Wireless characteristics

Slides used in TDDE48 (Mobile Networks) @ LiU, Sweden, Fall 2025
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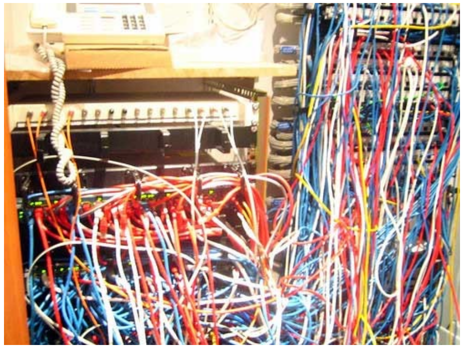
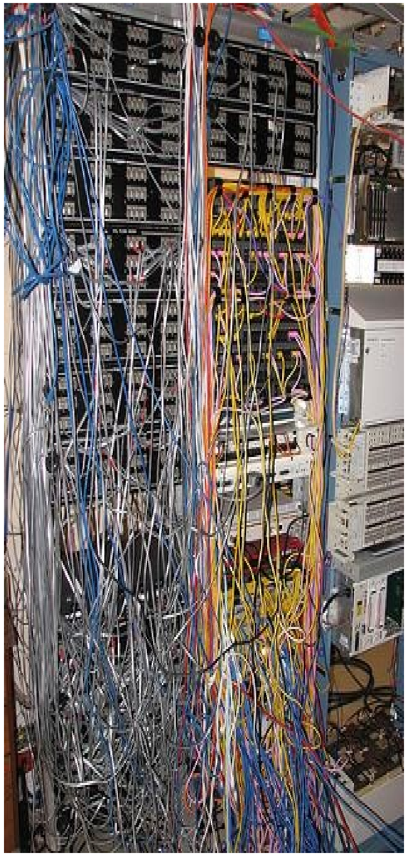
Slides in this course are adapted or based on various on-line resources (including lectures notes by Juha Takkinen, Anirban Mahanti, Carey Williamson, Jim Kurose, and Keith Ross)

What is Wireless Networking?

- Use of infra-red (IR) or radio frequency (RF) signals to share information between devices
- Promises *anytime, anywhere* connectivity
- No wires!

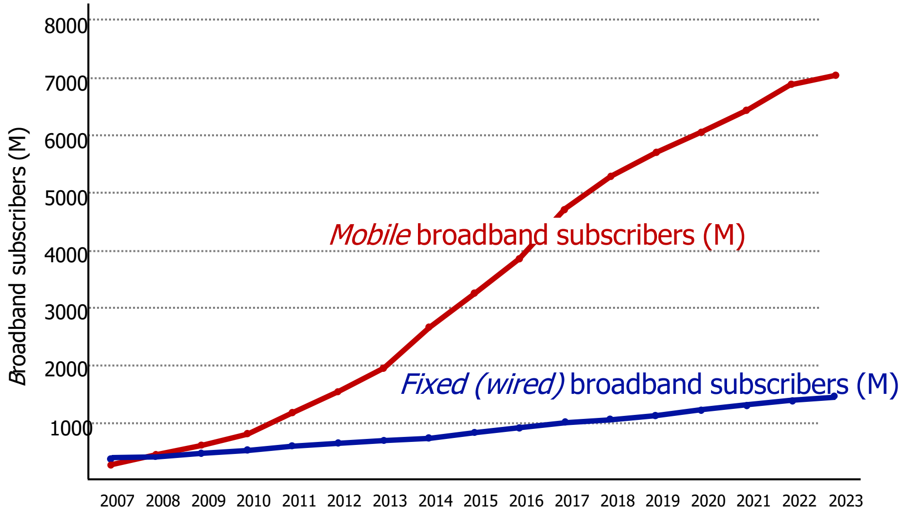




- Lots of acronyms

Wireless and Mobile Networks: context

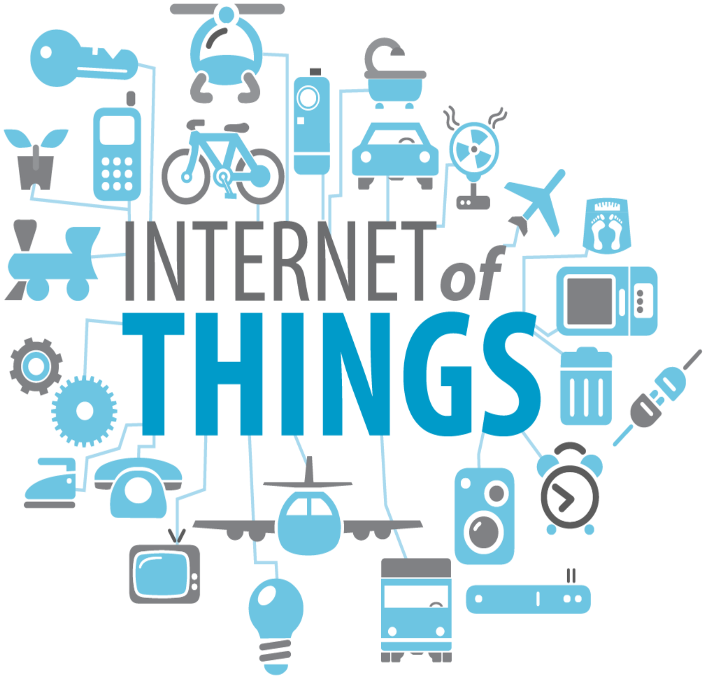
- more mobile-broadband-connected (cellular) devices than fixed-broadband-connected devices devices (5-1 in 2019)!
  - wireless connectivity even great when WiFi users considered (80% of broadband homes use WiFi)
  - 60% of Internet traffic from major web sites destinated to mobile device

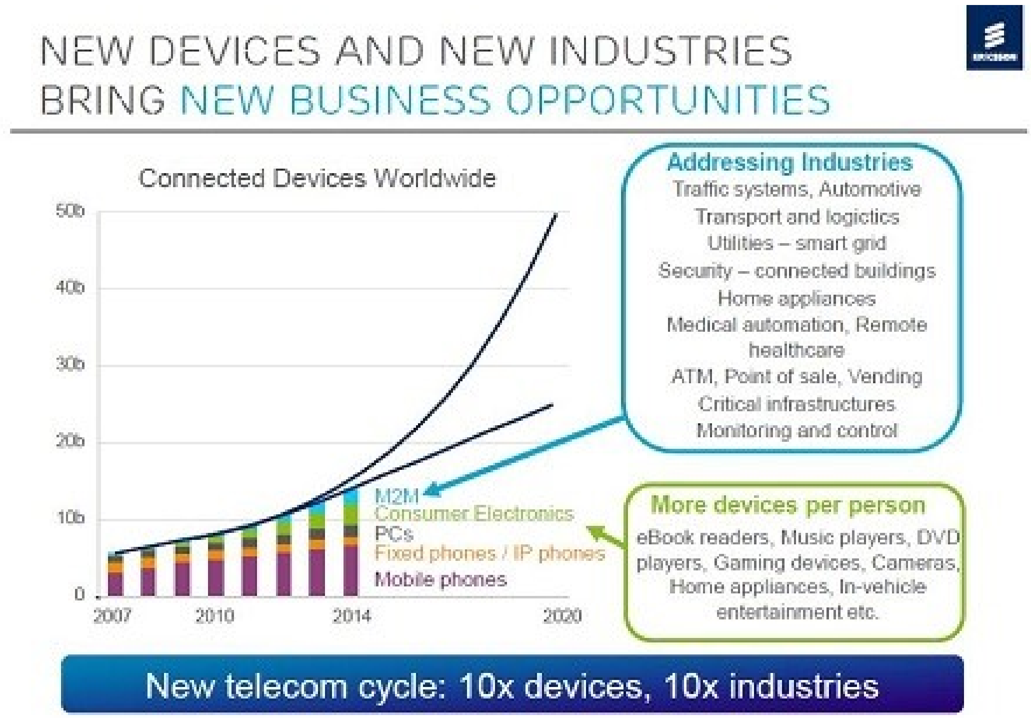


Data source: www.statista.com (1/25)

What is mobile device?

… trends towards the future …





Example trends

- Everything that can be connected will be connected
- IoT and smart cities
  - Machine-to-machine
- High-definition VR+3D streaming to heterogeneous clients

A connected world …

Also comes with privacy issues …

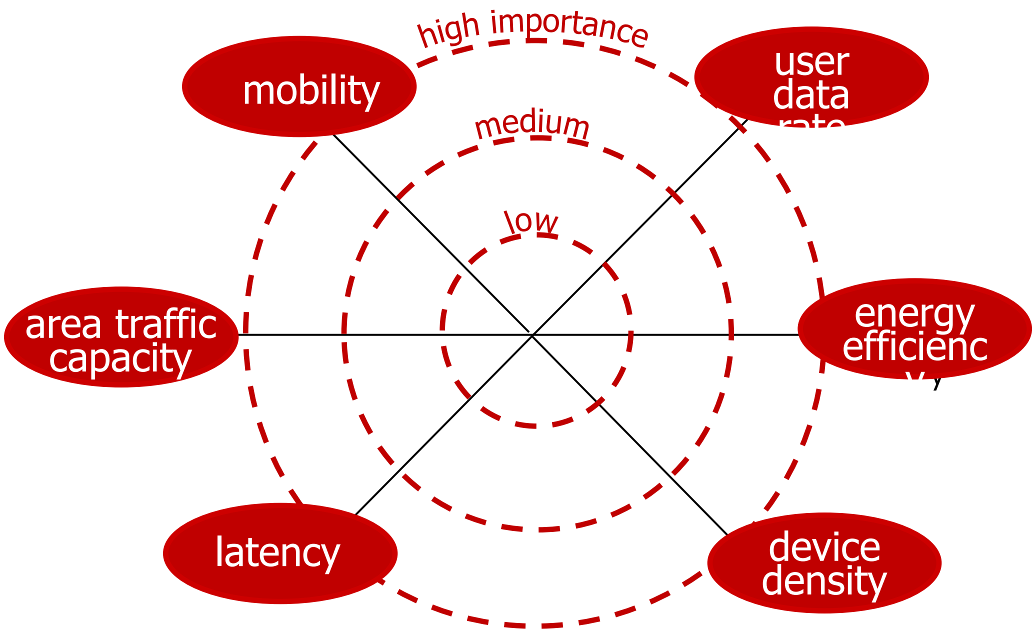
- Yes, many entities knows where you are and what you do
- E.g., phone: apps + services, OS, cellular/wifi providers, location services, Google/Apple services, third parties (e.g., ad providers), "fourth parties", malicious apps, hackers, governments and law enforcement, …

