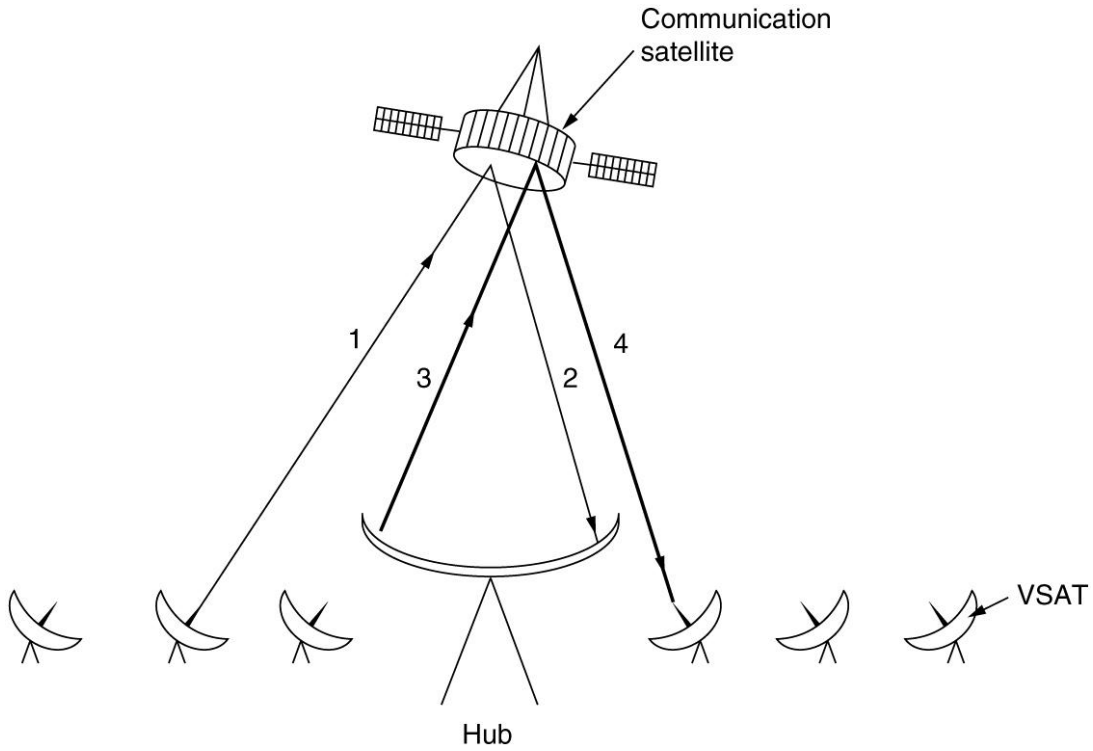
Communication Satellites

- Communication satellites and some of their properties, including altitude above the earth, round-trip delay time, and number of satellites needed for global coverage.
  - Geostationary Satellites (GEO)
  - Medium-Earth Orbit Satellites (MEO)
  - Low-Earth Orbit Satellites (LEO)



Communication Satellites

Geostationary Satellites (GEO)



In many VSAT systems, the microstations do not have enough power to communicate directly with one another (via the satellite, of course). Instead, a special ground station, the hub, with a large, high-gain antenna is needed to relay traffic between VSATs.

