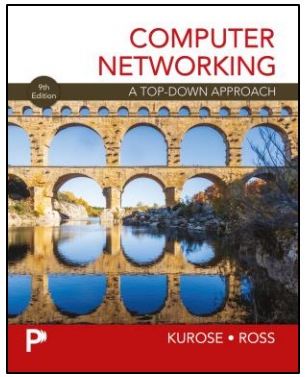


CSC 361
Computer Networks
WLAN and Physical Layer (Chapter 7)

Wenjun Yang

Summer 2026

Wireless and Mobile Networks: Overview

Chapter goals:

- understand principles of wireless networks:
  - physical layer: radio, influence on higher layers
  - access network: link-layer challenges/solutions in any wireless networks
  - core network: the "network" layer in a wireless network
  - user/device mobility: among access networks
  - application-specific wireless networks: Bluetooth, satellite, IoT
- wireless networks in practice:
  - WiFi
  - 5G (with a bit of 4G)
  - Bluetooth, satellite, IoT

For a more extensive treatment of wireless and mobile networks visit:

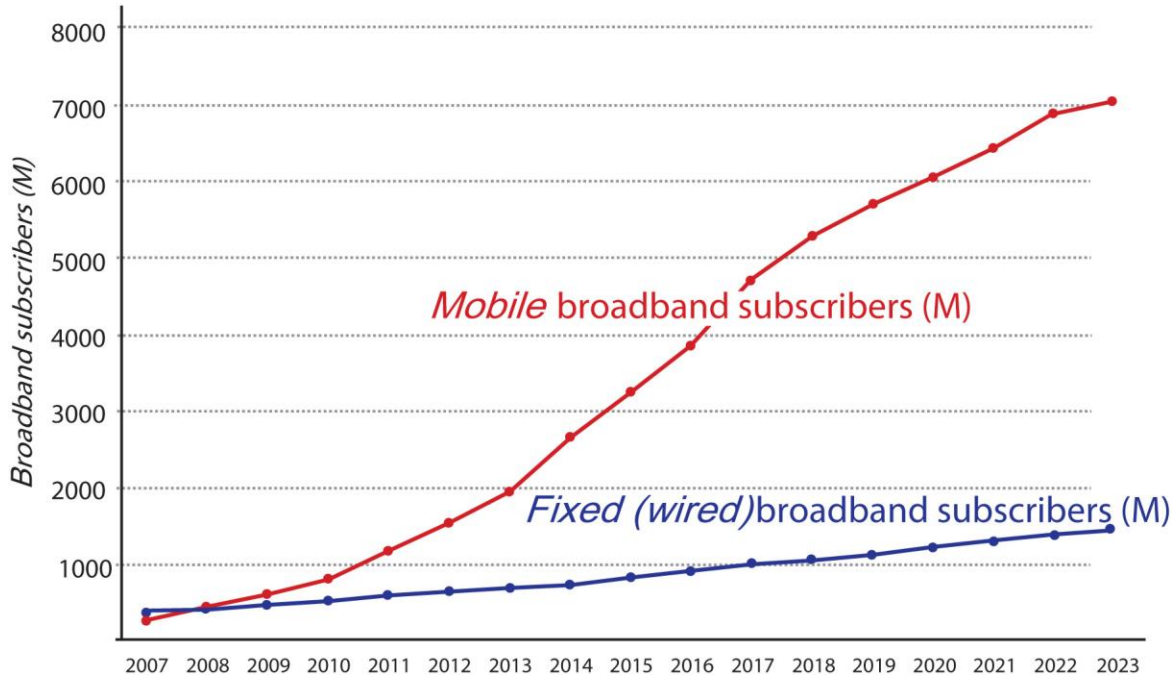
https://gaia.cs.umass.edu/wireless_and_mobile_networks

Chapter 7 Outline (1 of 10)

- introduction
- radio: the physical layer
- the wireless **access** network
  - principles, WiFi
- Satellite, IoT wireless networks

Wireless and Mobile Networks: 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



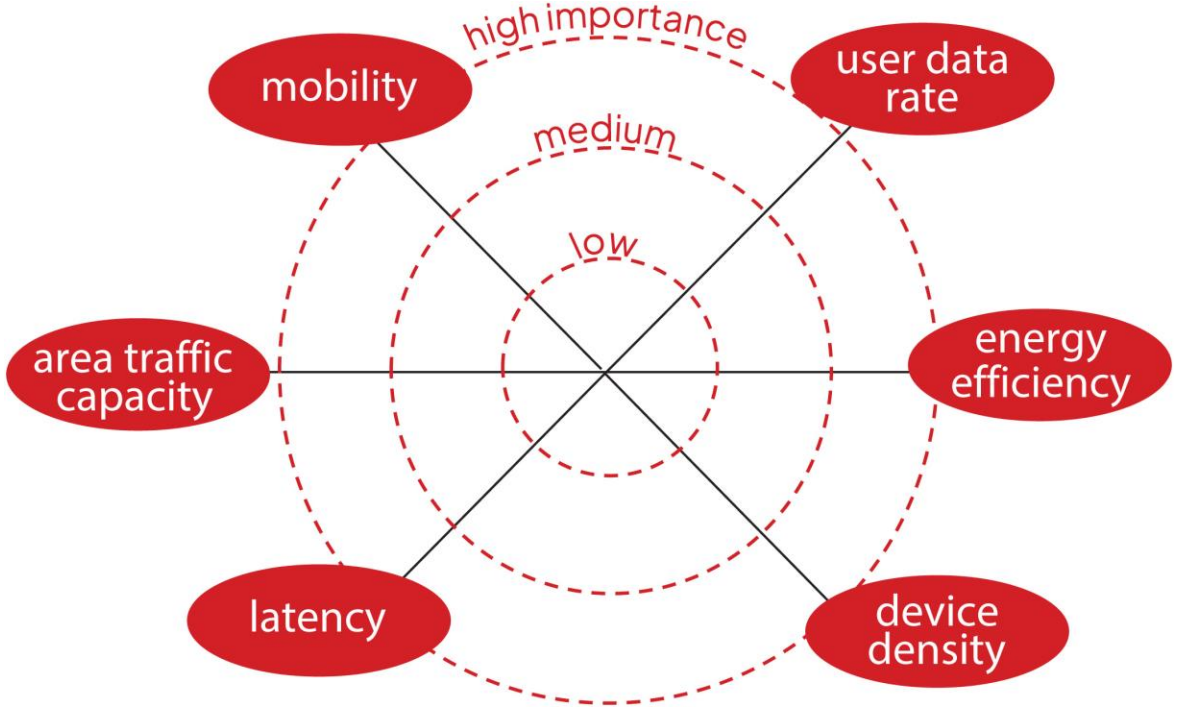
Data source: www.statista.com (1/25)

Wireless Applications their Needs

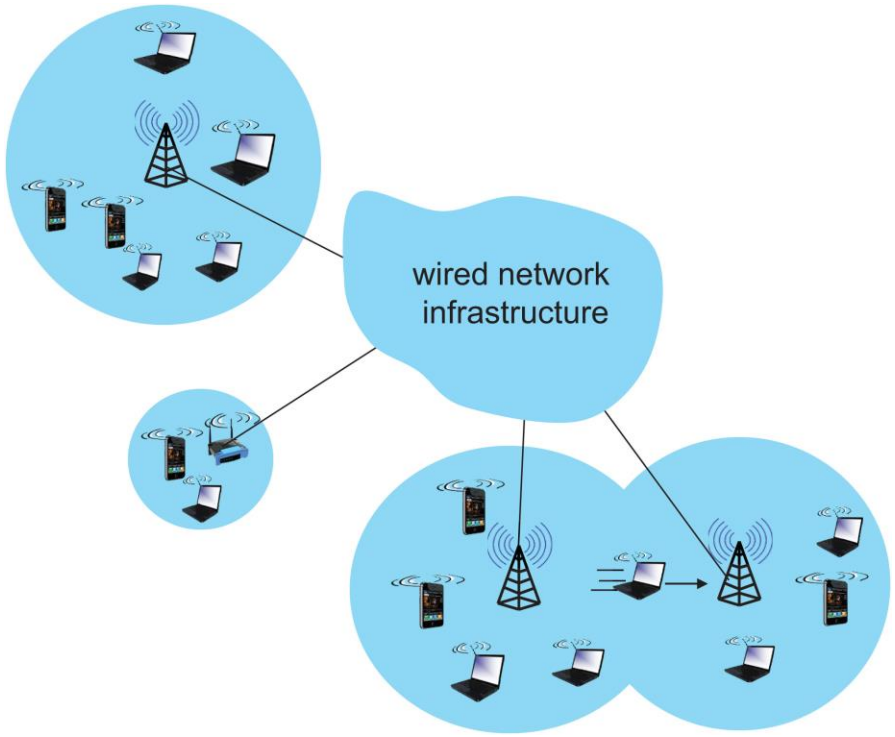
Six application areas :

- 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)

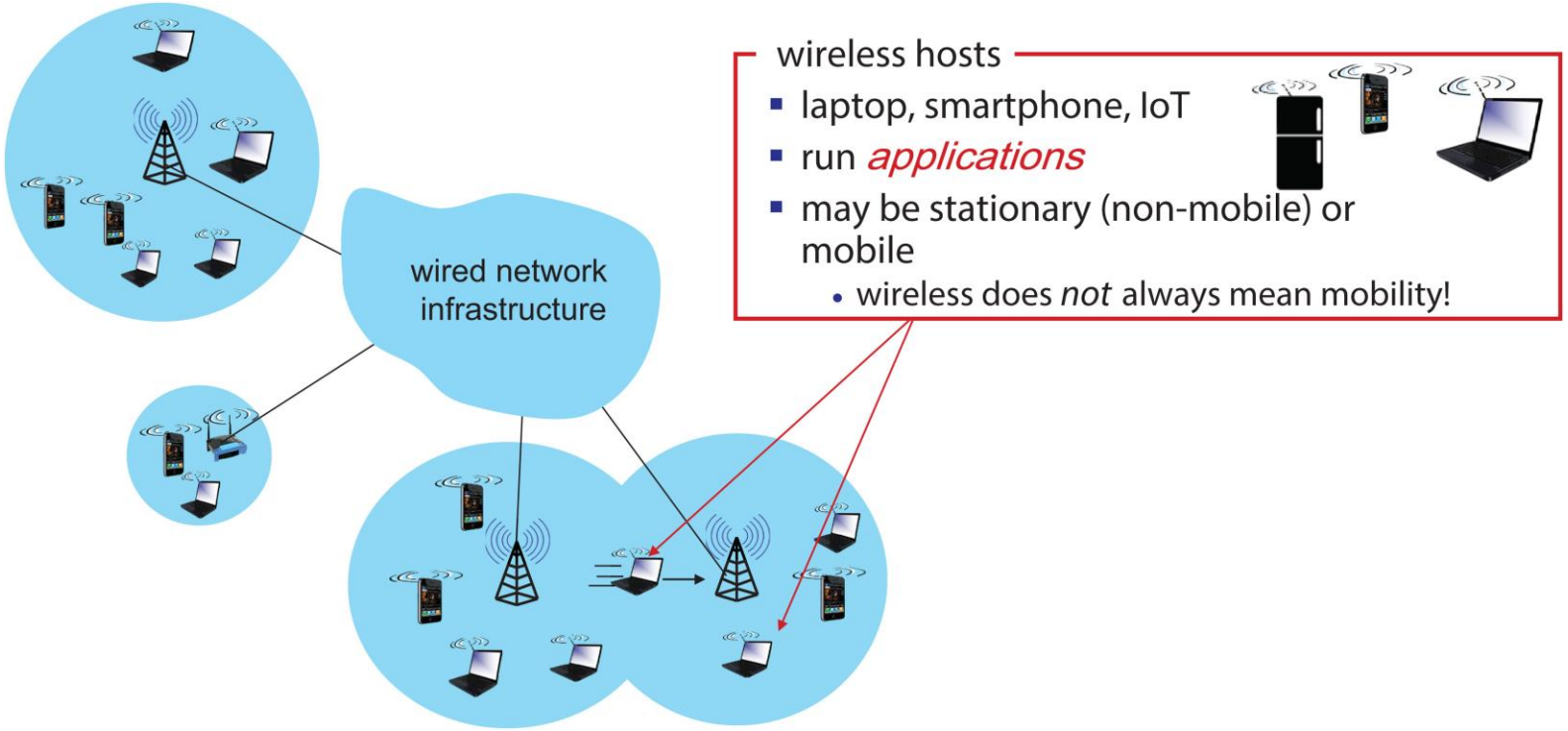
Application needs:



Elements of a Wireless Network (1 of 5)

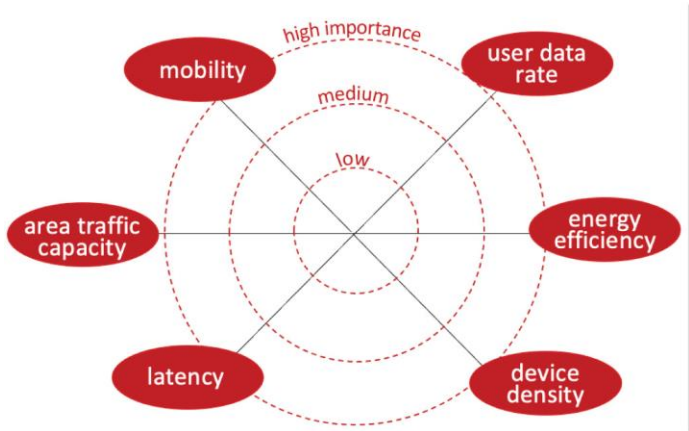


Elements of a Wireless Network (2 of 5)