Wireless applications their needs

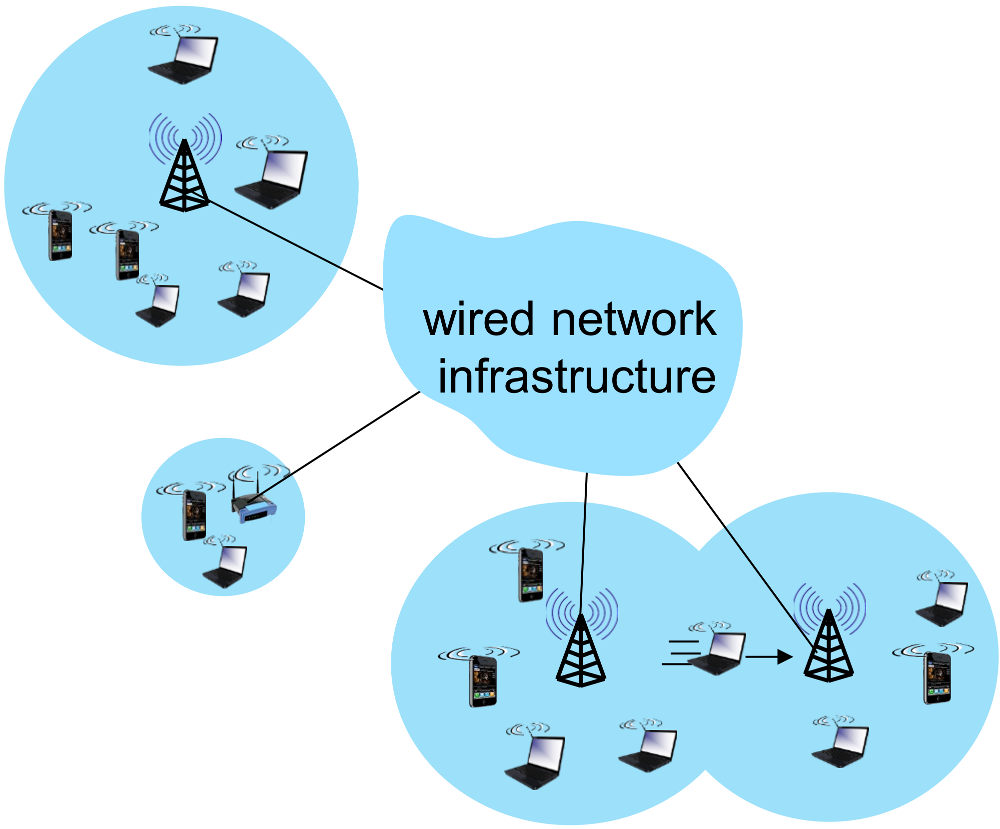
Six application areas

:
- 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)

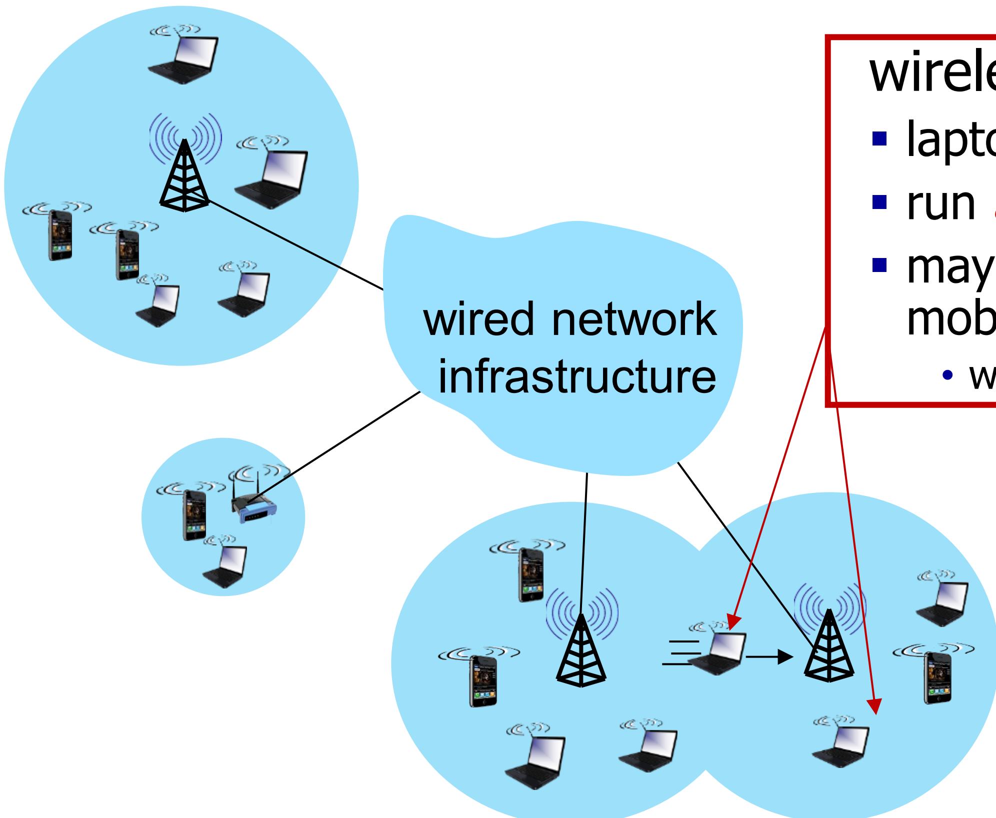
Application needs:



Elements of a wireless network

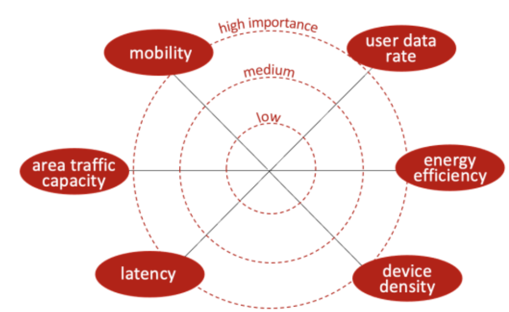


Elements of a wireless network

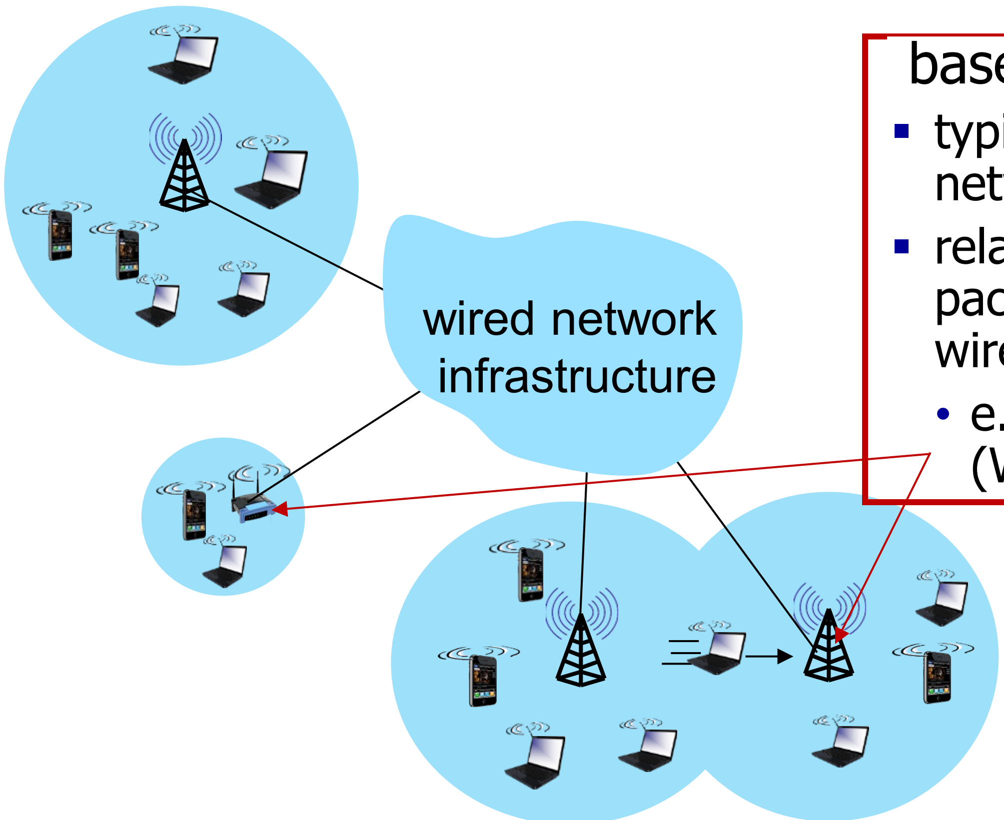


wireless hosts

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



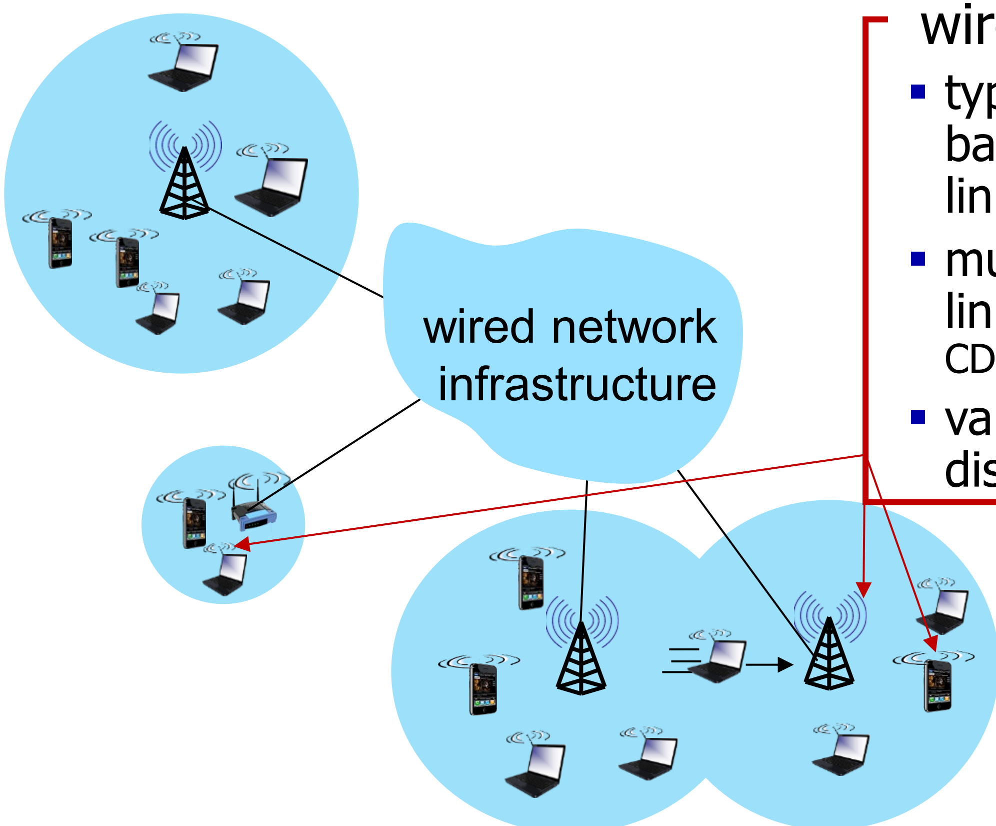
Elements of a wireless network



base station

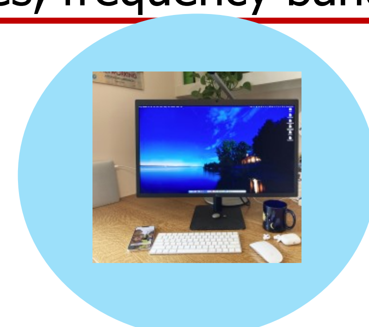
- typically connected to wired network
- relay - responsible for sending packets between wired network and wireless host(s) in its "area"
    - e.g., 4G/5G cell towers, 802.11 (WiFi) access points (APs)