Communication Satellites

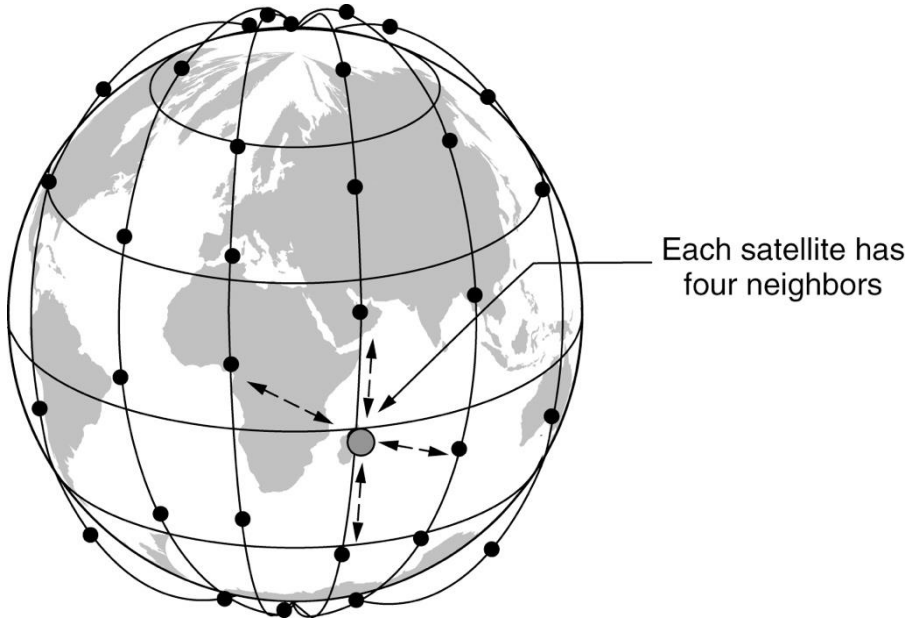
Medium-Earth Orbit Satellites (MEO)

- MEO (Medium-Earth Orbit) satellites
  - Found at lower altitudes - between the two Van Allen belts
  - Drift slowly in longitude (6 hours to circle the earth)
  - Must be tracked as they move through the sky
  - Have a smaller footprint on the ground
  - Require less powerful transmitters to reach them
- Used for navigation systems
- Example:
  - Constellation of roughly 30 GPS (Global Positioning System) satellites orbiting at about 20,200 km

Communication Satellites

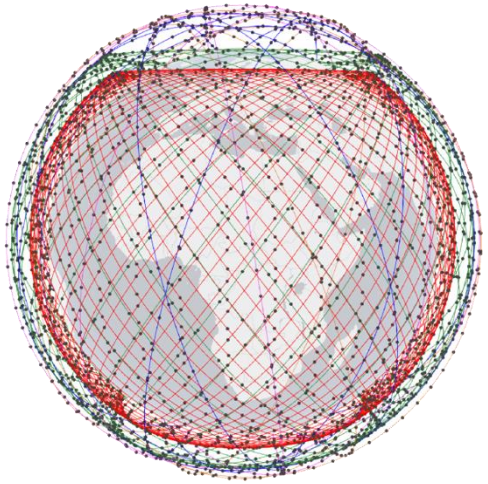
Low-Earth Orbit Satellites (LEO)

- Iridium: to provide worldwide telecommunication service using hand-held devices that communicate directly with the (66) Iridium satellites.

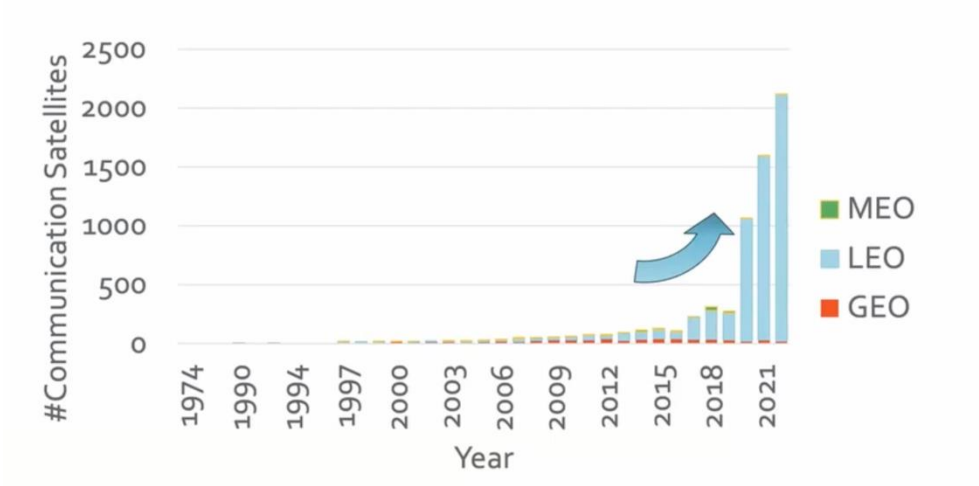


The Iridium satellites form six necklaces around the earth.