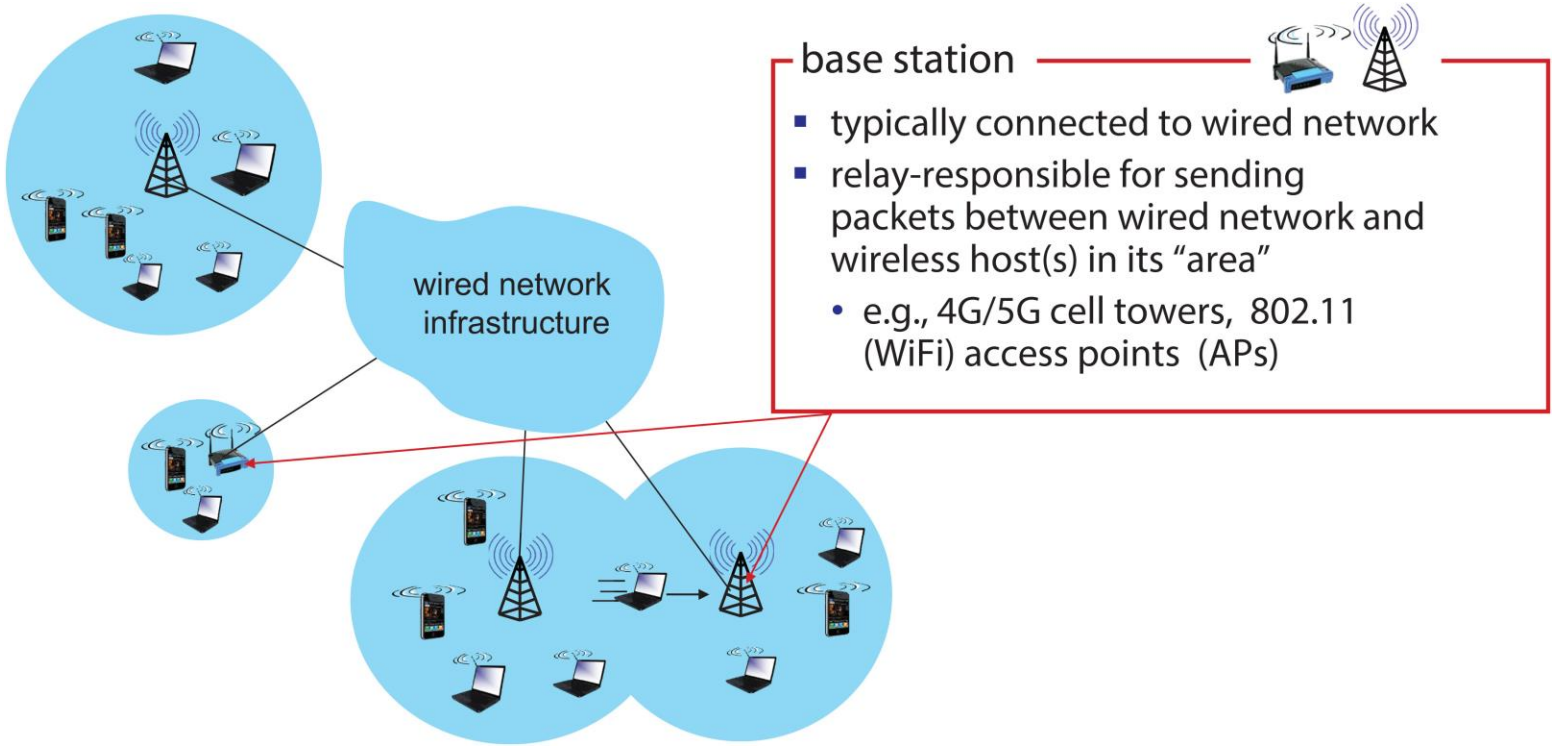


wireless hosts

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



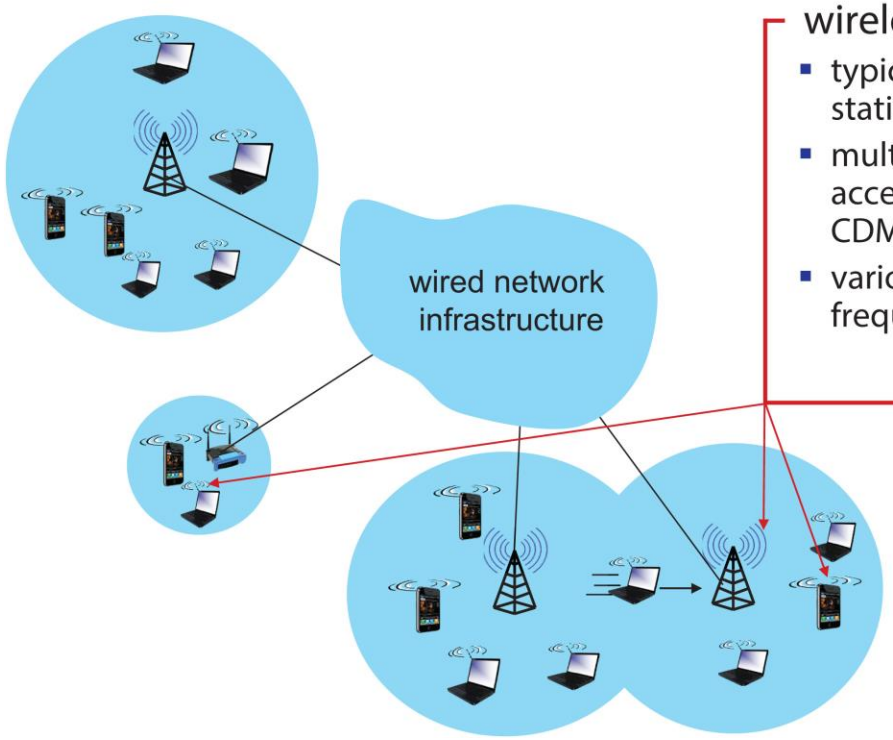
Elements of a Wireless Network (3 of 5)



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 (4 of 5)

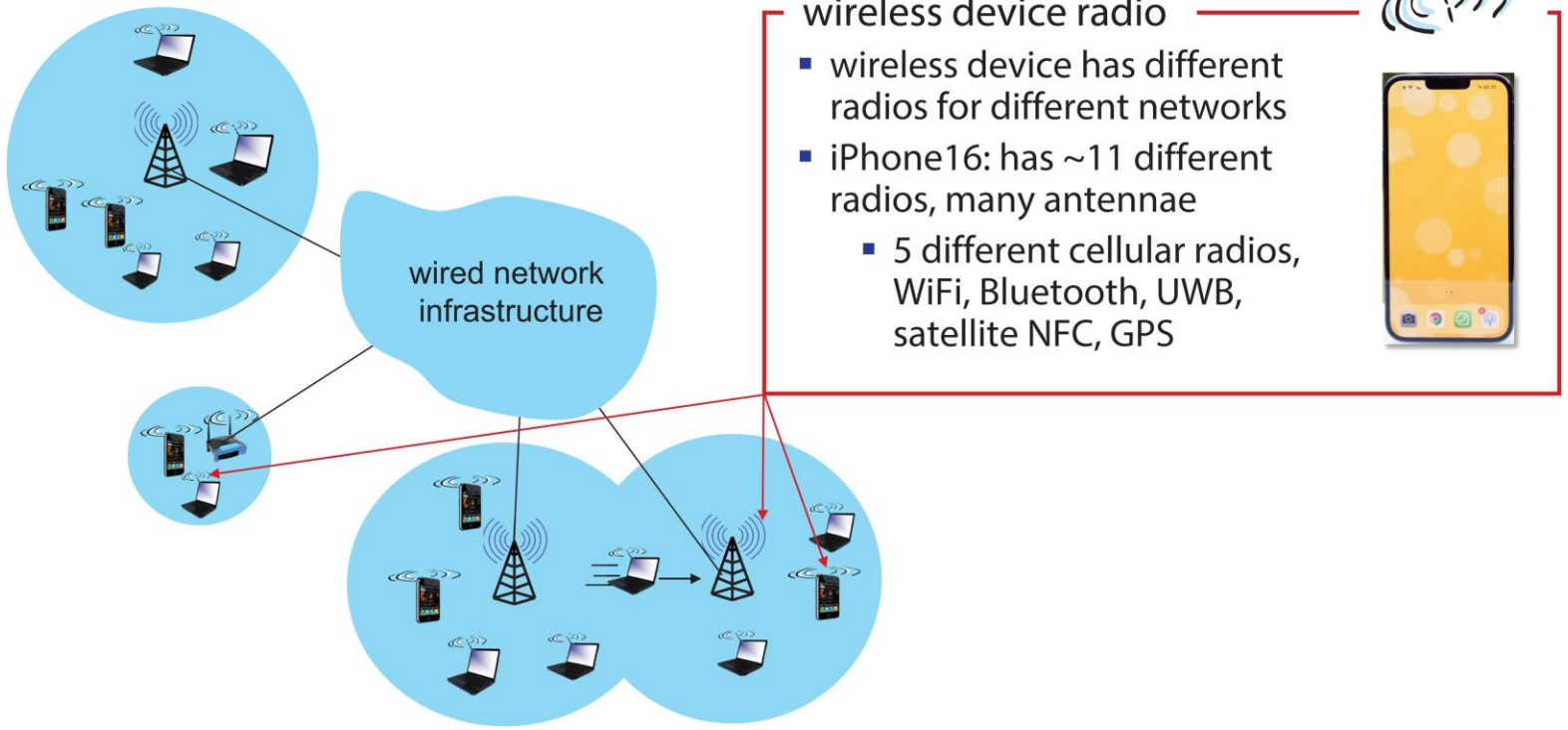


wireless link

- 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

Elements of a Wireless Network (5 of 5)

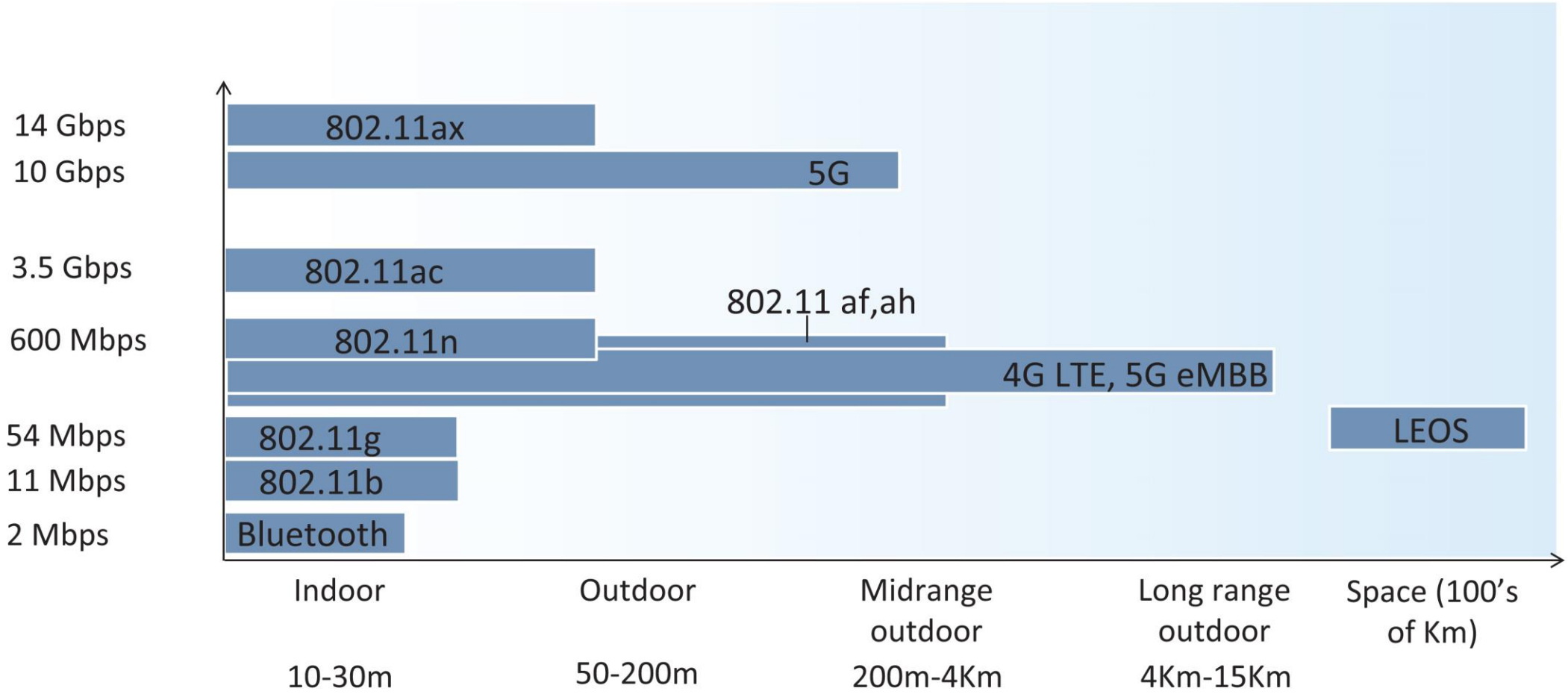


wireless device radio

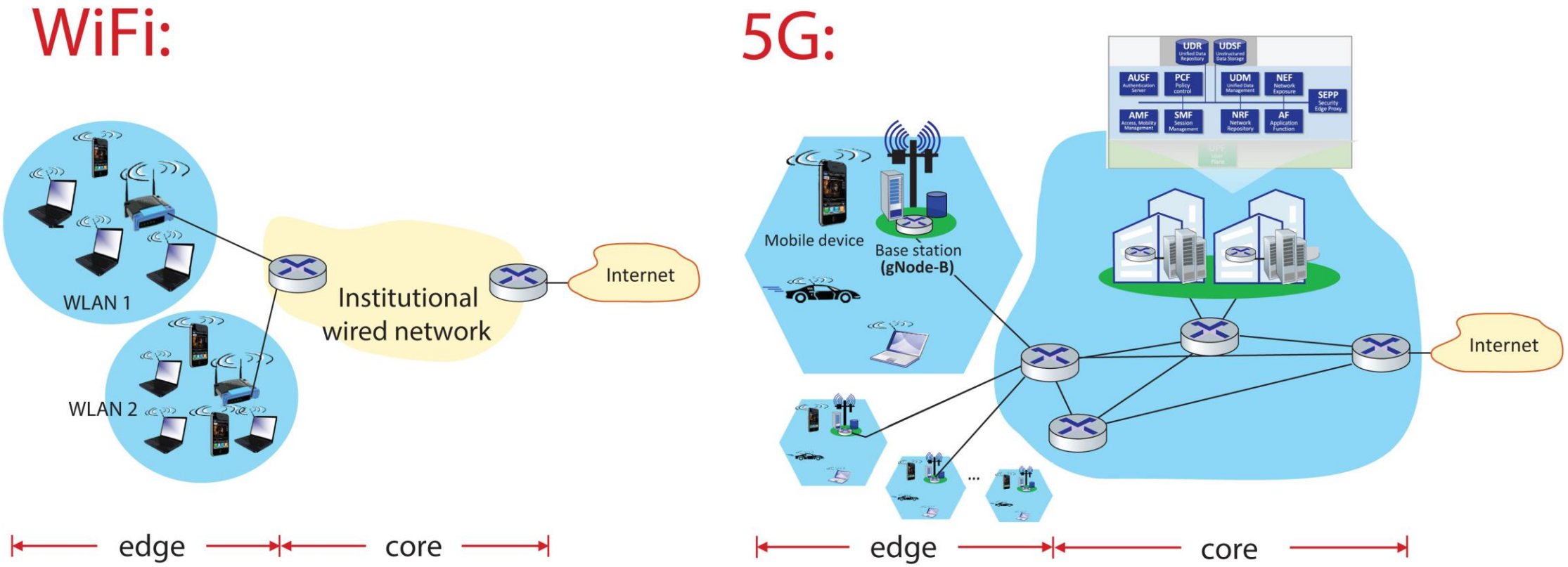
- wireless device has different radios for different networks
- iPhone16: has ~11 different radios, many antennae
  - 5 different cellular radios, WiFi, Bluetooth, UWB, satellite NFC, GPS