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

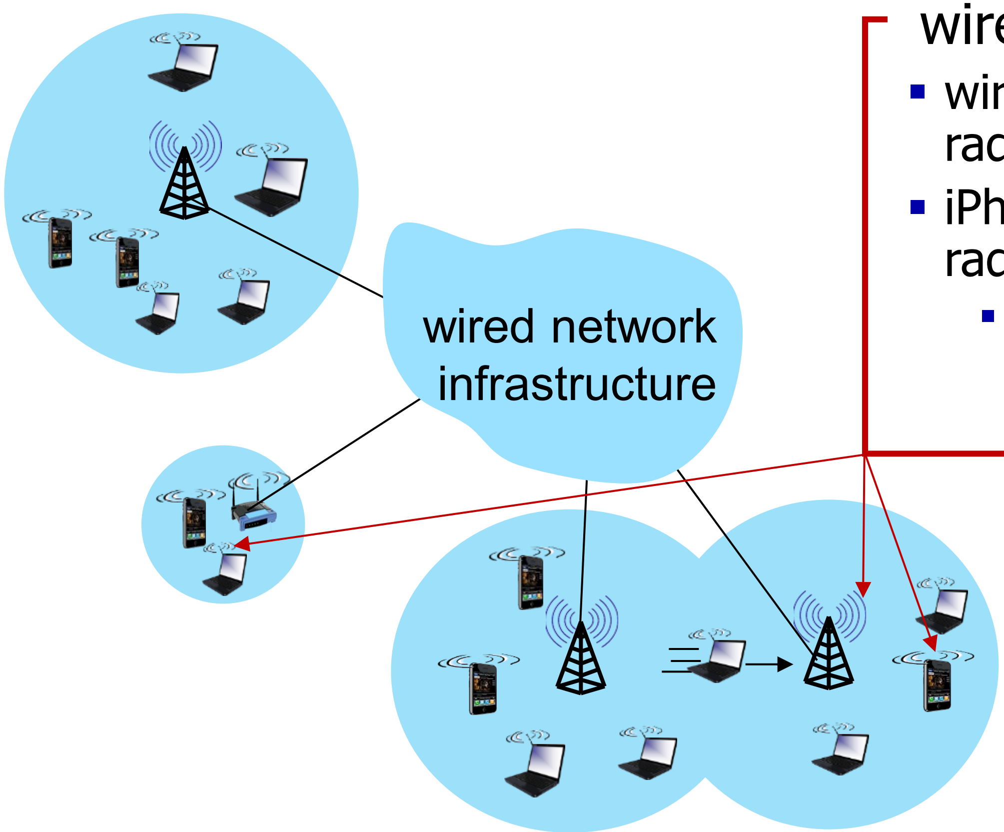


Ad hoc networks: not all wireless networks are connected into a larger network

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

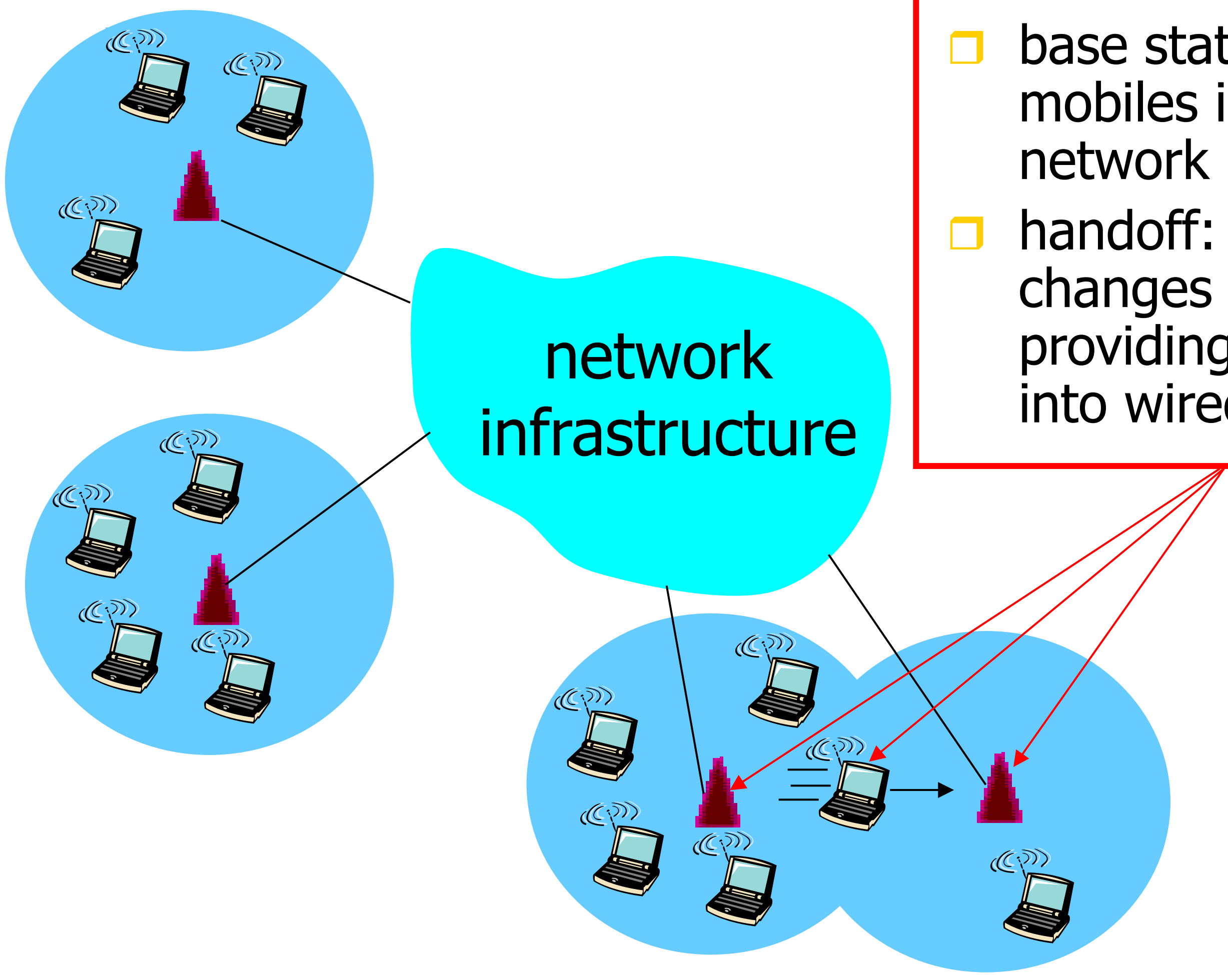


Ad hoc networks: not all wireless networks are connected into a larger network

Wireless Networking Technologies

- Operating modes
  - Infrastructure mode
  - Ad-hoc mode

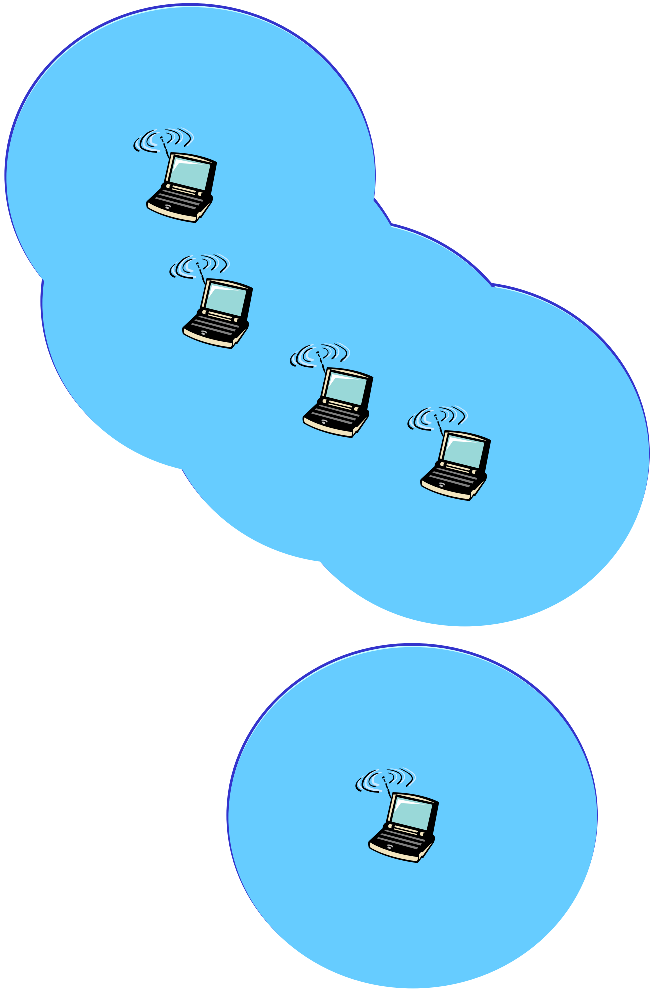
Infrastructure Mode



Infrastructure mode

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

Ad hoc Mode



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

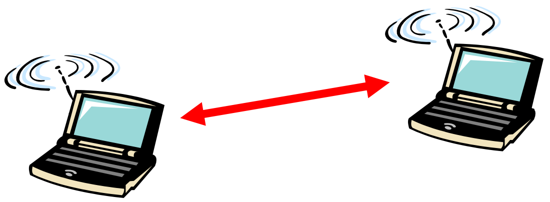
Two important (but different!) challenges

Two important (but different!) challenges

- Communication over wireless link
- Handling mobile user who changes point of attachment to network

Two important (but different!) challenges

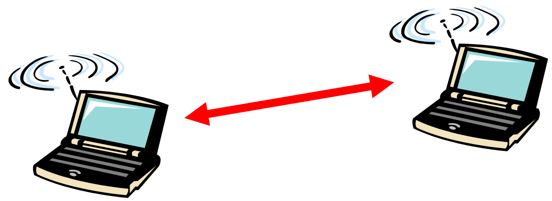
- Communication over wireless link



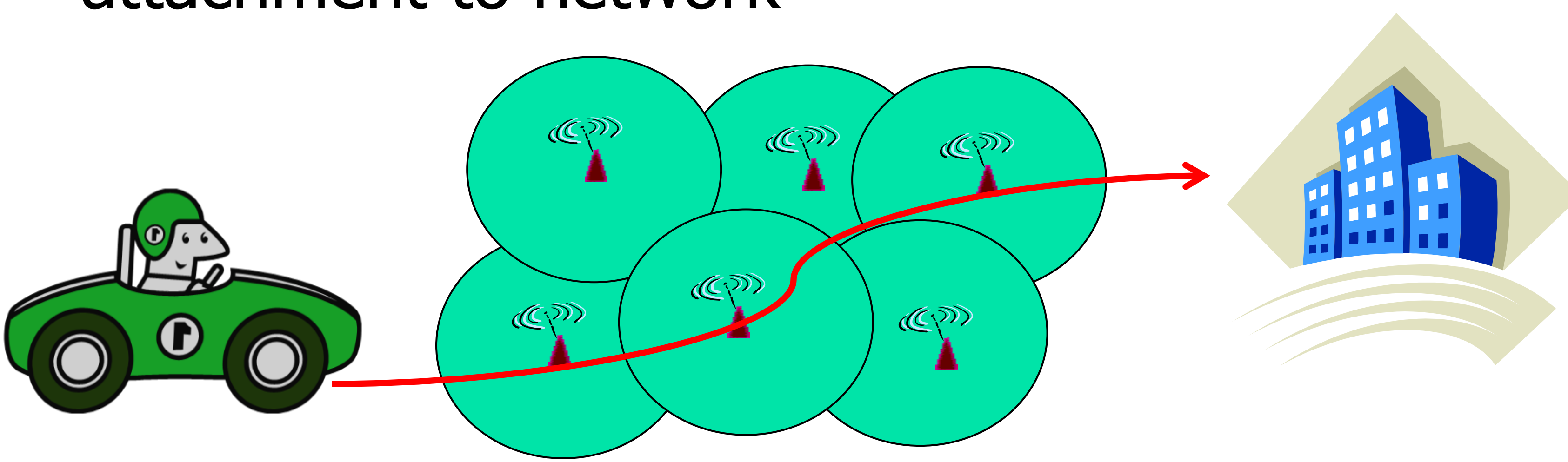
- Handling mobile user who changes point of attachment to network

Two important (but different!) challenges

- Communication over wireless link

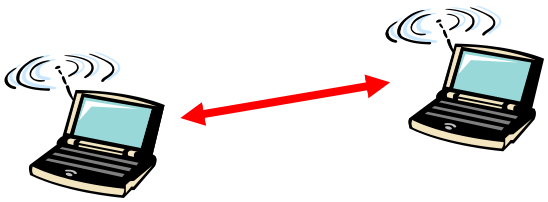


- Handling mobile user who changes point of attachment to network



Two important (but different!) challenges

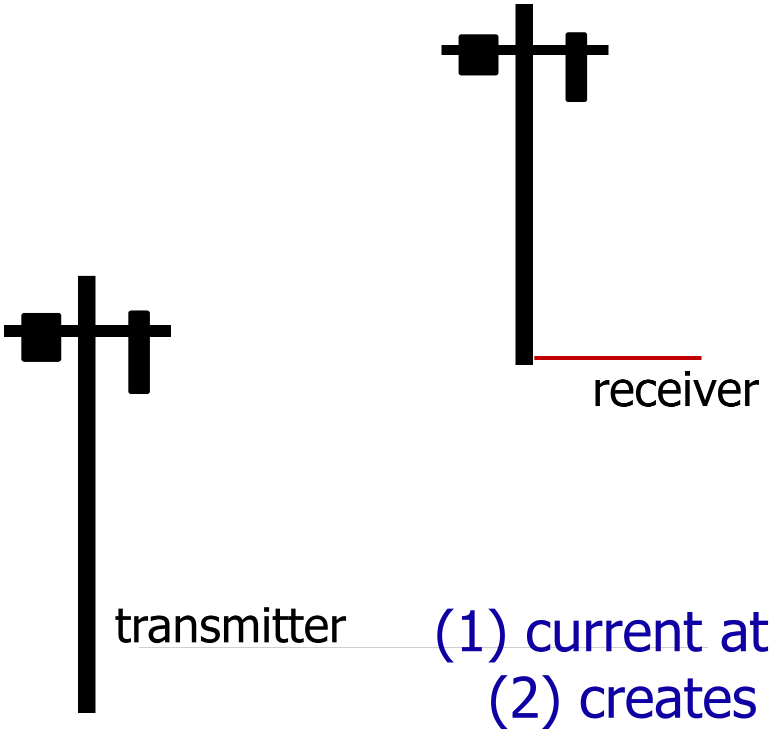
- Communication over wireless link



- Handling mobile user who changes point of attachment to network

** In this course we will look at unique challenges and opportunities in wireless communication, including the two above.