Satellites: why all the fuss?



Lots of (LEOS) satellites being launched

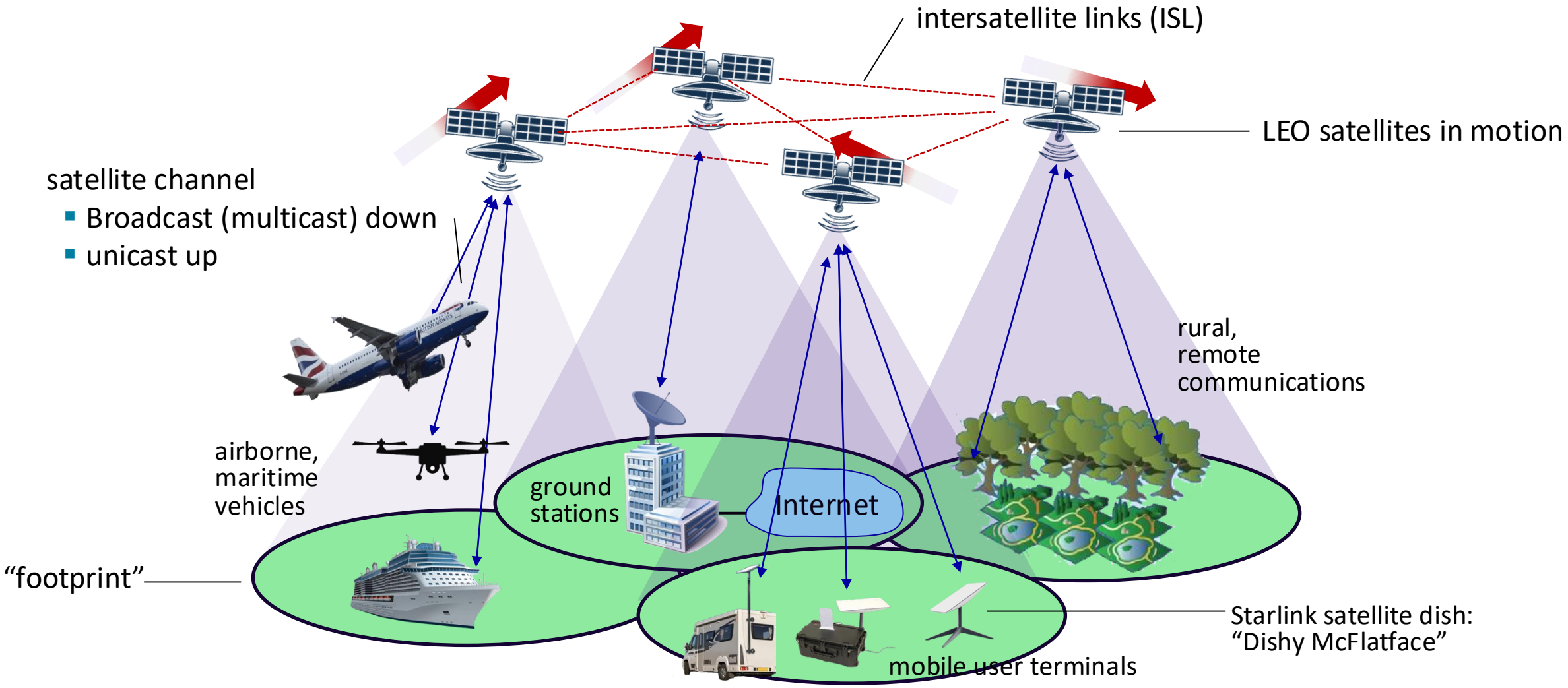


LEOS constellations

	# deployed (2025)	# planned	ISL planned?
Starlink	7,239	12,000 - 42,000	Yes
EutelSat Oneweb	648	716 – 6,372	No
Kuipers (Amazon)	27	3,236	?
Telesat	1	298 - 1671	Yes