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

Characteristics of Selected Wireless Links



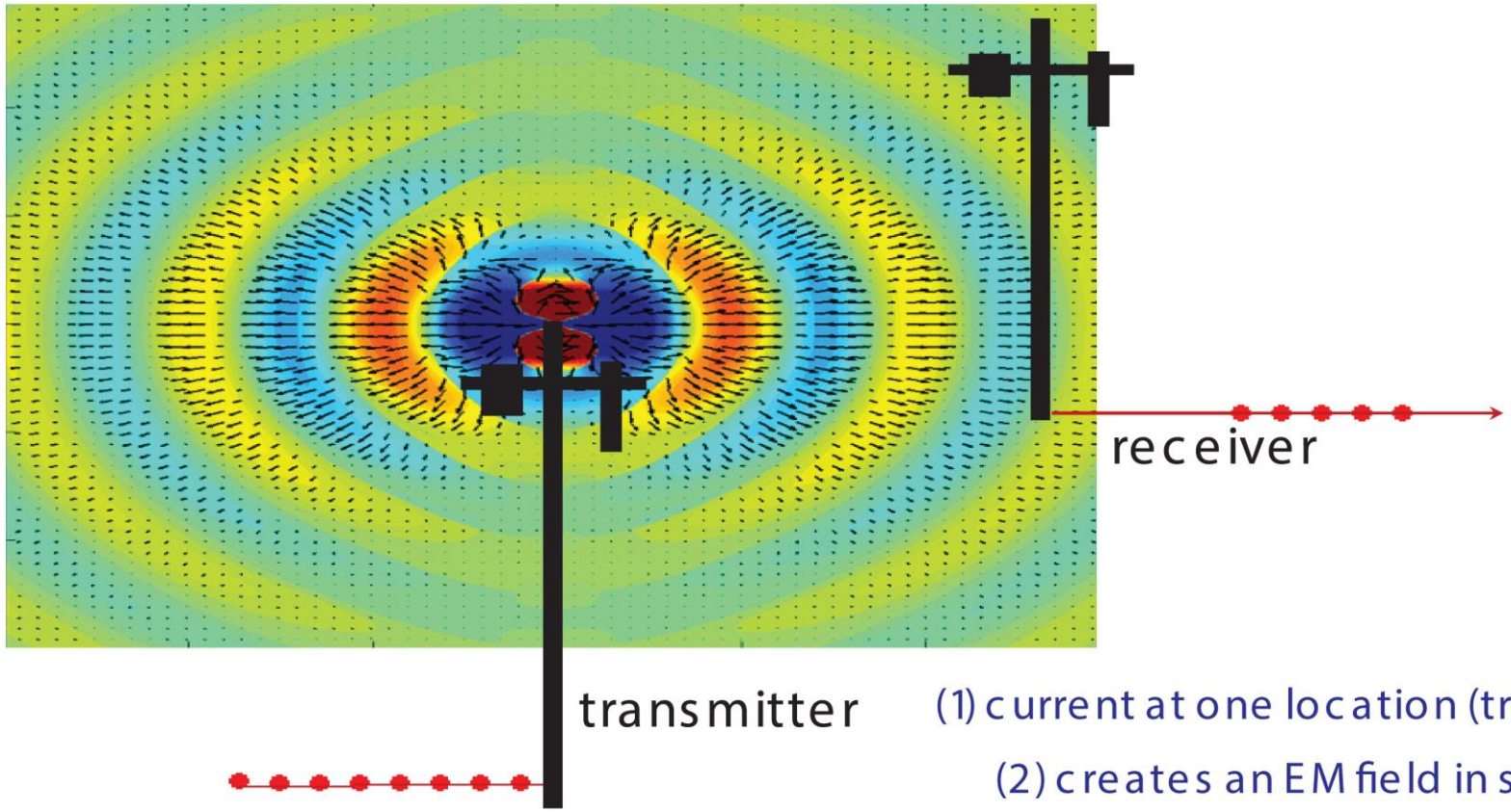
Wireless Networks: Edge and Core Networks



Chapter 7 Outline (2 of 10)

- introduction
- radio: the physical layer
  - radio principles
  - radio channels
  - radio spectrum
  - coding and modulation
- the wireless **access** network
- Satellite, IoT wireless networks

Electromagnetics: Enabling Communication

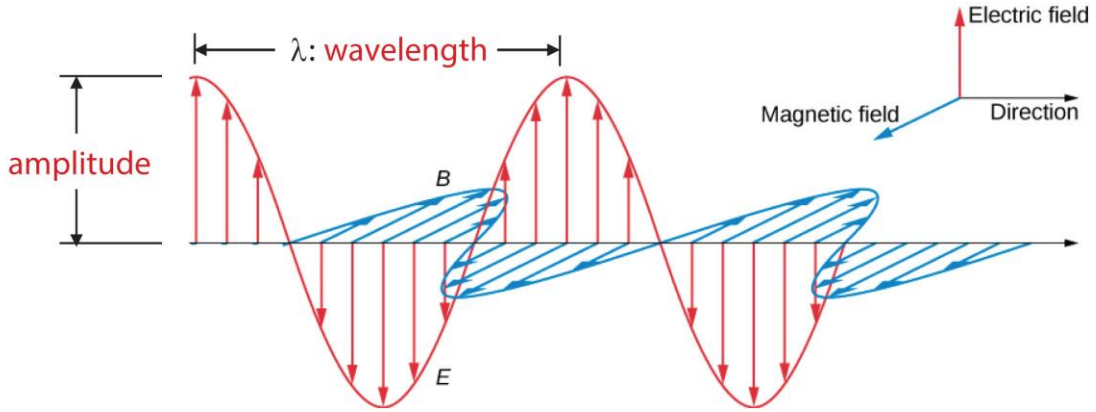


(1) current at one location (transmitter) ....

(2) creates an EM field in space ....

(3) induces a current at remote location (receiver)....

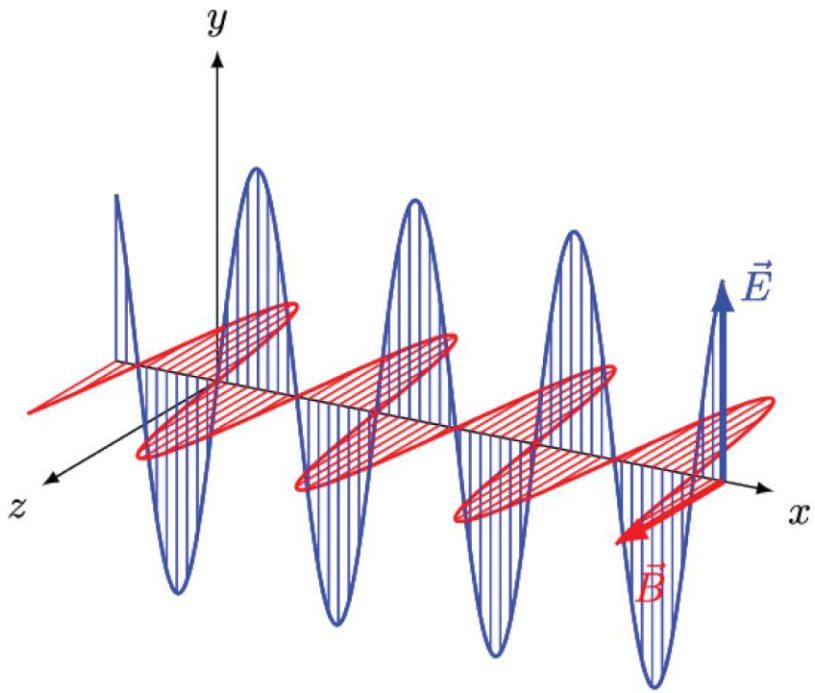
Radio Basics: Electromagnetic Waves



Electromagnetic wave has:

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

wave propagation:

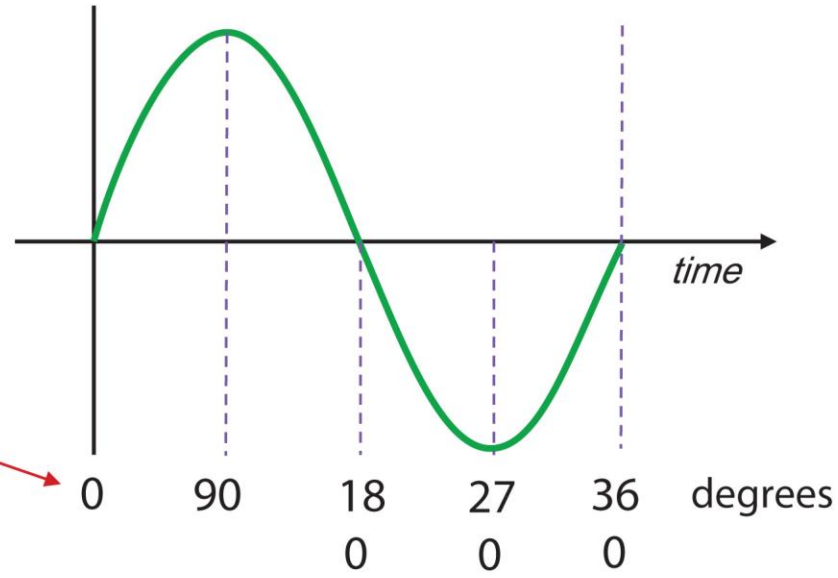


slide concept: S. Rangan (NYU)

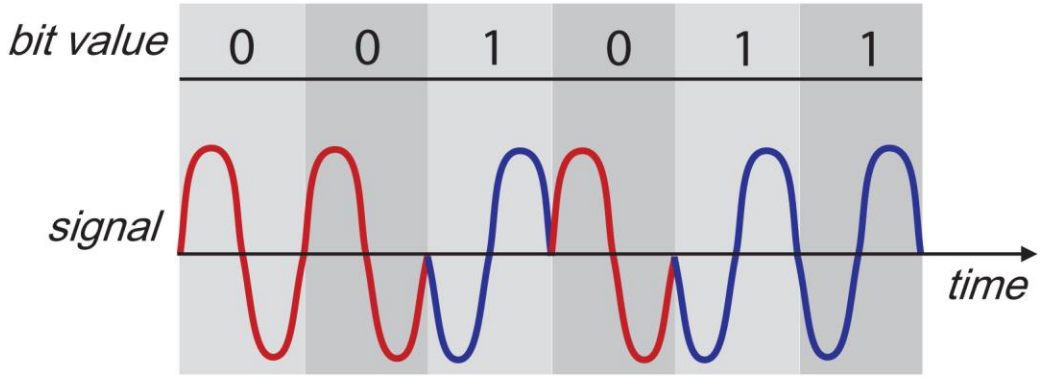
Radio Basics: Phase

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!)