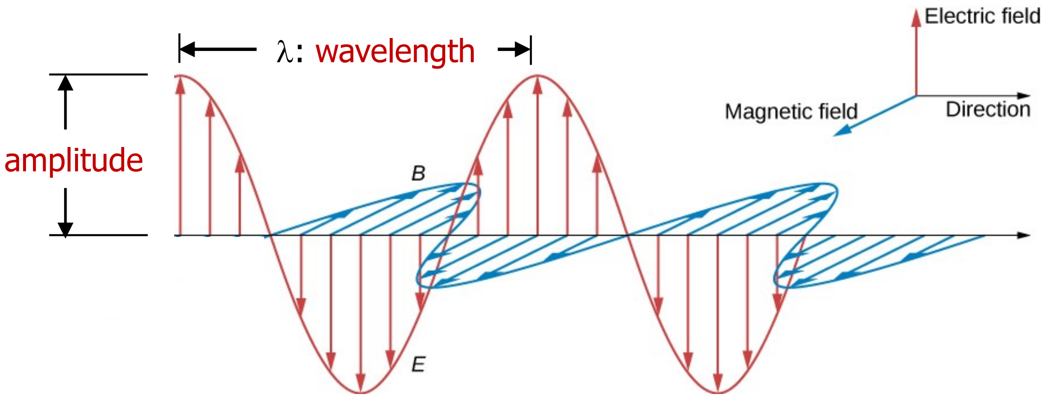
Electromagnetics: enabling communication



(1) current at one location (transmitter)
(2) creates an EM field in space ....
(3) induces a current at
remote location (receiver)....

slide concept: S. Rangan (NYU)

Radio basics: electromagnetic waves



wave propagation:

Electromagnetic wave has:

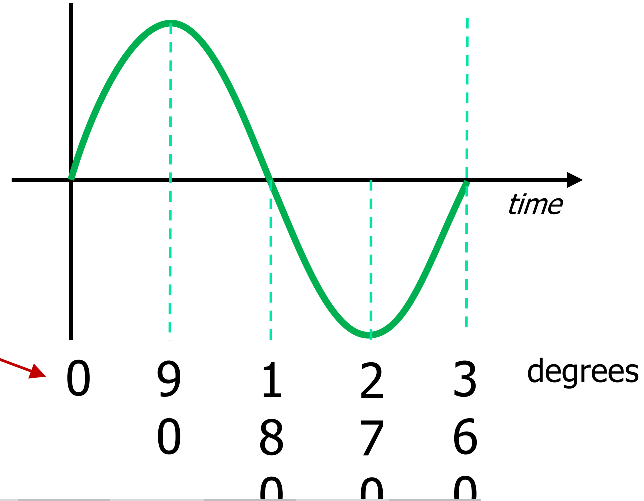
- wavelength (λ)
- frequency: speed of light / wavelength = c/λ
- directionality (of propagation)
- time-varying amplitude

slide concept: S. Rangan (NYU)

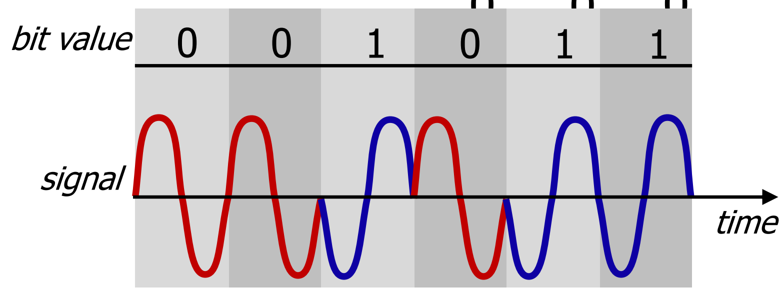
Radio basics: phase

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

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:

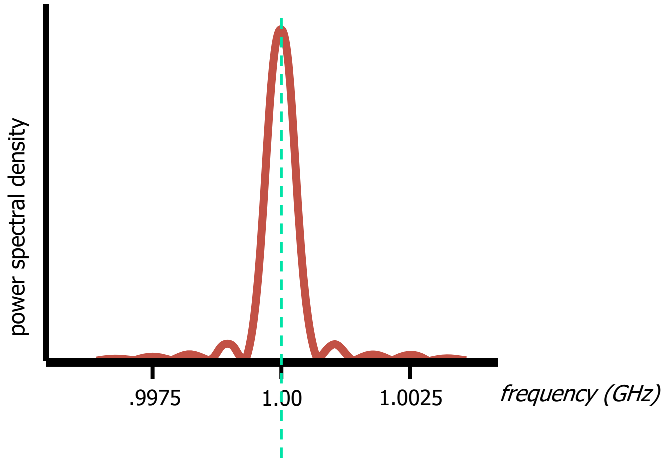
P_{mW} = 250 mW (typical max mobile transmit power)

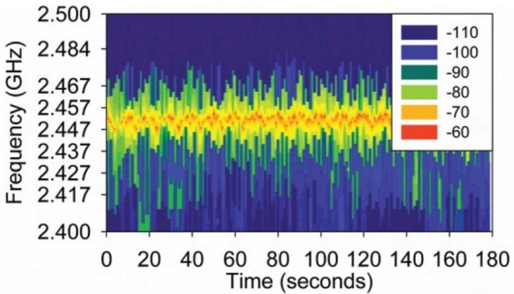
$$P_{dBm} = 10 \cdot \log_{10}\left(\frac{250mW}{1mW}\right)$$

$$= 24 \text{ dBm}$$

Power spectral density:

- power present in signal as a function of frequency

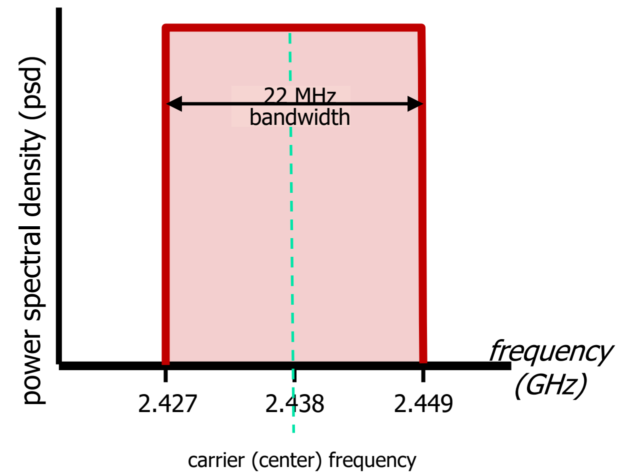




Radio signal characteristics

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)



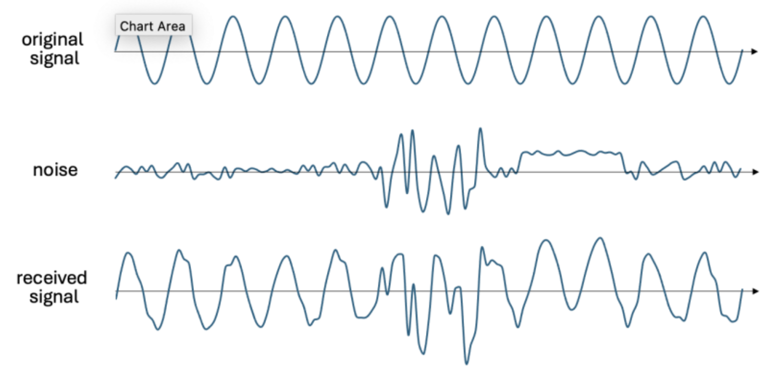
two meanings/usage of "bandwidth"

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

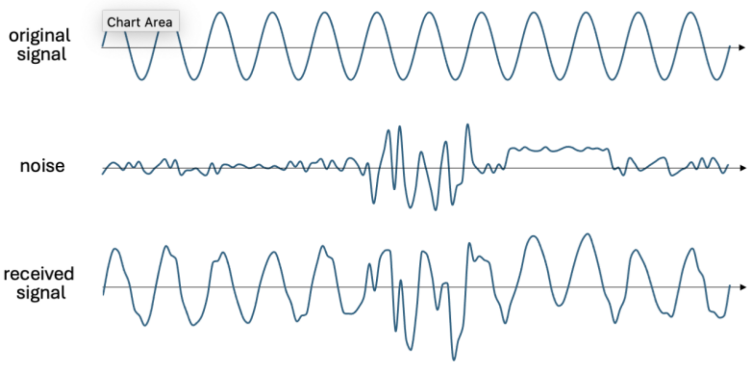
Signal to Noise Ratio (SNR)

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

Wireless link characteristics: path loss

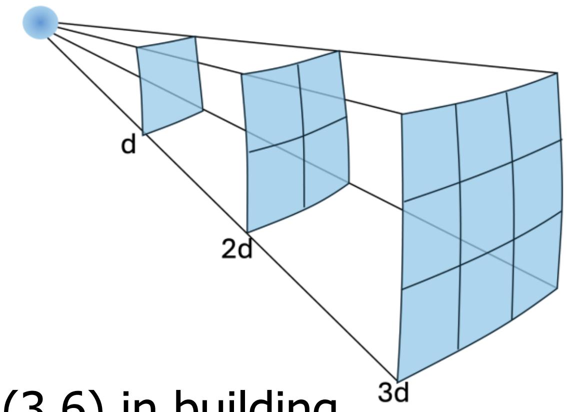
Wireless radio signal attenuates (loses power) as it propagates

path loss

(aka *fading*) reduction in power density (attenuation) of an electromagnetic wave as it propagates from transmitter to receiver

$$\frac{P_{received}}{P_{transmitted}} \sim \frac{1}{(fd)^2}$$

f: frequency
d: distance

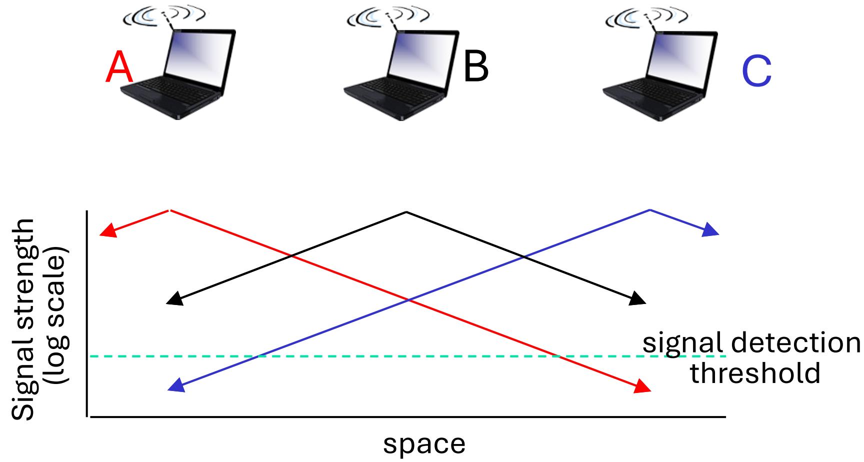


Generalized path loss ~ $(fd)^n$:

- n=2 (free space), n=(2.7,3.5) urban, n= (3,6) in building

“Hidden terminal problem” recalling
~ $(fd)^2$ path loss

Signal fading with~ $(d)^2$ path loss, causes a “hidden terminal” problem:

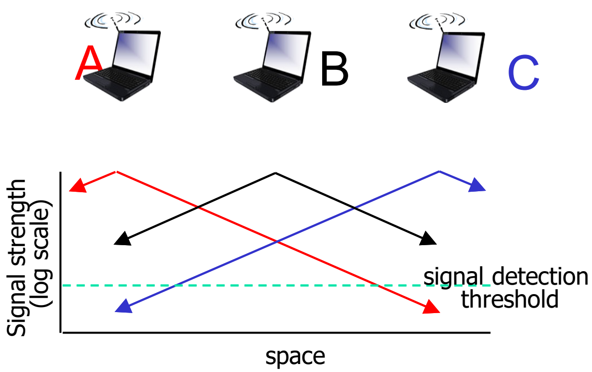


hidden terminals: A and B can hear each other, B and C can hear each other, but A and C can not hear each other

- complicates wireless channel sharing among A, B, C

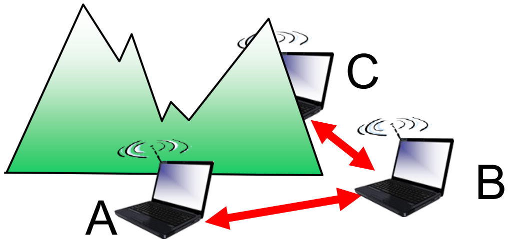
Wireless link characteristics: hidden terminals

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

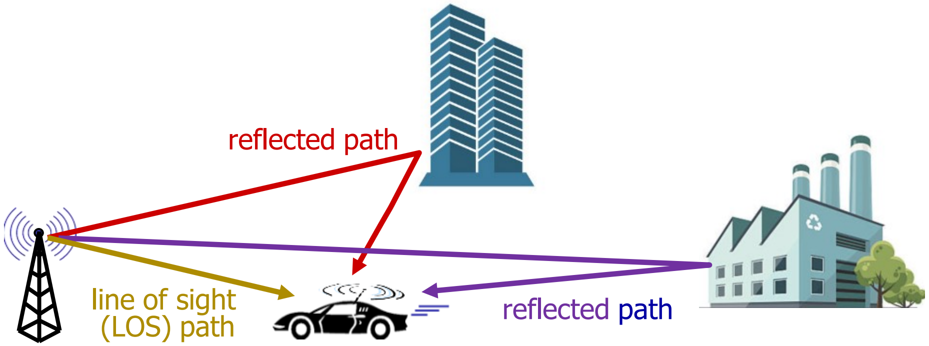
Objects cause "hidden terminals"



- 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

Wireless link characteristics: multipath

multipath propagation: radio signal reflects off objects ground, built environment, arriving at destination at slightly different times



Wireless link characteristics: multipath

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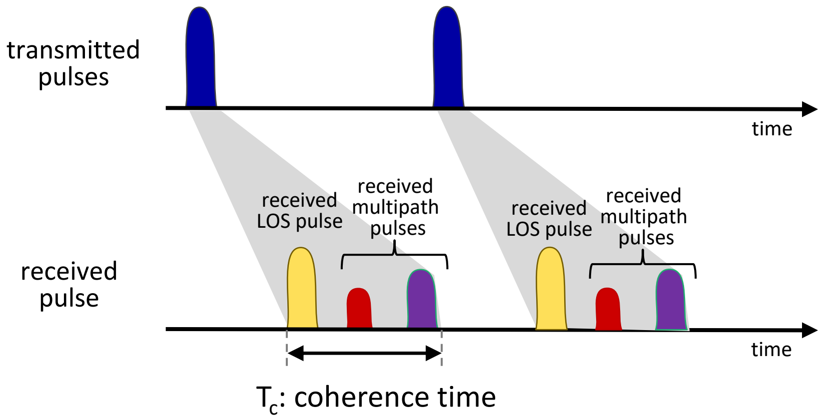


Coherence time:

- amount of time bit is present in channel to be received
- influences maximum possible transmission rate, since coherence times can not overlap
- inversely proportional to
  - frequency
  - receiver velocity

Wireless Link Characteristics

Differences from wired link ….

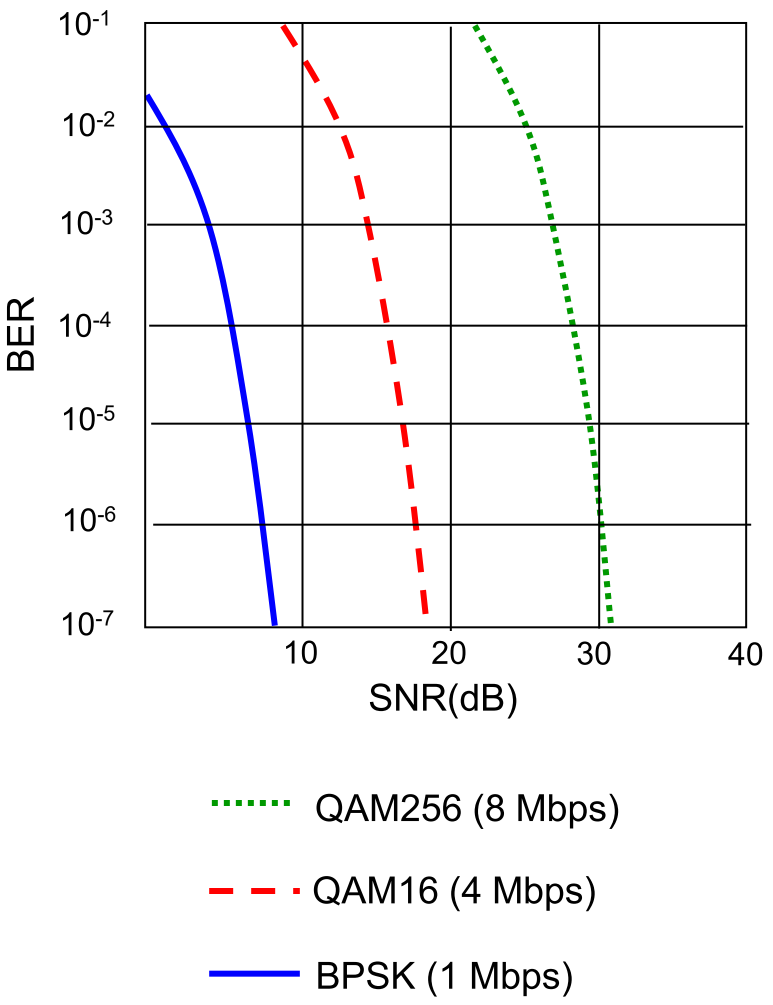
- Decreasing signal strength: radio signal attenuates as it propagates through matter (path loss)
- Interference from other sources: standardized wireless network frequencies (e.g., 2.4 GHz) shared by other devices (e.g., phone); devices (motors) interfere as well
- Multi-path propagation: radio signal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

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

- Higher error rates; lower bandwidths; non-uniform transmission characteristics; increased usage costs; and increased susceptibility to interference and eavesdropping

Wireless Link Characteristics

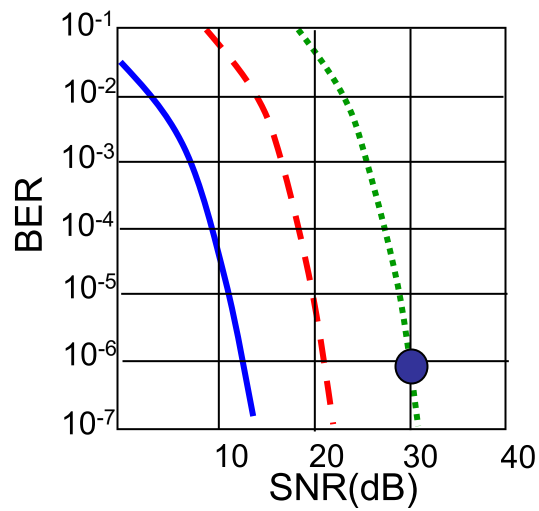
- SNR: signal-to-noise ratio
  - larger SNR – easier to extract signal from noise (a "good thing")
- *SNR versus BER tradeoffs*
  - *given physical layer:* increase power -> increase SNR -> decrease BER
  - *given SNR:* choose physical layer that meets BER requirement, giving highest throughput

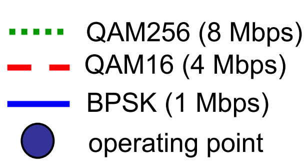


802.11: advanced capabilities

Rate Adaptation

- base station, mobile dynamically change transmission rate (physical layer modulation technique) as mobile moves, SNR varies



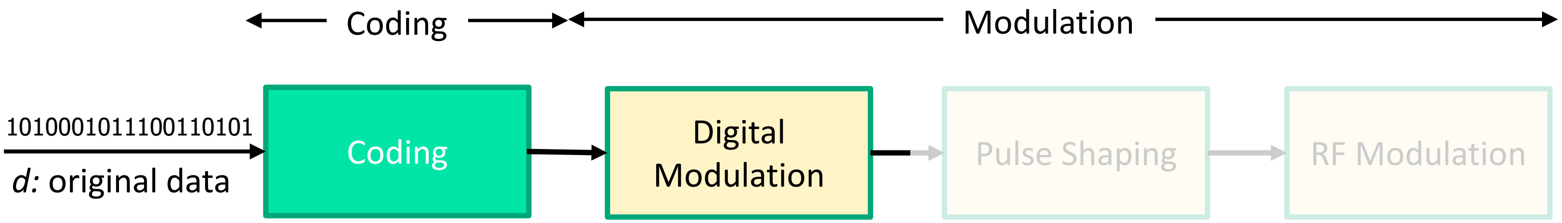


1. SNR decreases, BER increase as node moves away from base station

2. When BER becomes too high, switch to lower transmission rate but with lower BER

How can this be done?