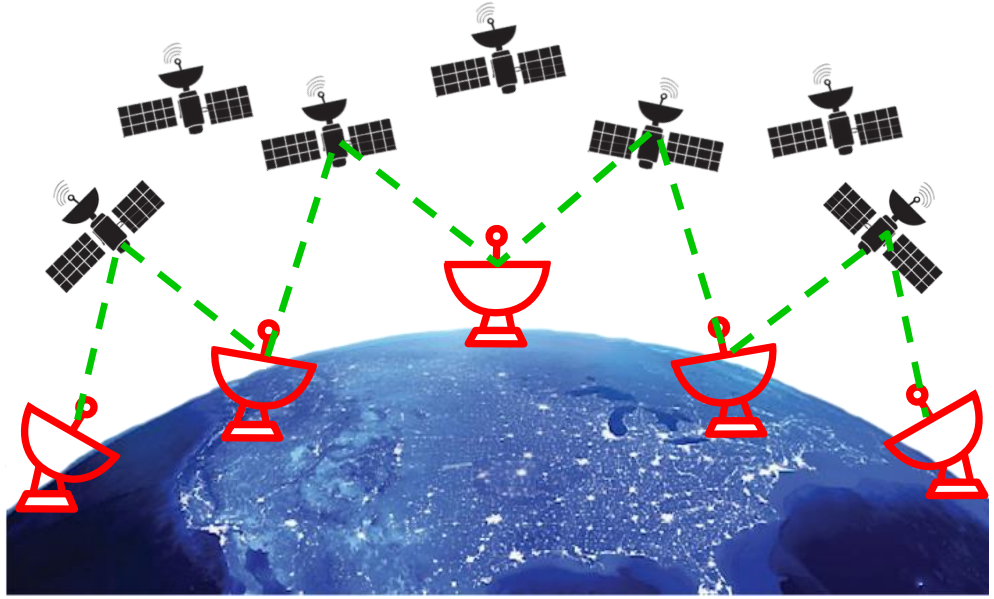
Sources: A. Raman, LEO Satellite Mega Constellations, networkingchannel.eu;
N.Pachler et al., An Updated Comparison of Four Low Earth Orbit Satellite Constellation Systems to Provide Global Broadband; company literature

Components of a LEO satellite network



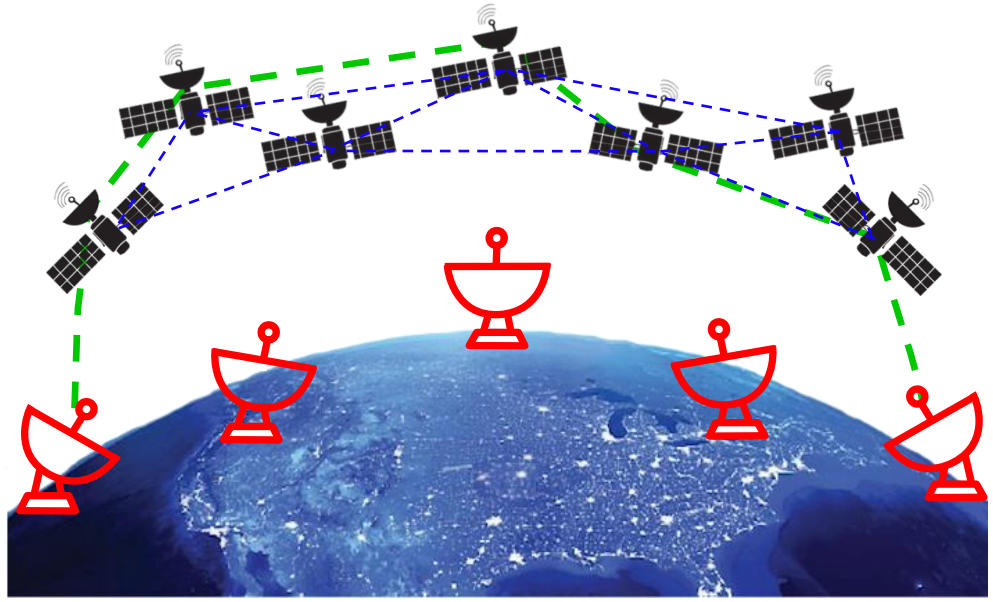
Satellite networking: a *link* or a *network?*

links in the sky



- single satellite hop between base stations
- AKA “bent pipe” architecture

network in the sky:



- multiple satellite hops between base stations
- routing among satellites

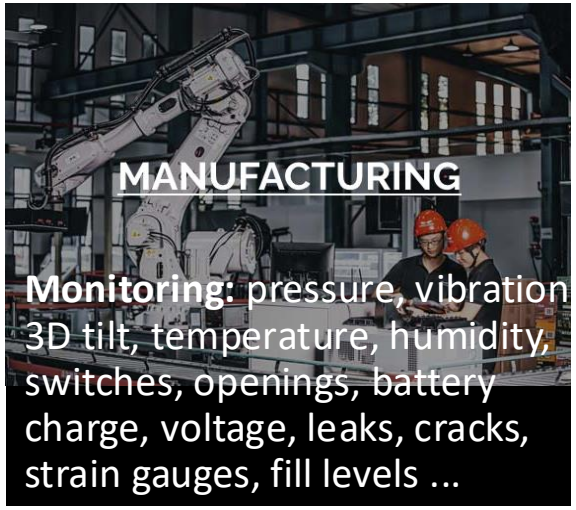
Starlink

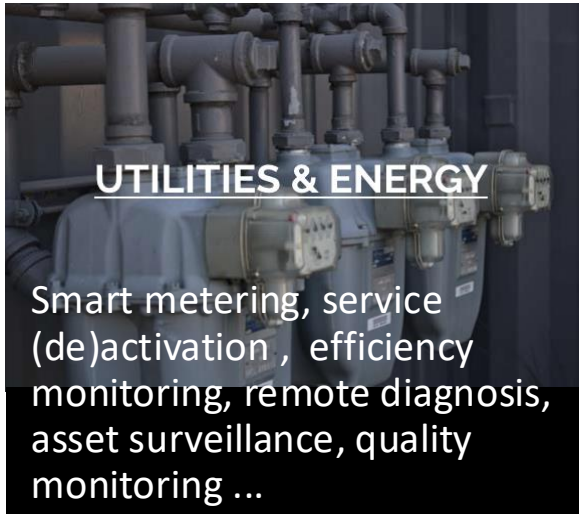
- April 2025: ~7,239 operational LEO satellites (planned: 12K, requesetd:30K)
  - first launches: 2019
  - three low-Earth-orbit orbital shells, at 525, 530, 535 km
  - satellites: 500 – 2700 lbs

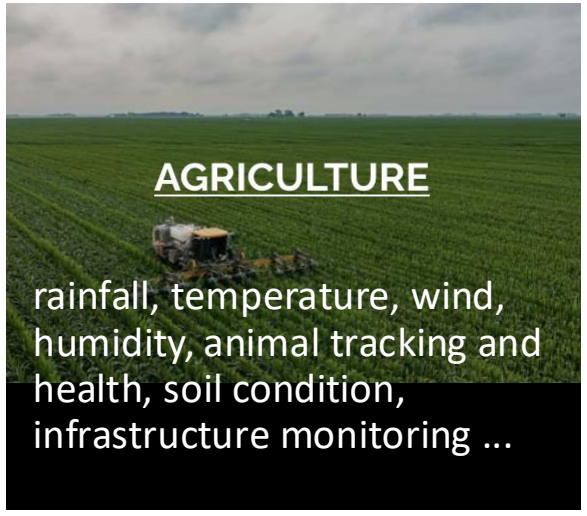
60 Starlink satellites stacked together before deployment on 24 May 2019

- services:
  - Internet service: 4M subscribers in Sept 2024 (residential US: $120/mo)
  - service in Ukraine (terrestrial networks damaged)
  - 2024: testing direct-to-smartphone tests would use cellular spectrum from SpaceX's U.S. mobile partner T-Mobile

IoT: many, many use cases!







.... and there's many more!