Radio Signal Characteristics (1 of 2)

Power: antenna receive/transmit energy per unit time

- linear: measured in watts (or milliwatts)
- logarithmic: measured in decibels (db)

$$P_{dBm} = 10 \cdot \log_{10}\left(\frac{P_{mW}}{1mW}\right)$$

- example:

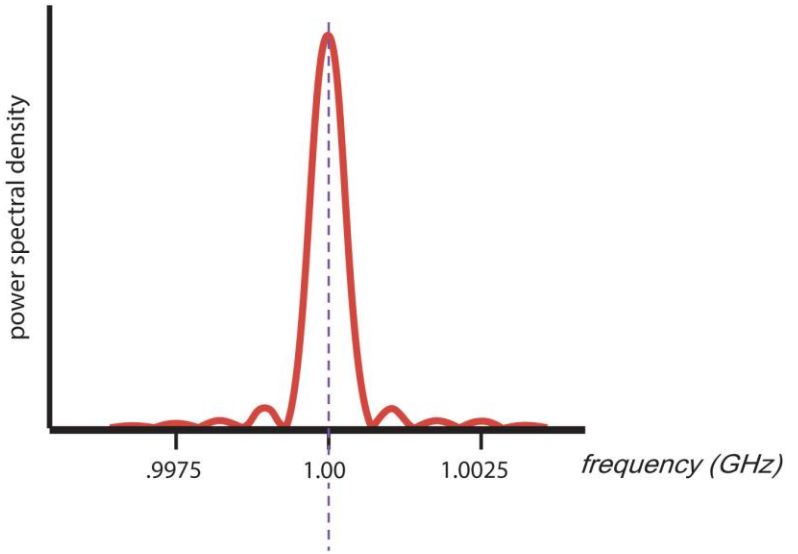
$P_{mW} = 250$ mW (typical max mobile transmit power)

$$P_{dBm} = 10 \cdot \log_{10}\left(\frac{250\,mW}{1mW}\right)$$

$$= 24 \text{ dBm}$$

Power spectral density:

- power present in signal as a function of frequency

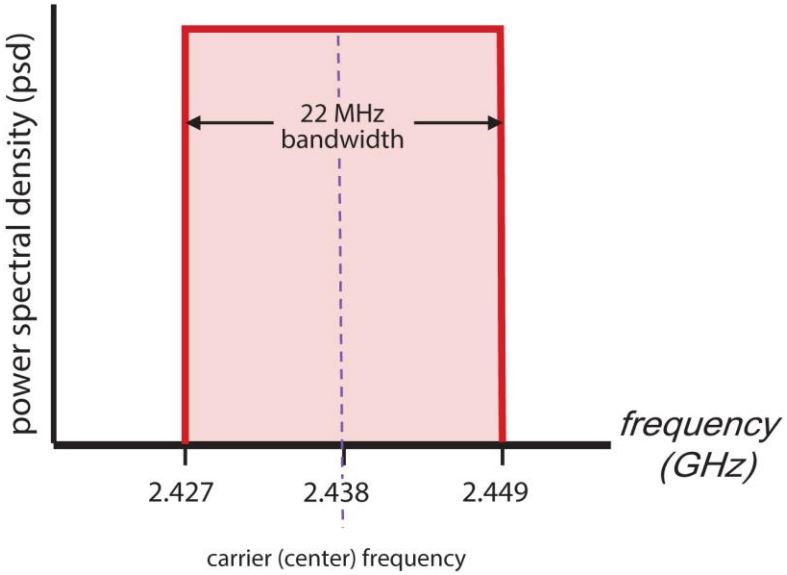


carrier (center) frequency

Radio Signal Characteristics (2 of 2)

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)



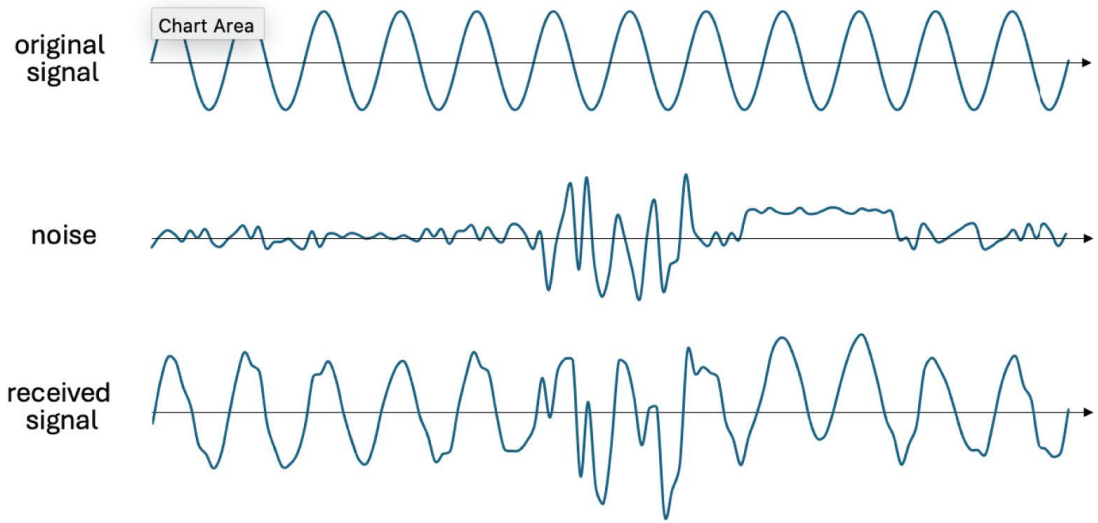
two meanings/usage of "bandwidth"

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

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)

Signals and Noise

- interference: other transmitters/EM radiaters in 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

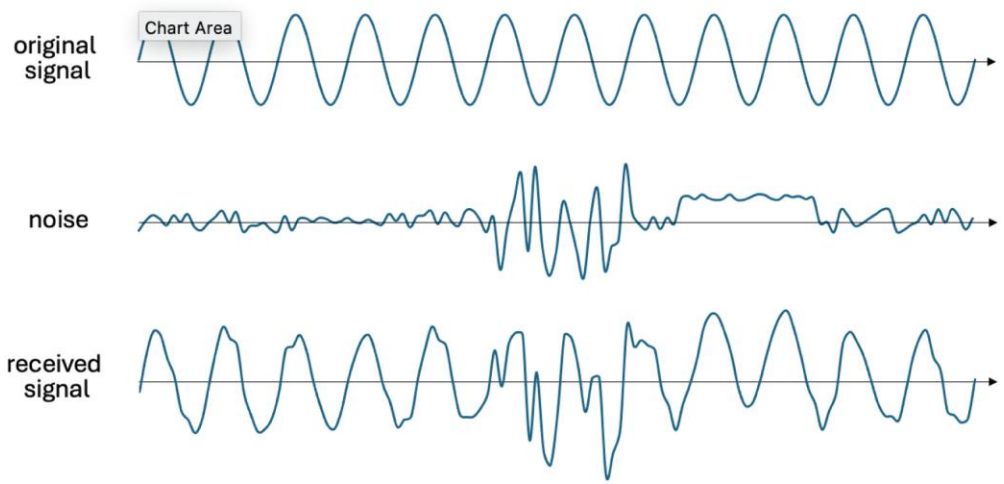
Signal to Noise Ratio (SNR)

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

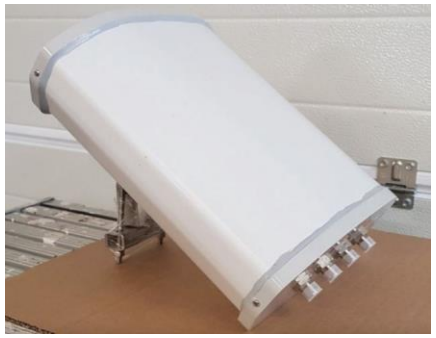
Antennas

Antennas both transmit and receive radio waves

single antenna: old school

multiple antenna: common now in wireless networks

MIMO: **M**ultiple **i**nput **m**ultiple **o**utput antenna



- Gigabit LTE with 4 × 4 MIMO
- Wi-Fi 6 (802.11ax) with 2 × 2 MIMO

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

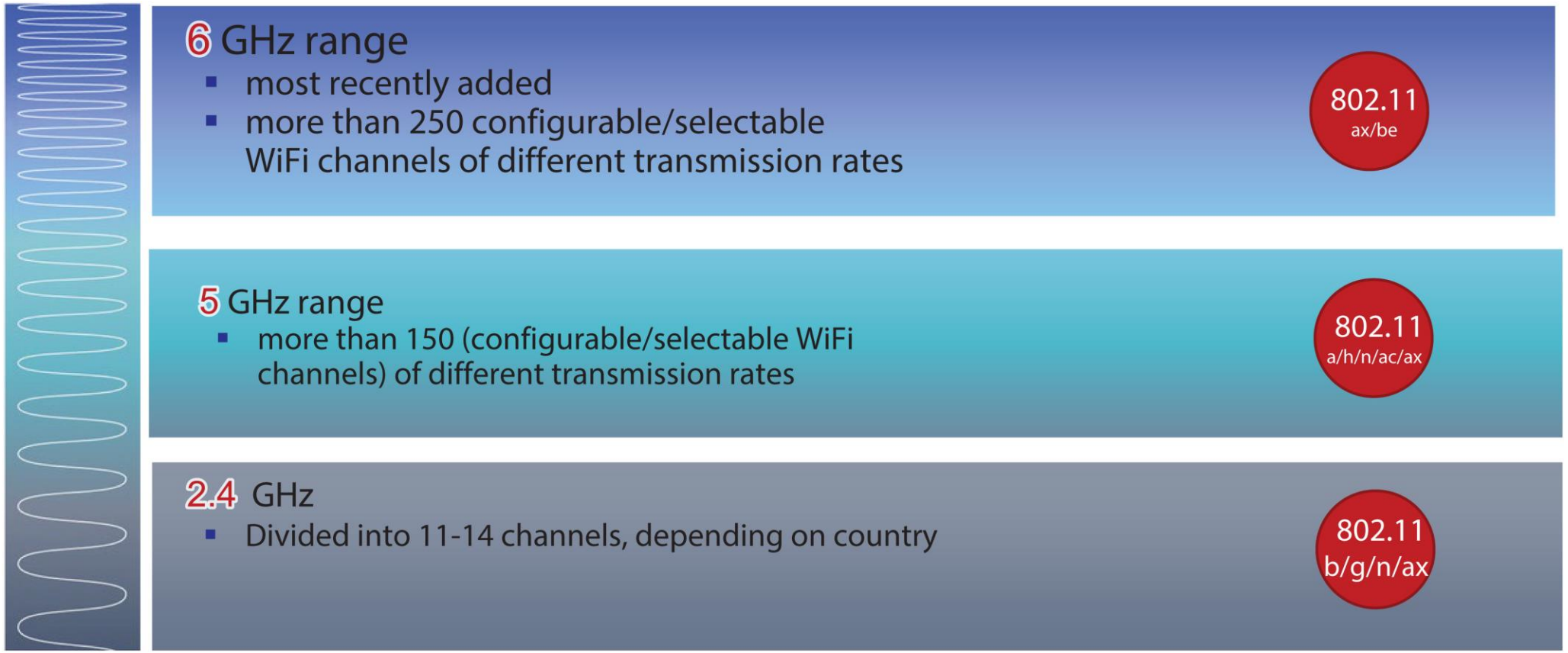
shared:

- 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)
- 2.4G Hz and 5 Ghz WiFi
- 3.5GHz "Private 5G" (aka CBRS)