Physical Layer: coding and modulation



Add error detection, correction bits at physical layer

Choose digital modulation technique that maximizes number of reliably transmitted bits/sec based on observed channel impairments e.g., in family of Quadrature amplitude modulation (QAM)

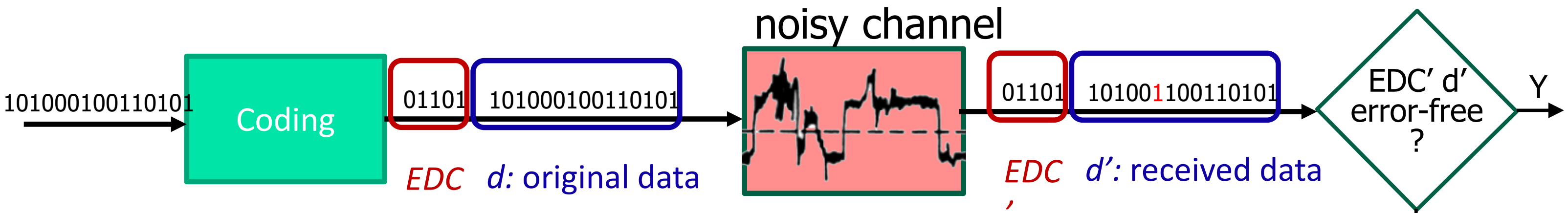
match transmission bandwidth to channel bandwidth using pulse shaping

transmit signal as an electromagnetic wave over assigned *carrier frequency*

We won't cover this (look at ECE for courses)

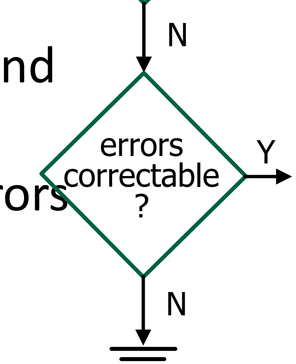
Carrier: waveform at a given frequency, f_c (carrier frequency), modified (modulated) with an information-bearing signal

Physical Layer: Error detection, correction coding



EDC: error detection, correction bits
- additionally transmitted bits (in addition to *d*)
- added so receiver can detect and possibly correct errors in *d* bits
- example: parity bits, redundancy bits

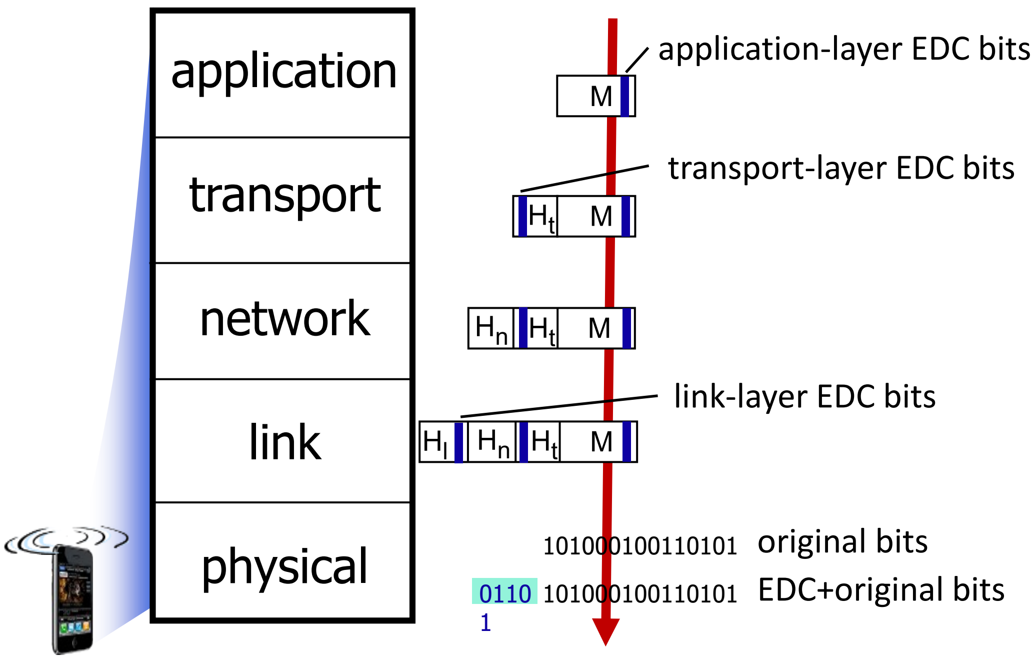
- received *EDC'* and received *d'* bits may contain errors



EDC used at many layers: channel (physical), link, network, transport, application layers

Physical Layer: Error detection, correction coding

Wireless *physical layer* may add EDC bits, into addition to:

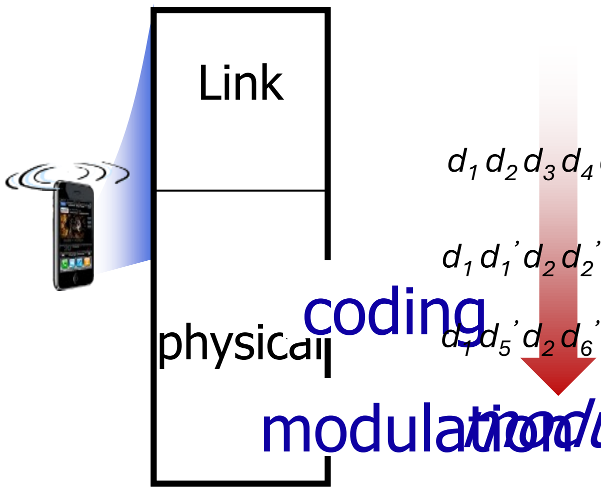


adding physical-layer EDC makes sense!

- detect/recover locally, rather than wait for end-end
- physical layer techniques adapted to local radio error characteristics

Physical Layer: EDC shuffling example

A burst of noise in this interval causing 3 bits to be unintelligible , with no shuffling, would mean receiver can not determine d_4



$d_1 d_2 d_3 d_4 d_5 d_6 d_7 d_8$ — original bits from link layer, including EDC

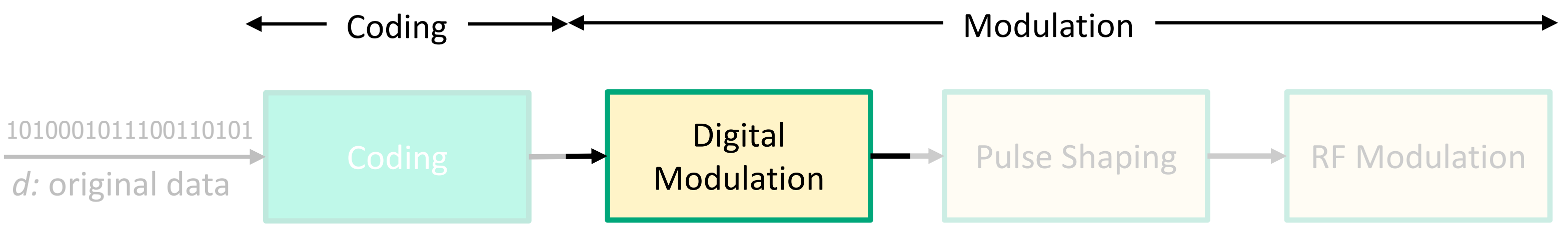
$d_1 d_1' d_2 d_2' d_3 d_3' d_4 d_4' d_5 d_5' d_6 d_6' d_7 d_7' d_8 d_8'$ — *add* EDC duplicate bits in PHY

$d_1 d_5' d_2 d_6' d_3 d_7' d_4 d_8' d_5 d_1' d_6 d_2' d_7 d_3' d_8 d_4'$ — *shuffle* for resistance to burst errors

modulation: from bits to symbols to waveforms

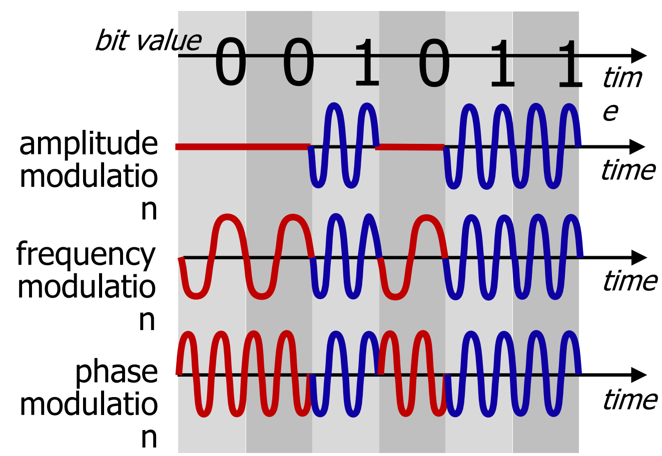
A burst of noise in this interval, causing 3 bits to be unintelligible still allows receiver to determine all original bits

Modulation



digital modulation

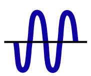
encoding bits (1's, 0's) into analog RF carrier signal by changing ("**modulating**") a characteristic of the RF carrier signal: *amplitude, frequency, or phase.*



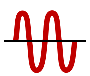
Modulation schemes: ASK, PSK

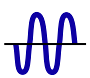
Amplitude shift keying (ASK): signal's *amplitude* encodes bits

0:

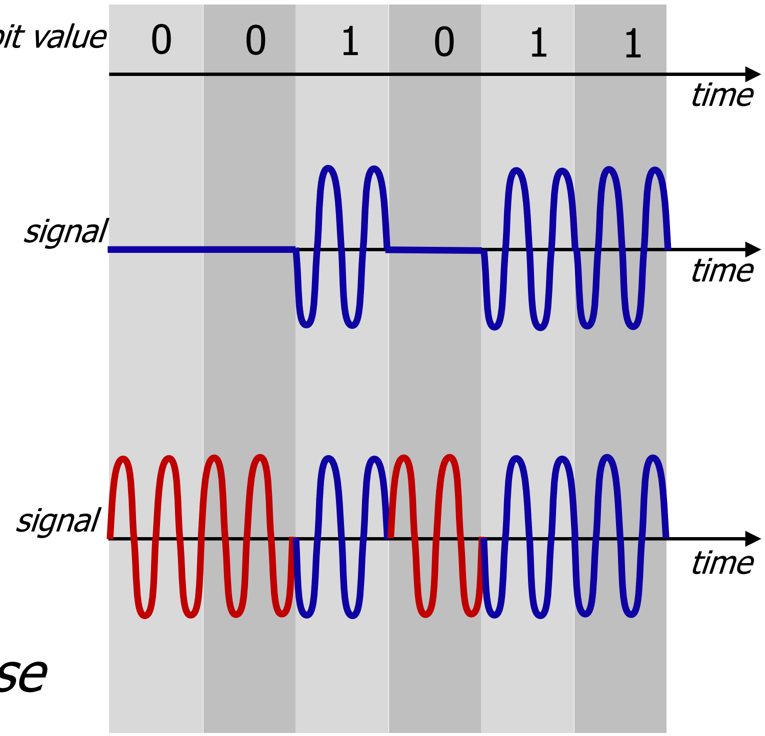
1: 

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

0: 

1: 

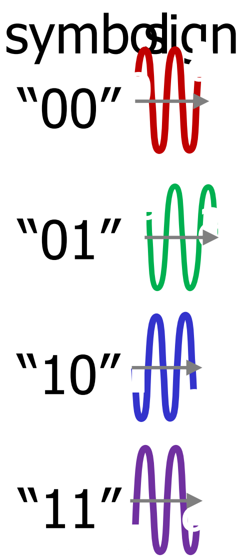
PSK: 0 and 1 signals *out of phase* by 180°, but at same carrier frequency

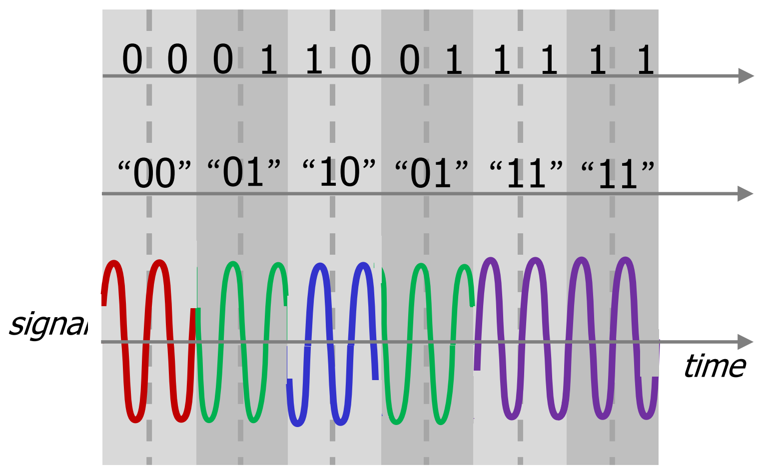


Modulation schemes: QPSK

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



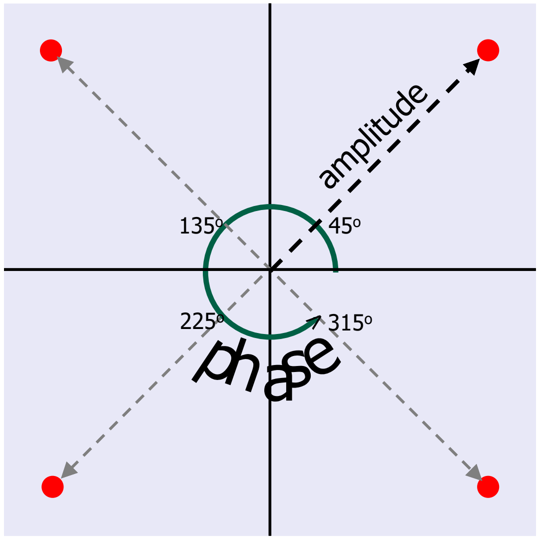


QPSK frequency same as BPSK, but twice the data rate!

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

Constellation diagrams

graphical characterization of modulation: amplitude, phase of symbols



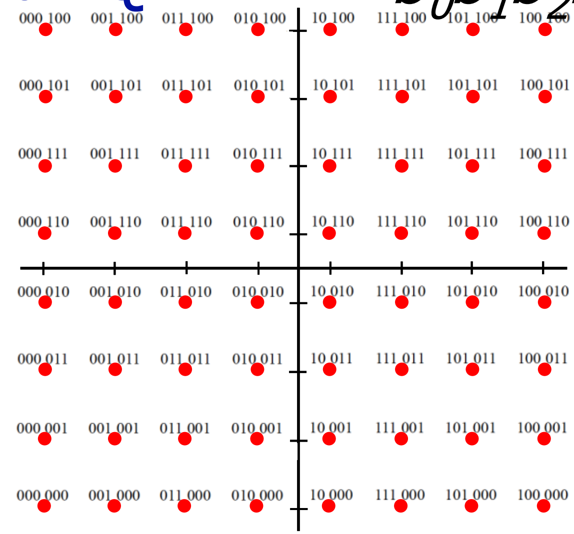
QPSK constellation diagram

- 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*

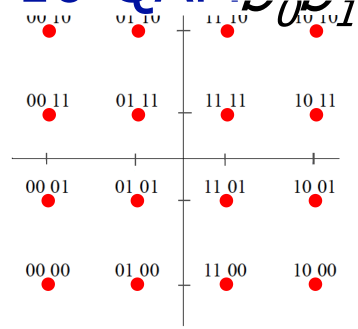
QAM: Quadrature Amplitude Modulation

- generalizing QPSK
- *m*-QAM: using *m* different amplitude/phase values to encode log2(m) bits

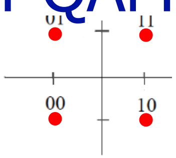
64-QAM $b_0b_1b_2b_3b_4b_5$



16-QAM $b_0b_1b_2b_3$

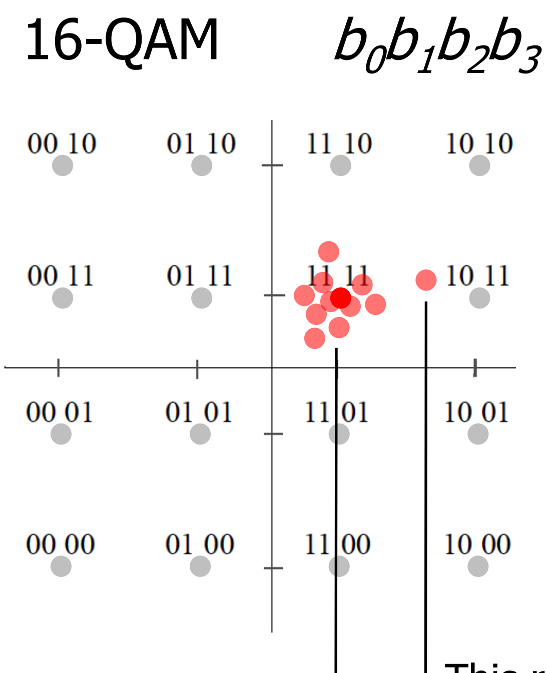


4-QAM b_0b_1



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

Constellation diagrams: how bit errors occur



These received signals correctly classified as 1111 (received amplitude, phases closest to 1111)

This received signal, is misclassified as 1011 since its amplitude, phases are closer to 1011 than 1111

Transmitter transmits waveforms for 12 1111 symbols, sequentially

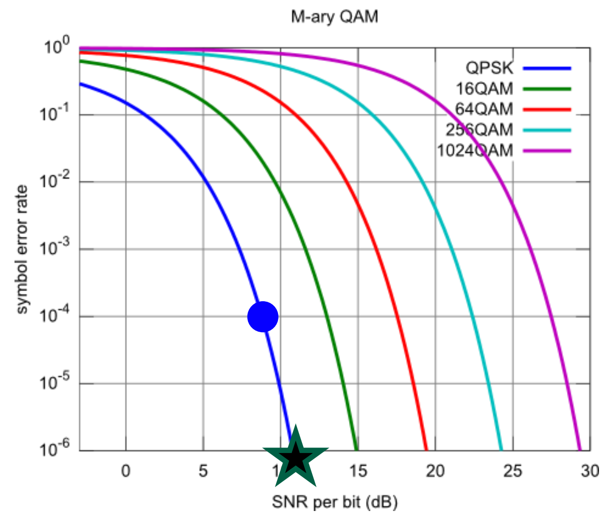
- phase/amplitude of transmitted signal
- phase/amplitude of received signals

- receiver measures amplitude, phase of received signal
- receiver classifies symbol as bit pattern with amplitude, phase closest to received signal amplitude, phase

Adaptive modulation

given modulation scheme :

- has nominal data rate (assuming no errors)
- SNR can increase/decrease:
  - changing interference
  - sender transmitter power
- move along SNR vs BER tradeoff curve



Idea: change modulation scheme, power on the fly, getting highest data rate possible (at acceptable BER, acceptable energy expenditure), as SNR changes

Max data rate:

16 QAM: 11.5 Mbps

64 QAM: 26.9 Mbps

Extra slides …