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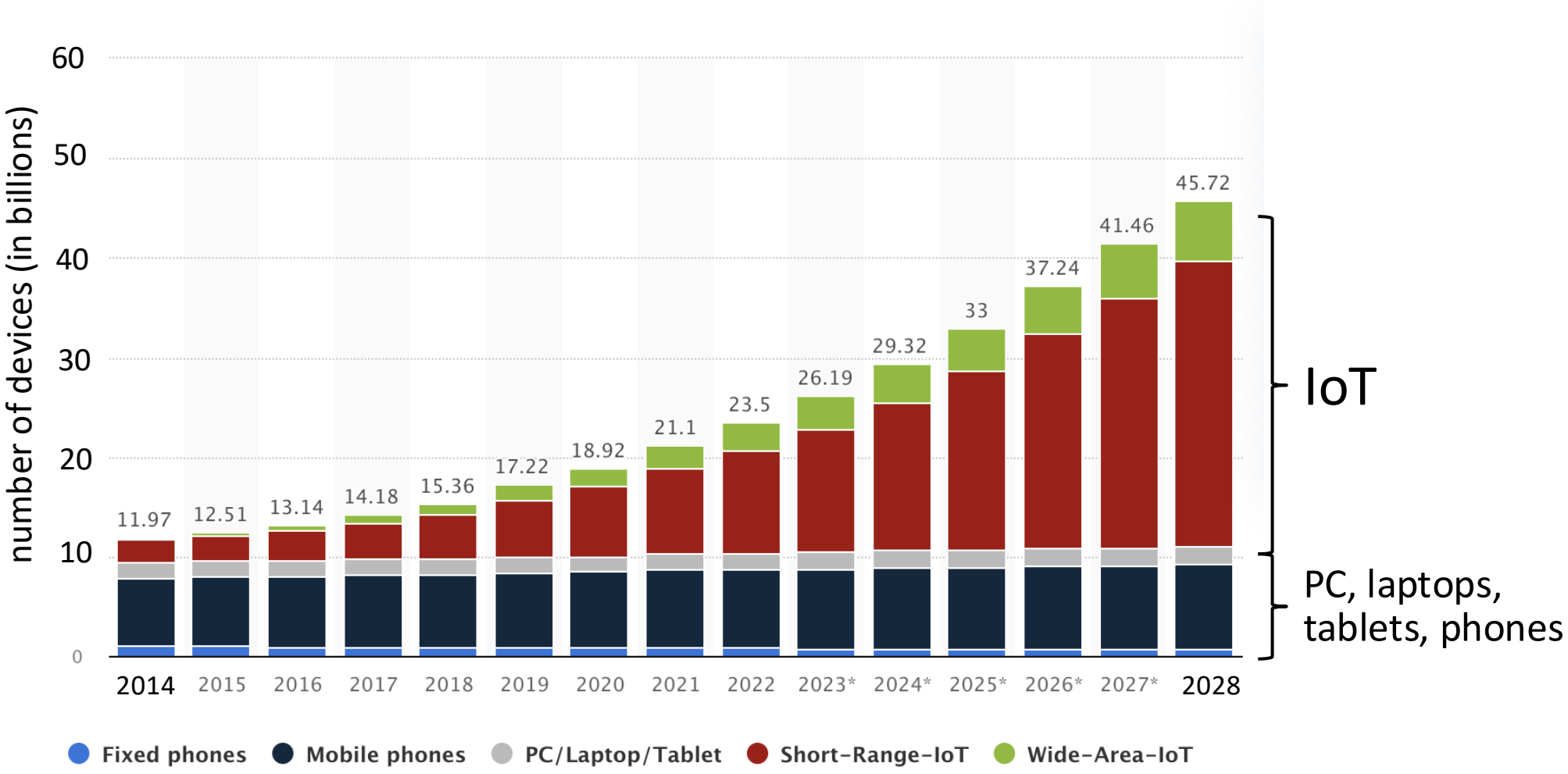
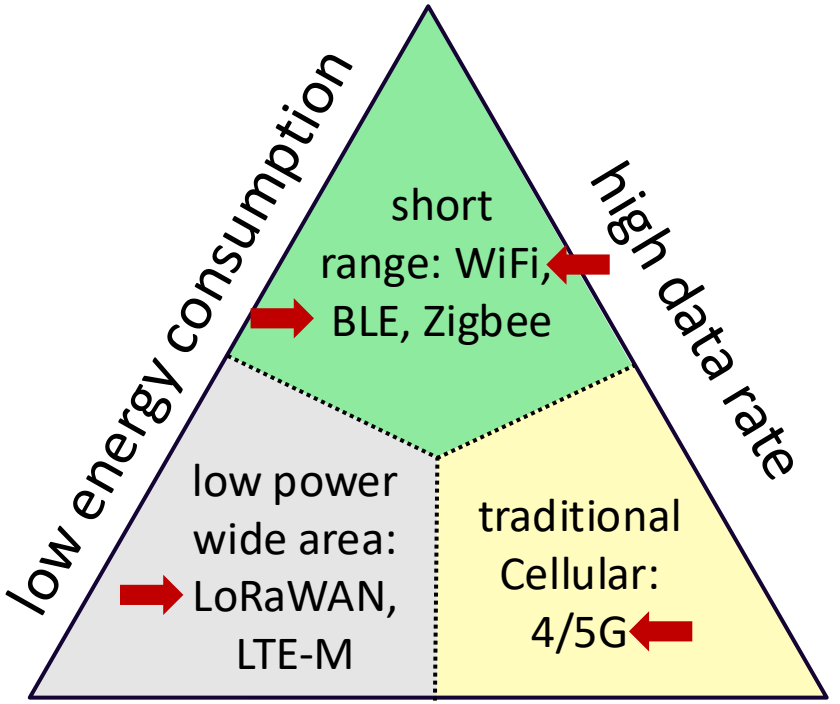
Lots of connected IoT devices, and more soon!