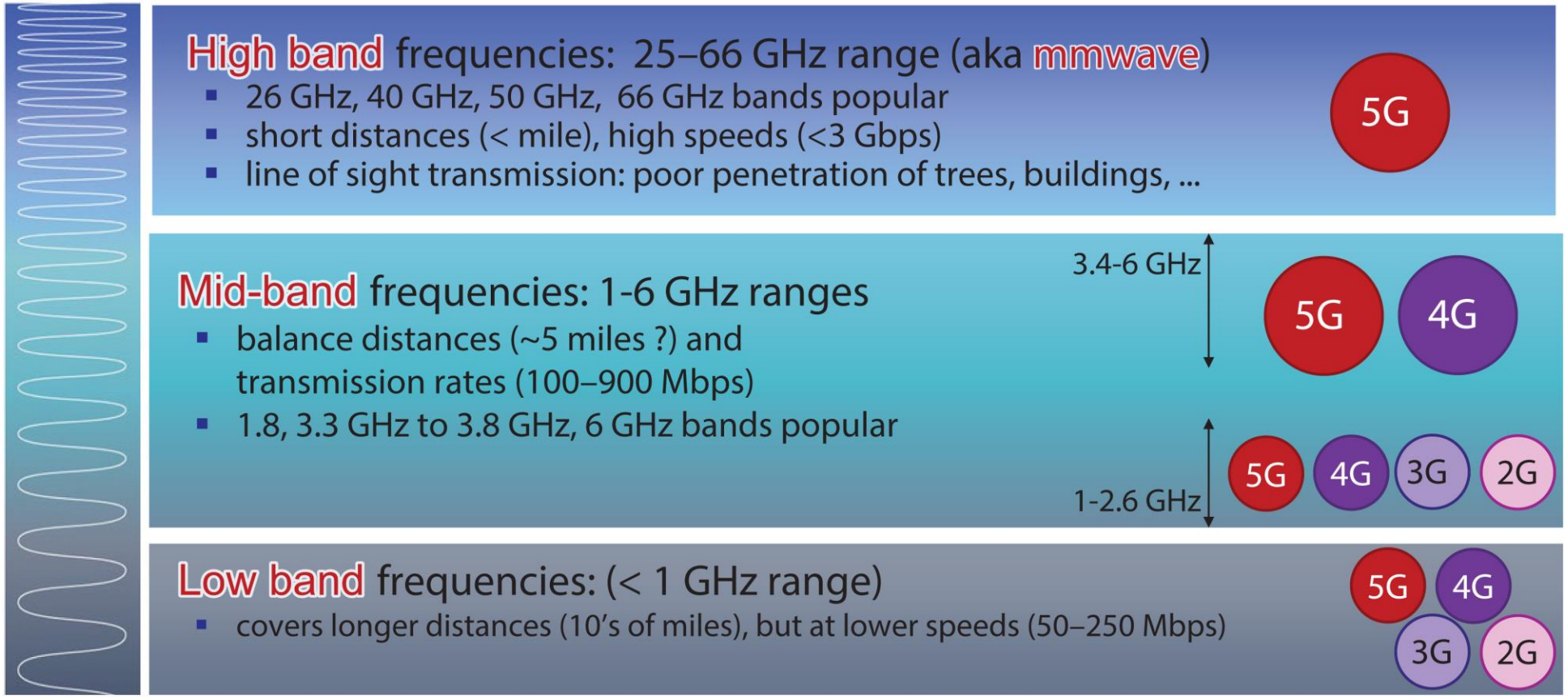
WiFi Spectrum Bands



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

5G Spectrum: Three Spectrum Bands*

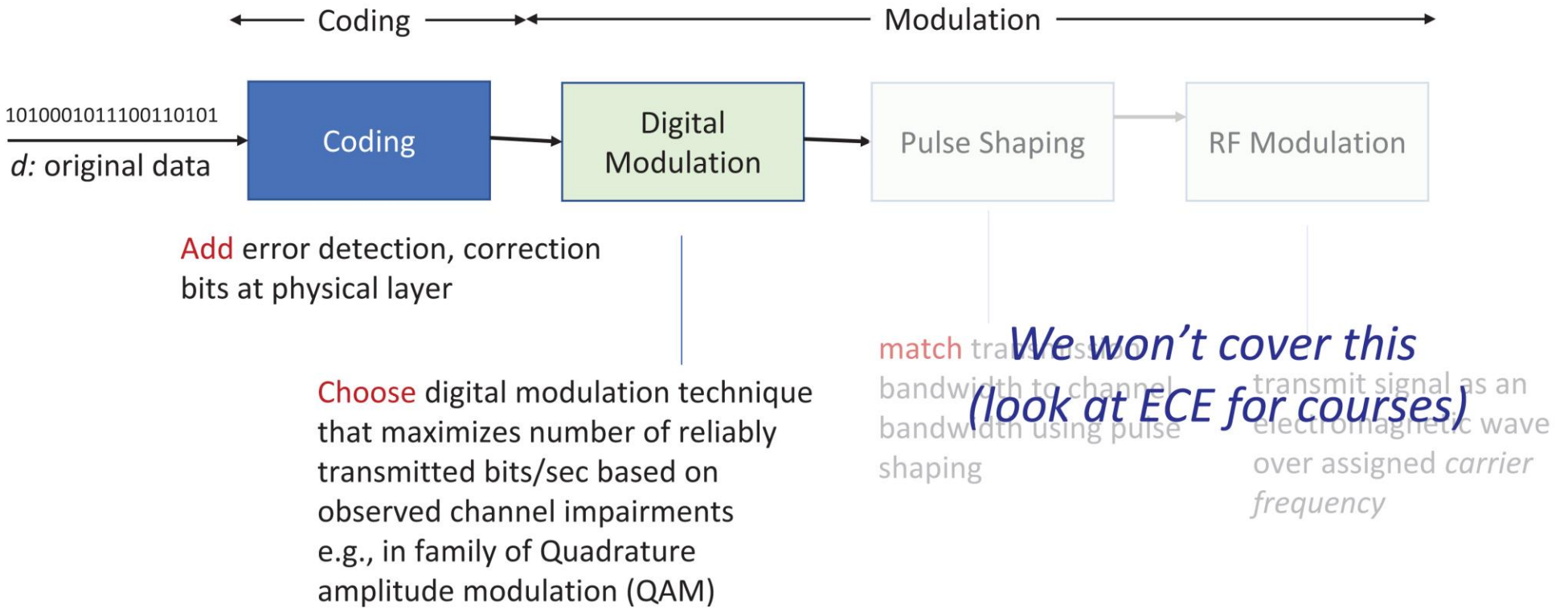
* No single, well-accepted ranges for “low”, “mid” and “high”



Chapter 7 Outline (3 of 10)

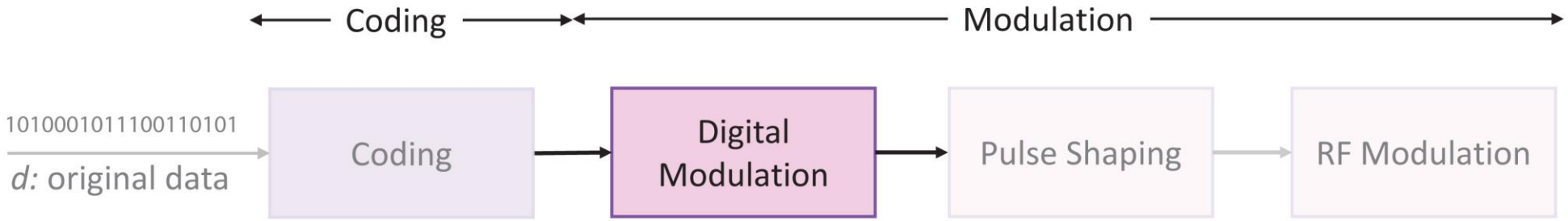
- introduction
- radio: the physical layer
  - radio principles
  - radio channels
  - antennas: MIMO
  - radio spectrum
  - coding and modulation
- the wireless *access* network
- the wireless core network
- mobility
- Bluetooth, satellite, IoT wireless networks

Physical Layer: Coding and Modulation



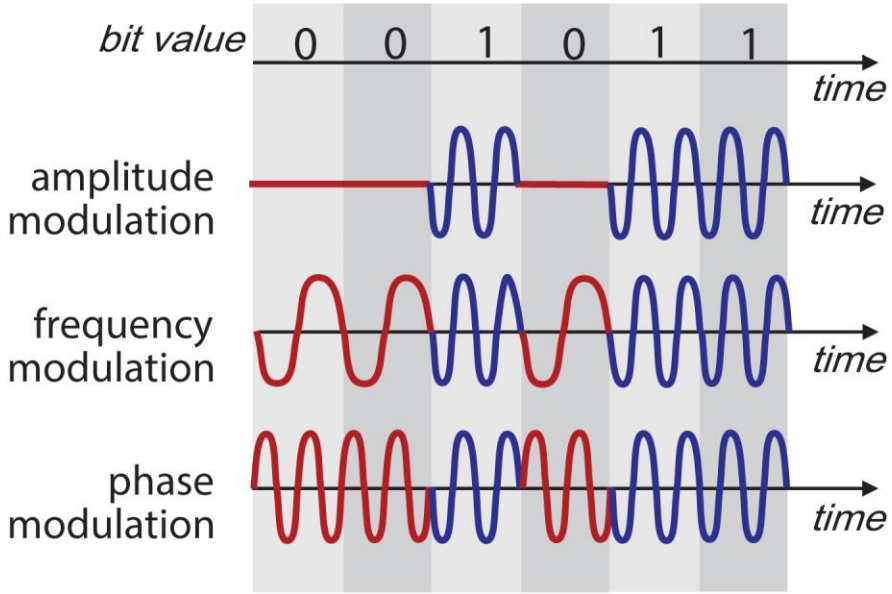
Carrier: waveform at a given frequency, f_c (carrier frequency), modified (modulated) with an information-bearing signal

Modulation



digital modulation

encoding bits (1's, 0's) into analog RF carrier signal by changing ("**modulating**") a characteristic of the RF carrier signal: **amplitude, frequency, or phase.**



Modulation Schemes: ASK, PSK

Amplitude shift keying (ASK):
signal's *amplitude* encodes bits

0: —

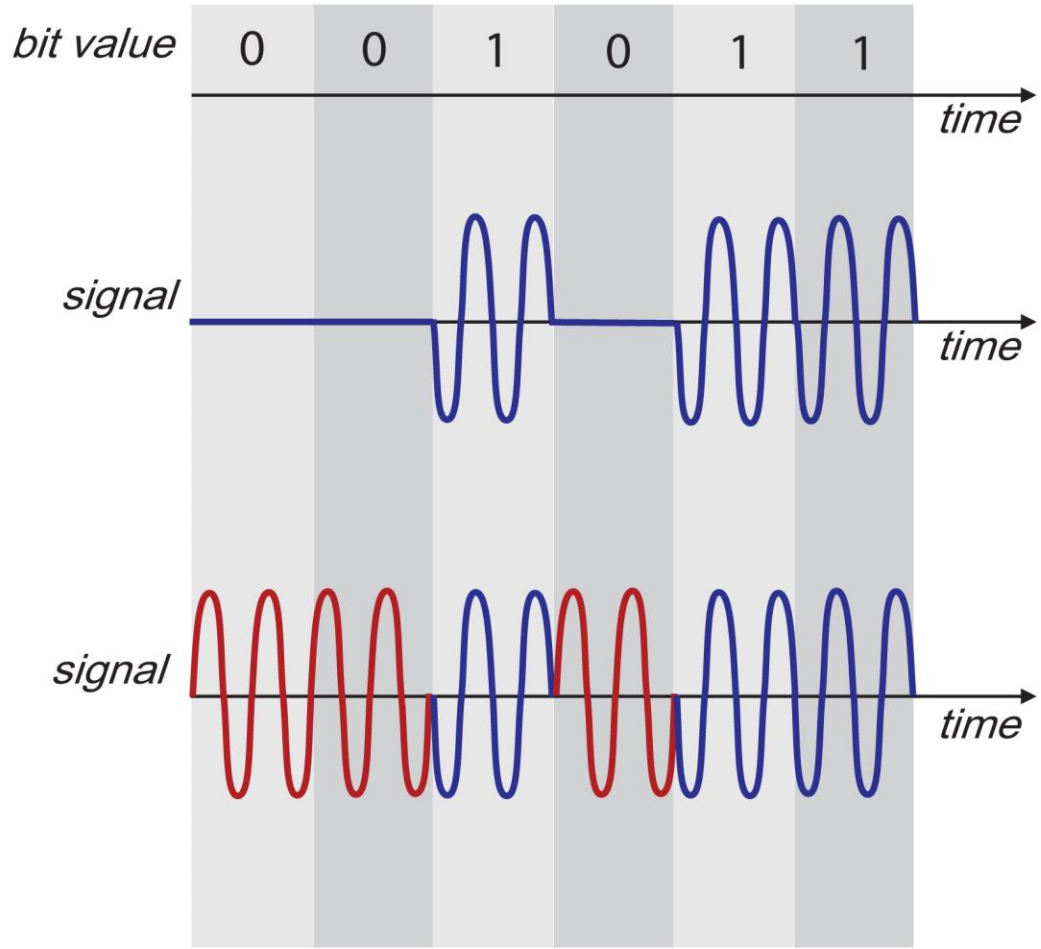
1: ∿∿∿

Binary Phase shift keying (BPSK):
signal's *phase* encode bits

0: ∿∿∿

1: ∿∿∿

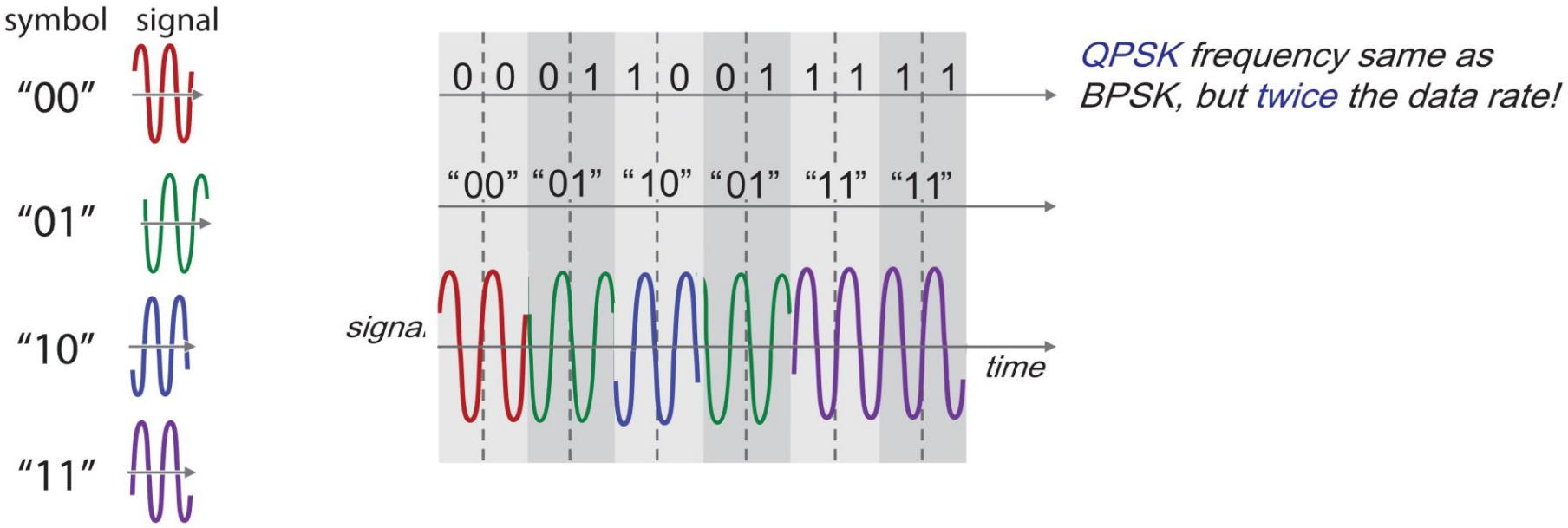
PSK: 0 and 1 signals *out of phase* by 180°, but at same carrier frequency



Modulation Schemes: QPSK

Why stop at just two phases?

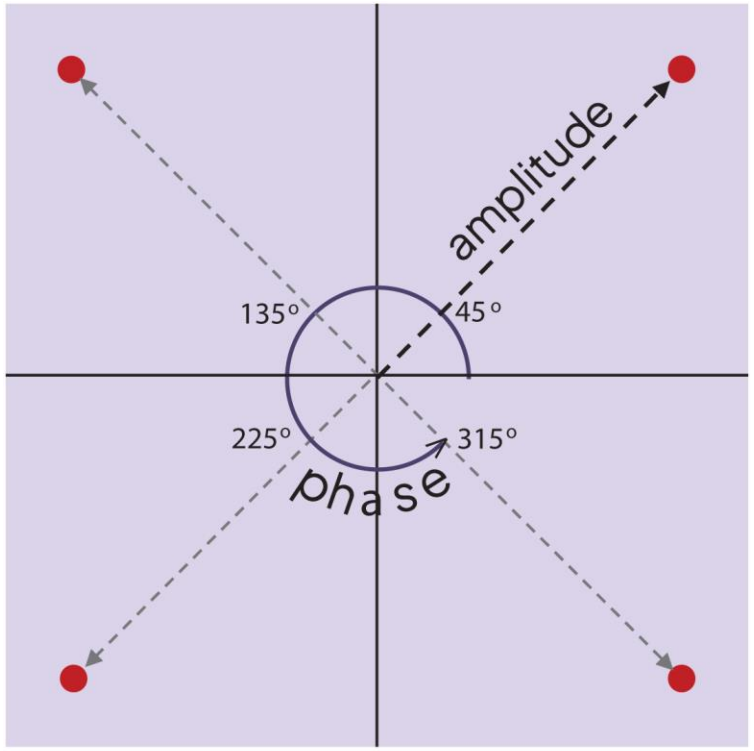
- two bits grouped to become one "symbol" (2 bits -> 4 symbols)
- QPSK: Quadrature Phase Shift Keying: 4 symbols encoded using 4 phases



Fun interactive QPSK tool: https://www.geogebra.org/m/enkymjtg

Constellation Diagrams

graphical characterization of modulation: amplitude, phase of symbols

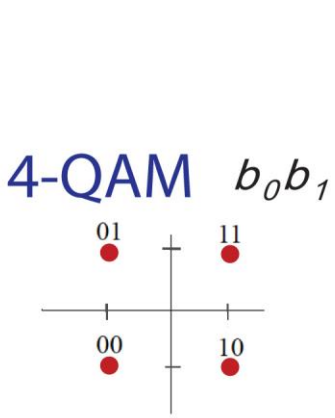


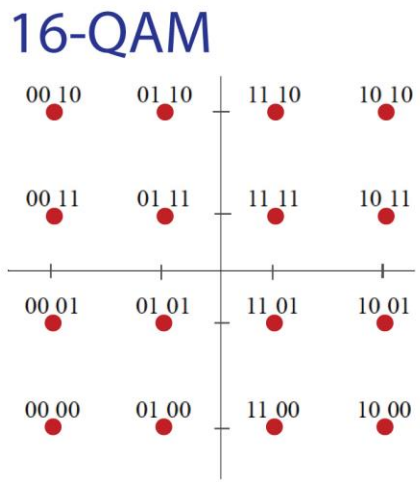
QPSK constellation diagram

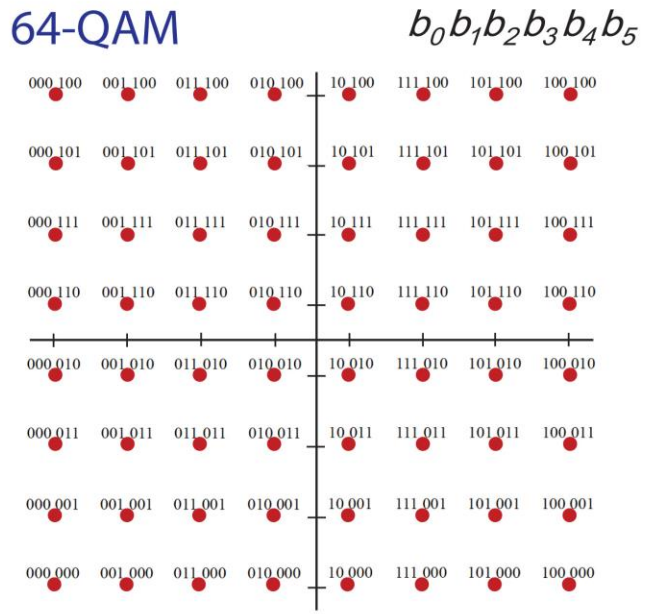
- point in constellation diagram depicts symbol's phase (degrees counterclockwise from east) and amplitude (distance from origin)
- QPSK constellation diagram: four symbols represented by four signal waveforms:
  - four different **phases**
  - identical **amplitude**

QAM: Quadrature Amplitude Modulation

- generalizing QPSK
- *m*-QAM : using *m* different amplitude/phase values to encode $\log_2(m)$ bits





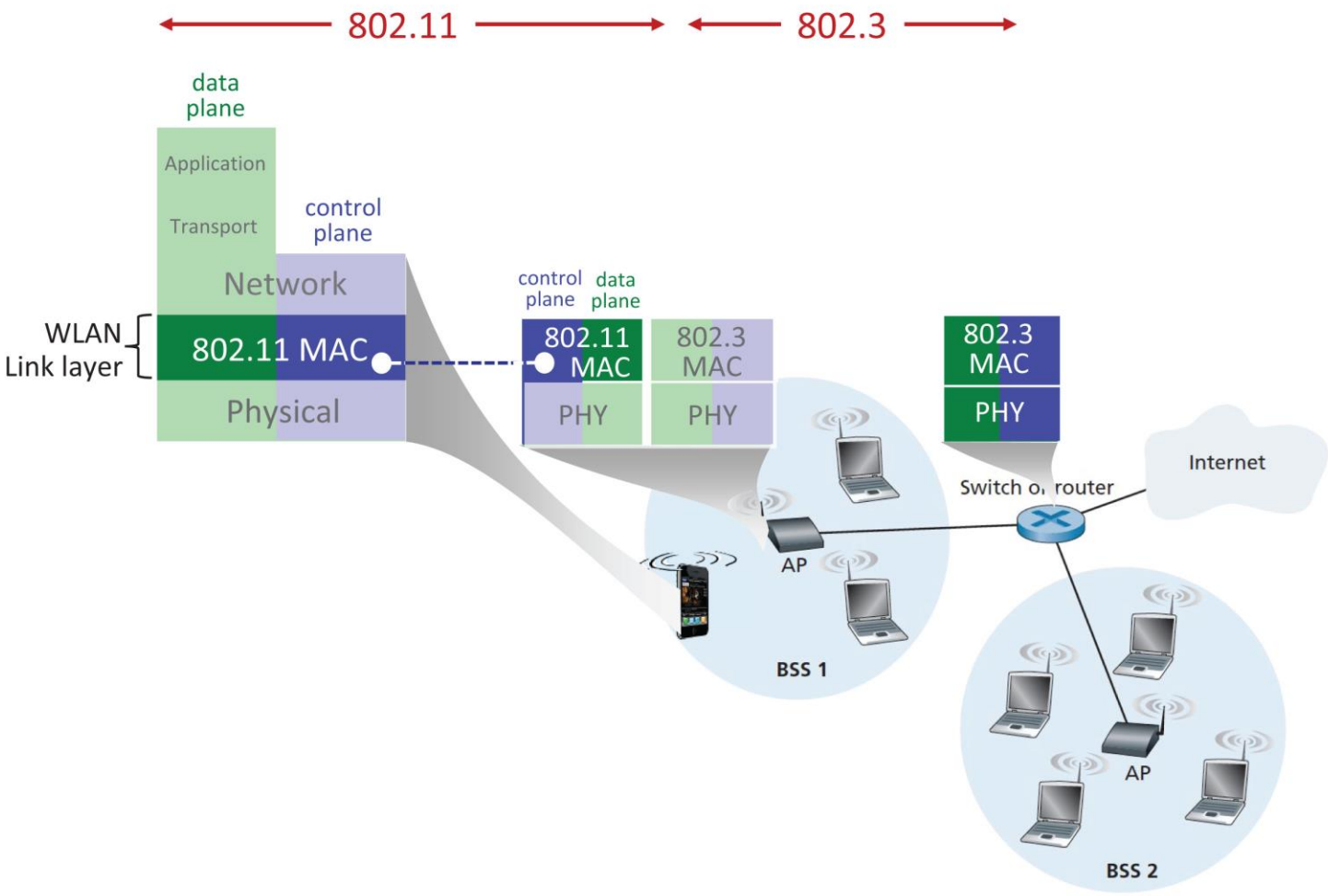


bit encodings for 4-QAM, 16-QAM, 64-QAM (for WiFi)

Chapter 7 Outline (5 of 10)

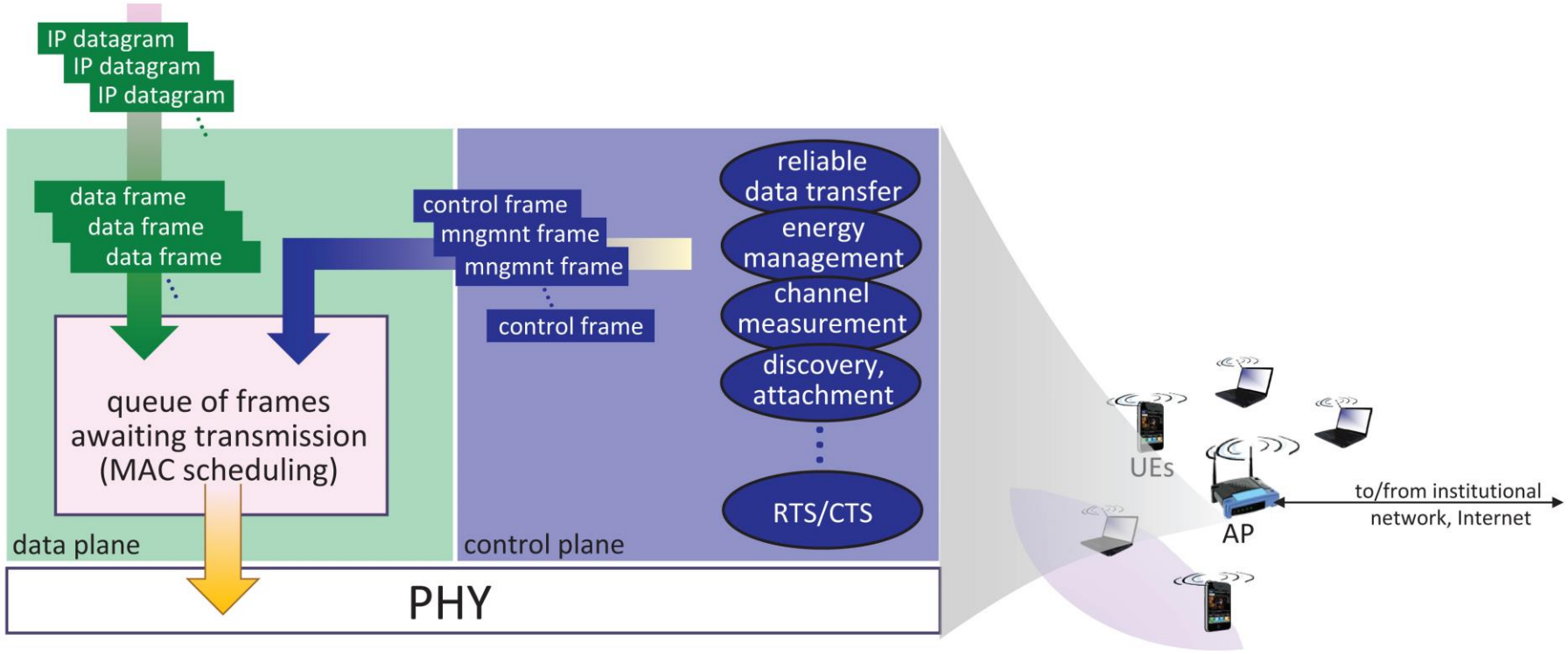
- introduction
- radio: the physical layer
- the wireless *access* network
  - WiFi wireless LAN
- Satellite, IoT wireless networks