https://www.statista.com/statistics/512650/worldwide-connected-devices-amount/

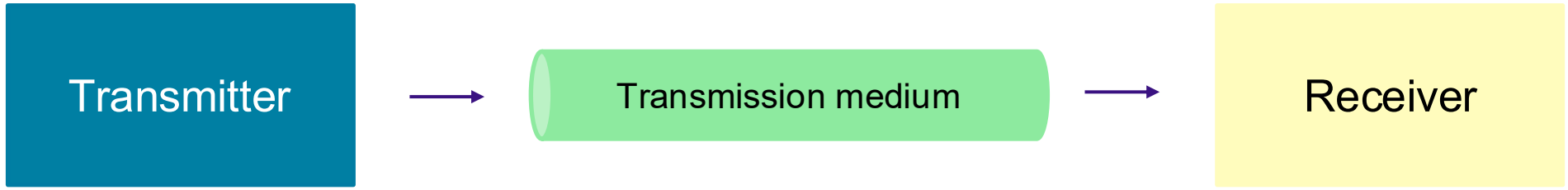
IoT communication requirements

- wireless
- distance: from meters to kilometers
- data rate: 100's bps when active (metering) to ~1 Mbps (video surveillance)
- energy: always a consideration
  - up ~10 years without external power
  - local energy harvesting



IoT technical tradeoffs

Summary: A Transmission System



- Transmitter
  - Converts information into signal suitable for transmission
  - Injects energy into communications medium or channel
    - From waves to bits
- Transmission medium
  - Guided transmission media
    - Twisted pair
    - Coaxial cable
    - Optic fiber
  - Unguided transmission media
    - Radio
    - Microwave
    - Infrared
- Receiver
  - Receives energy from medium
  - Converts received signal into form suitable for delivery to user

- Examples of communication systems: Wired LANs: Ethernet, Cellular networks, Communication satellites

Summary

- Transmission media
- From waveforms to bits
- Examples of communication systems
  - Wired LANs: Ethernet
  - Wireless access network
    - Sharing a wireless access channel: OFDMA, CSMA/CA
    - WiFi wireless LAN
    - Cellular networks
    - Bluetooth, Satellite, IoT wireless networks