802.11 Wireless Link Layer

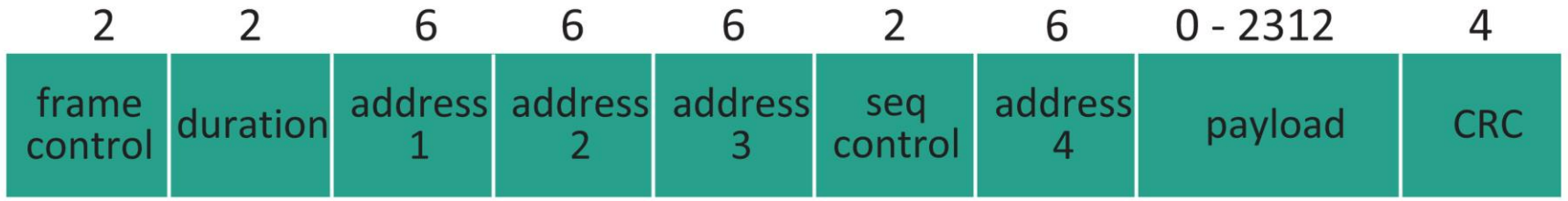


802.11 Downlink (AP-to-device) Frame Flow

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



802.11 Frame: Addressing (1 of 2)



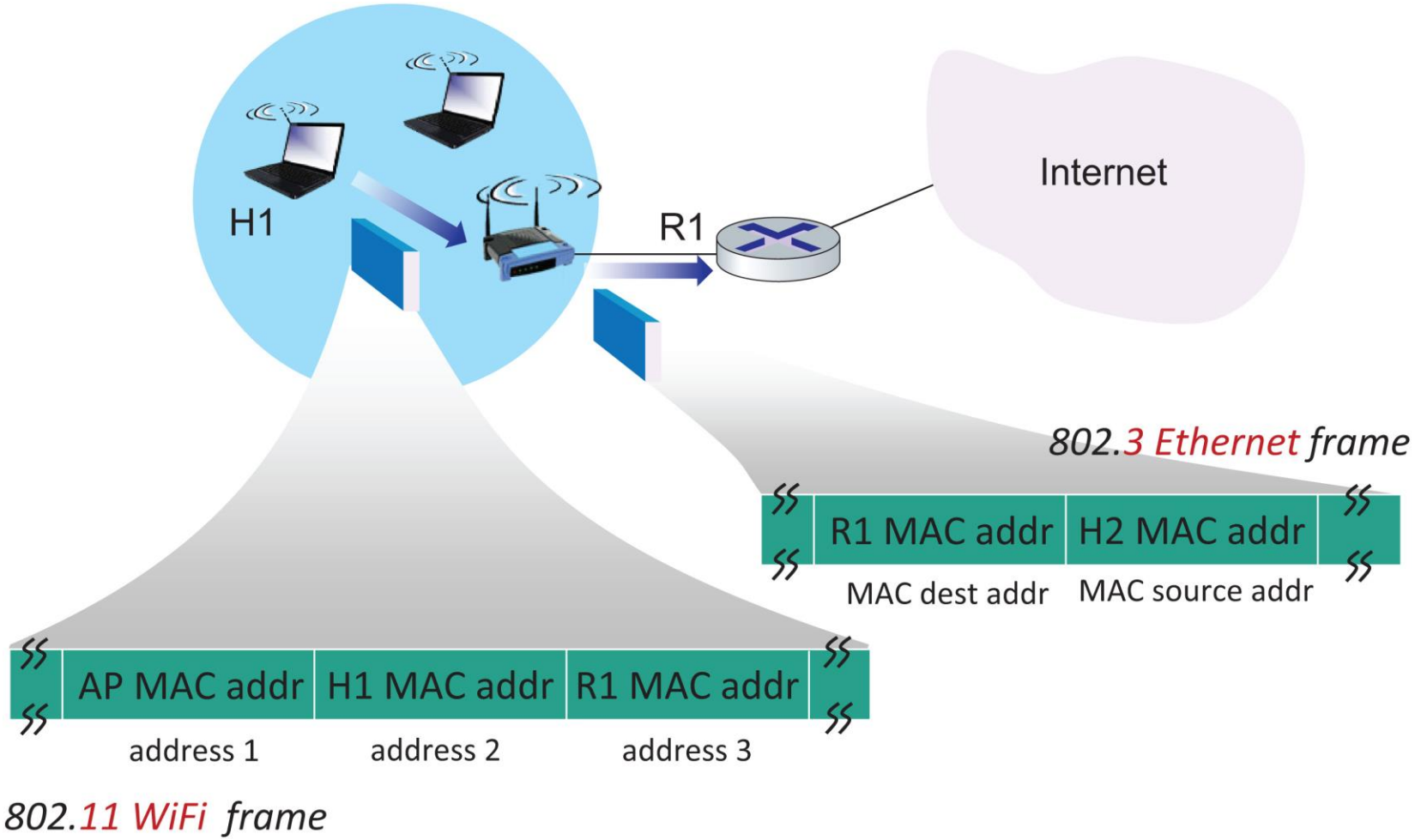
Address 1: MAC address of wireless host or AP to receive this frame

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

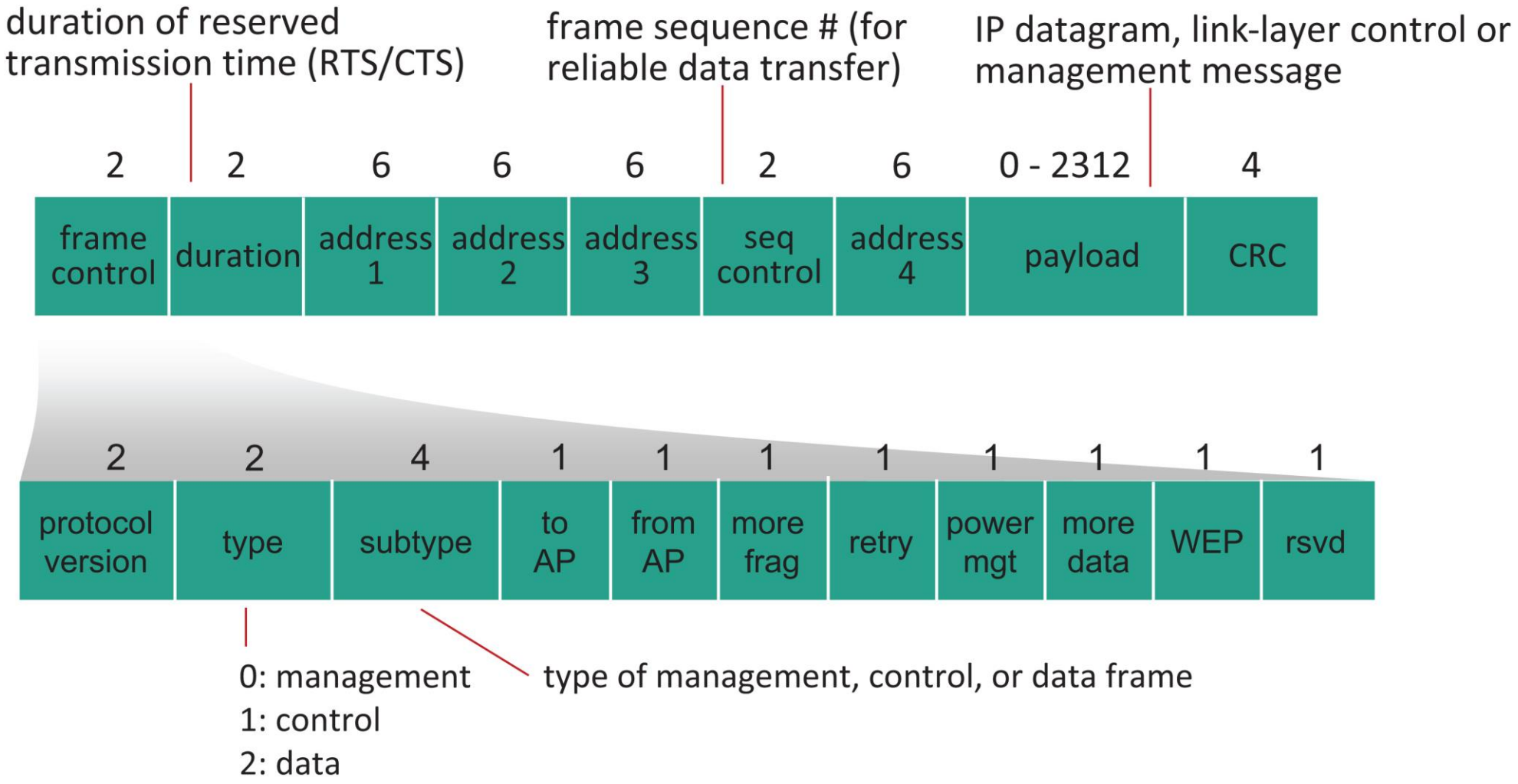
Address 3: MAC address of router interface to which AP is attached

Address 4: used only in ad hoc mode

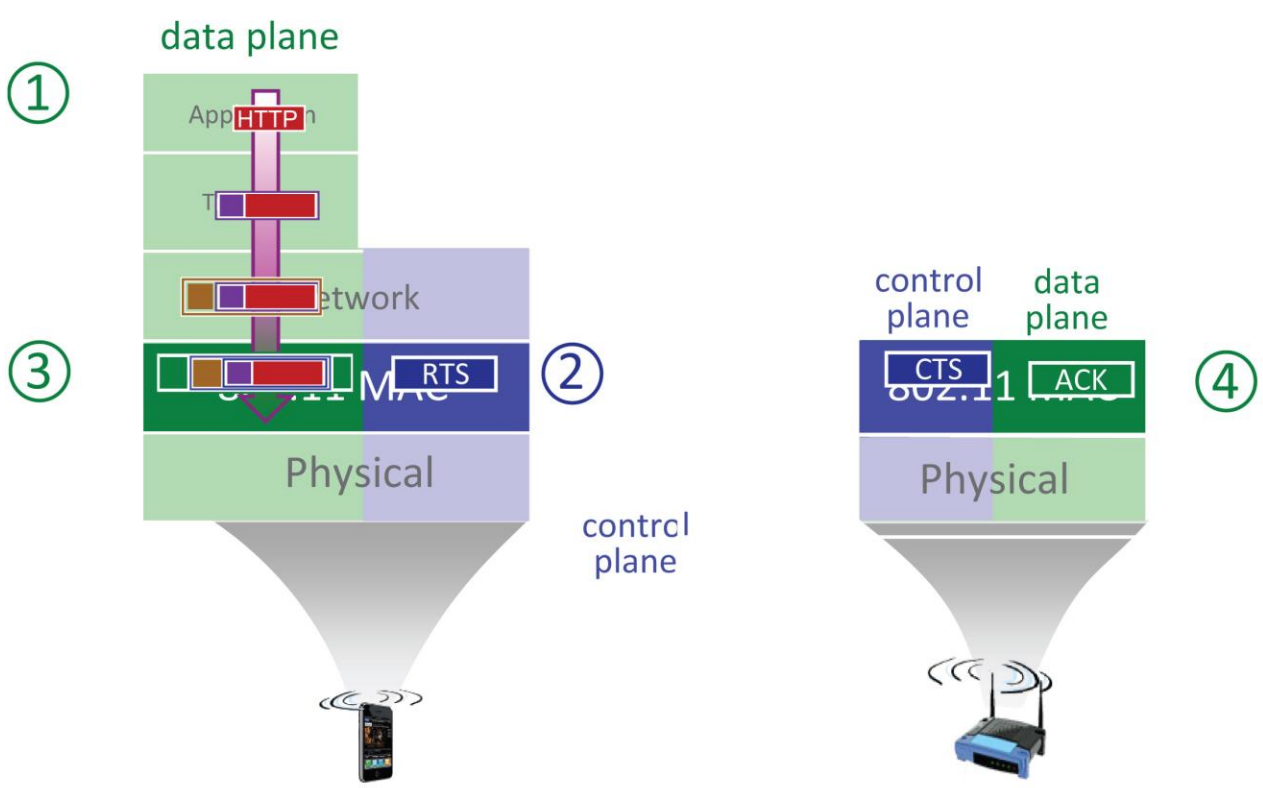
802.11 Frame: Addressing (2 of 2)



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

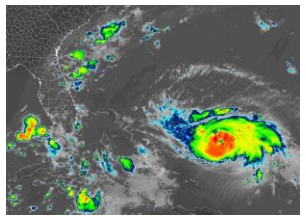
   AP can now forward frame to router

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

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

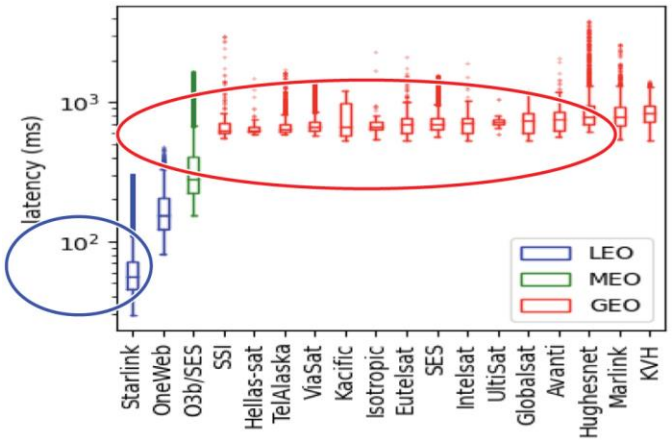
Internet:

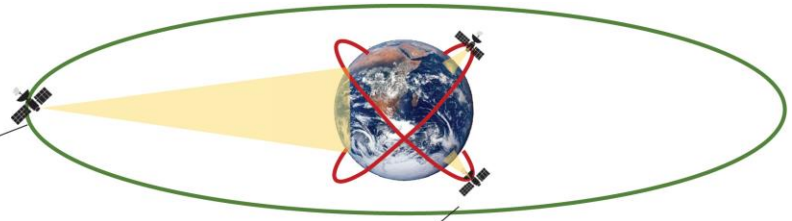
- connectivity to unserved regions, alternative to wired Internet
- low latency over long distances
- access in airplanes

STARLINK

Fly-Fi
CONNECTED BY Viasat

GEO and LEO Satellites





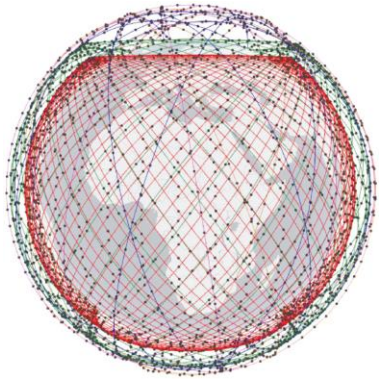
GEO:

- *geosynchonous:* stationary with respect to ground
- 35,768 km above earth
- ~800 msec RTT
- wide area coverage / satellite

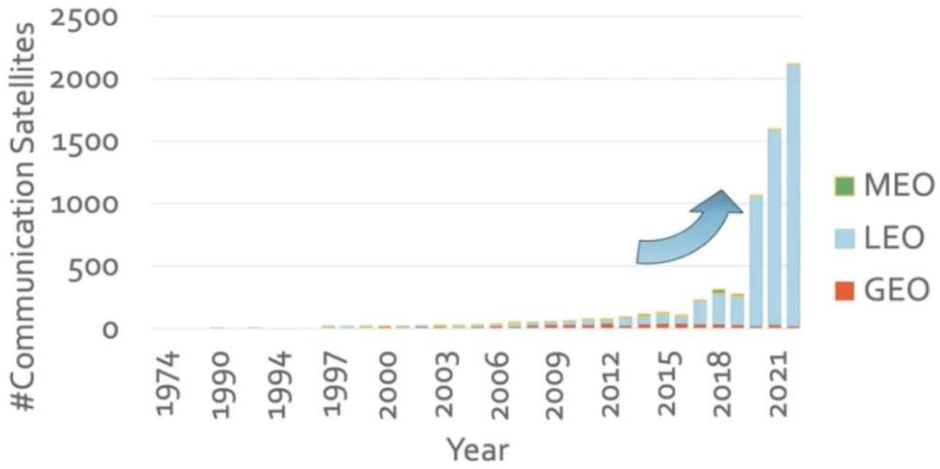
LEO:

- *Low Earth Orbit:* satellite moves with respect to ground: 27,000 km/hour
  - within line of sight (LOS) of ground station for 5-15 mins
- 550 - 1200 km above earth
- ~30 msec RTT in practice
- smaller area coverage / satellite
  - constellation (network) of multiple LEO satellites to cover wide area
  - inter-satellite links (ISL)

Satellites: Why all the Fuss?



Lots of (LEOS) satellites being launched

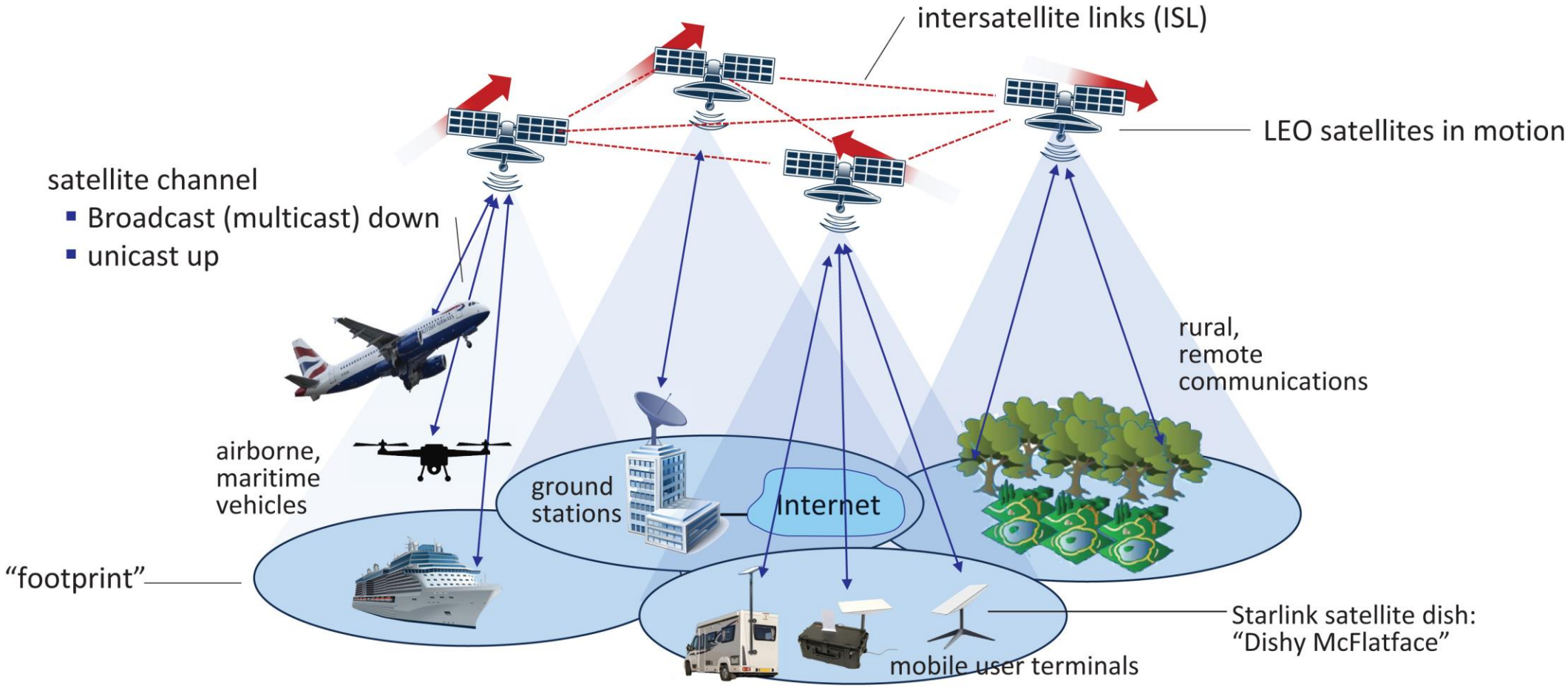


LEOS constellations

	# 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

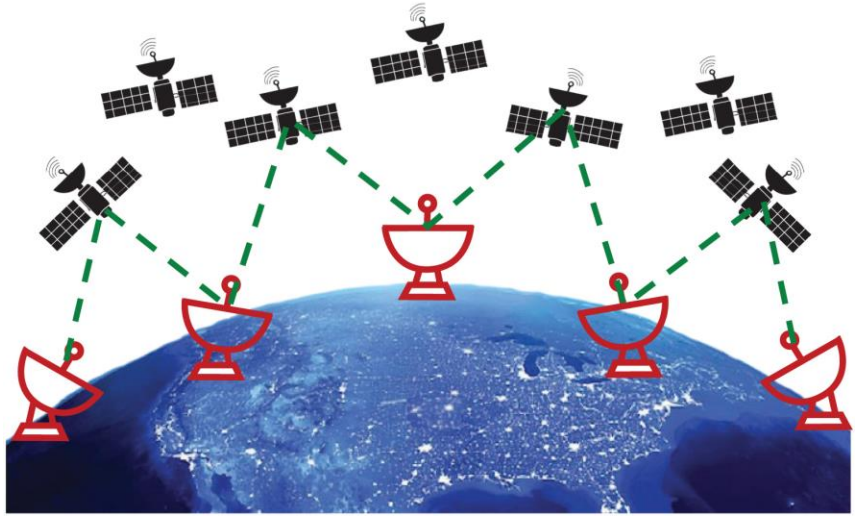
Sources: A. Raman, LEO Satellite Mega Constellations, networkingchannel.eu; N.Pachler et al., An Updated Comparison of Four Low Earth Orbit Satellite Constellation Systems to Provide Global Broadband; company literature

Components of a LEO Satellite Network



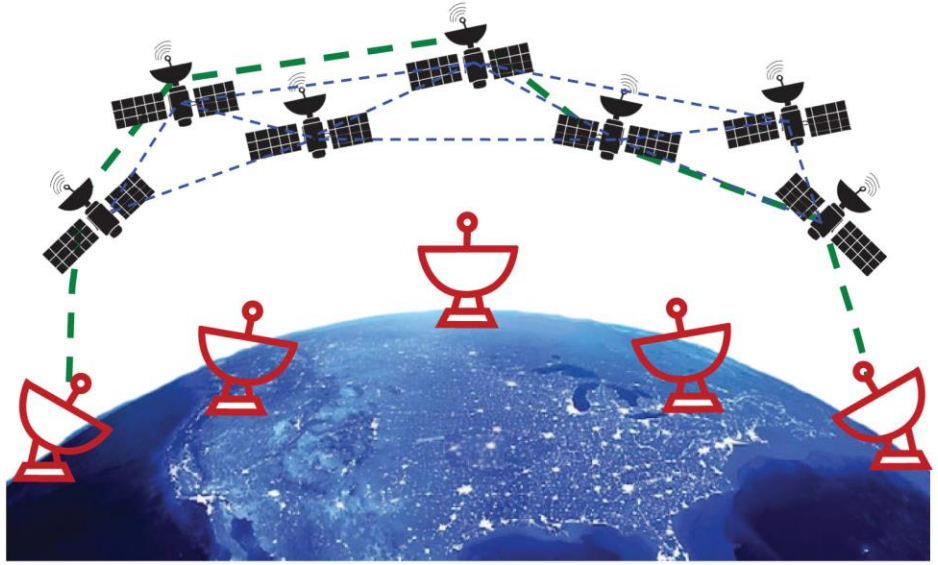
Satellite Networking: a Link or a Network?

links in the sky



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

network in the sky:



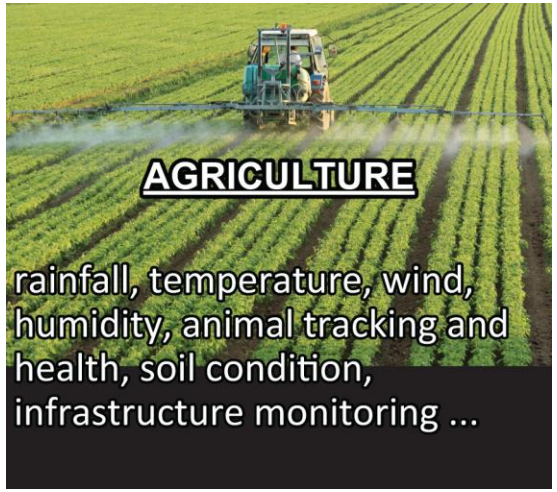
- multiple satellite hops between base stations
- routing among satellites

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
- 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

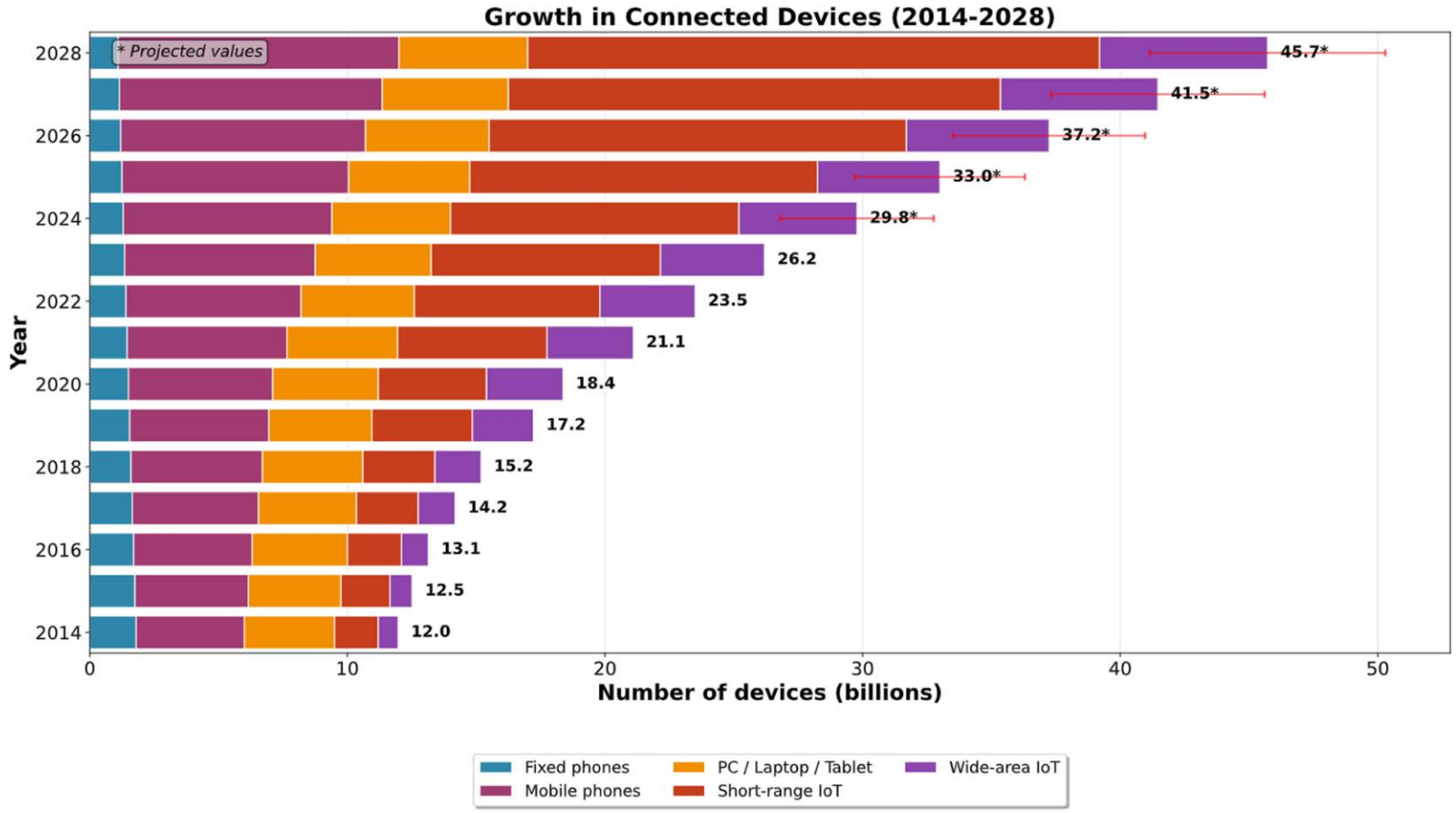
60 Starlink satellites stacked together before deployment on 24 May 2019

IoT: Many, Many Use Cases!



.... and there's many more!

Lots of Connected IoT Devices, and More Soon!

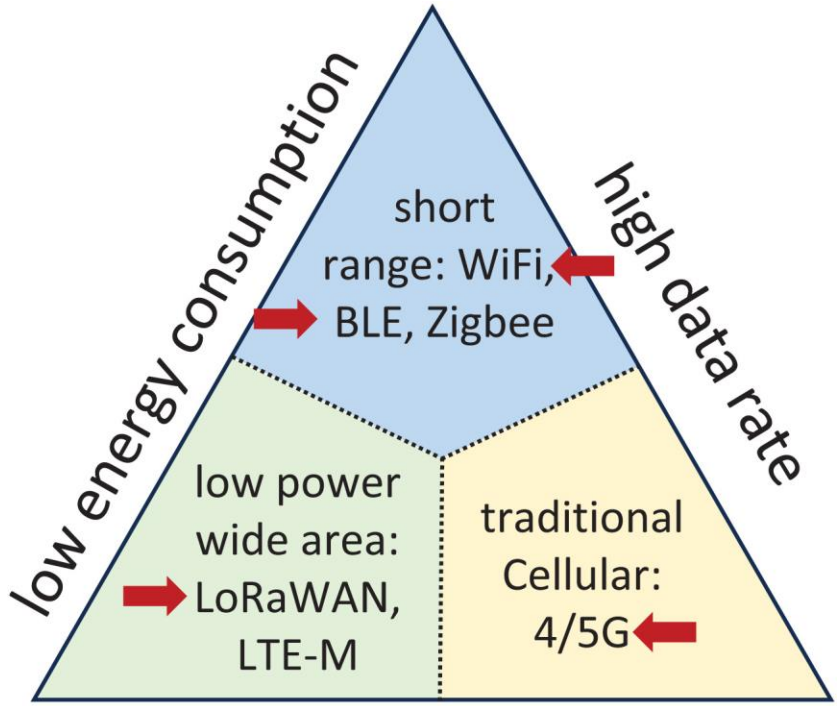


https://www.statista.com/statistics/512650/worldwide-connected-devices-amount/

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