Lecture 11
Introduction to Wireless

Mobile

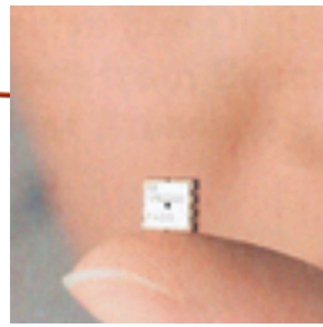
Evolution

What has changed?

Wireless Home

Wireless Robots

Wireless devices that saves the world



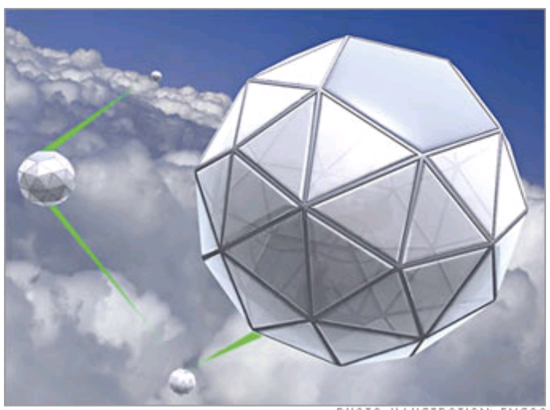
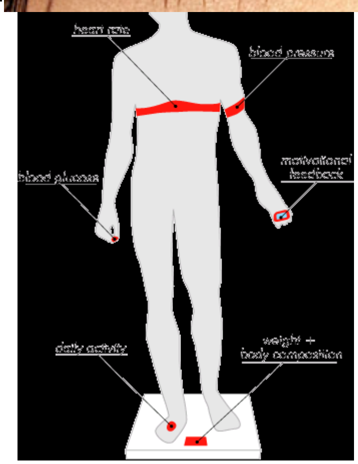
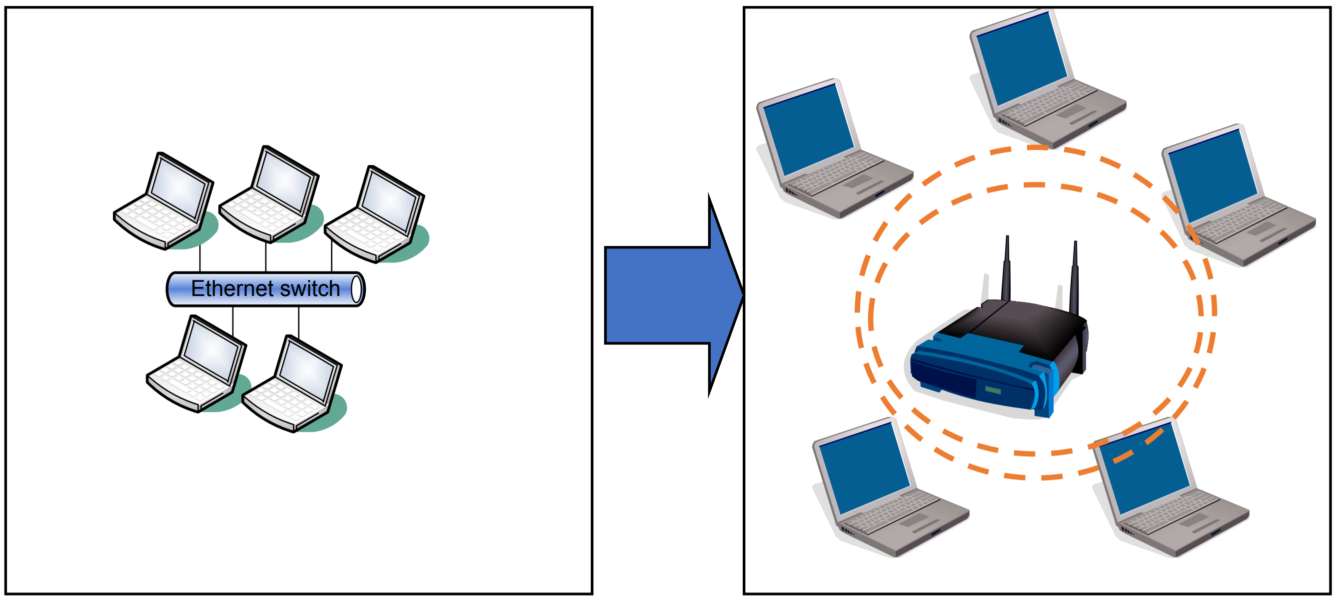


PHOTO-ILLUSTRATION: ENSCO



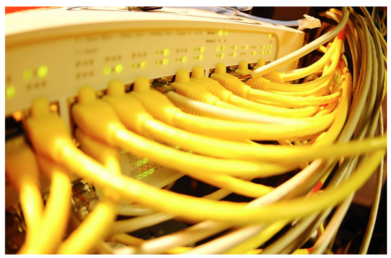
Part 1:
What Makes Wireless Different?

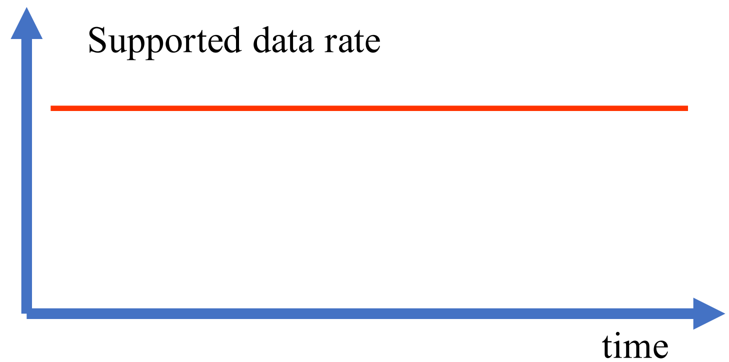
From Wired to Wireless

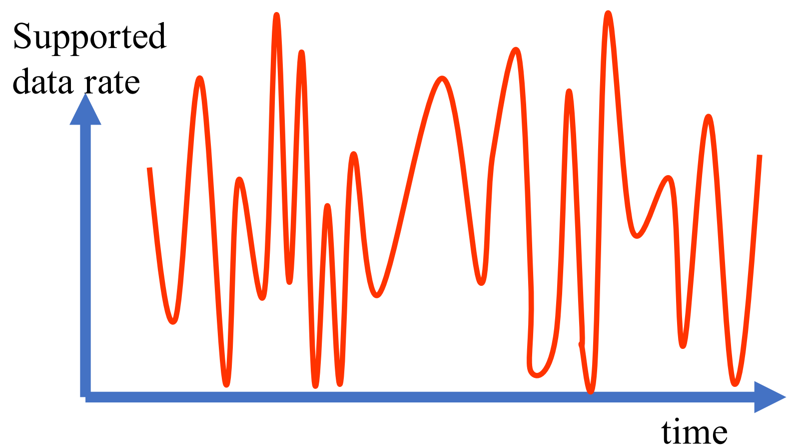


How Does Your Voice Travel?

The Difference: # 1



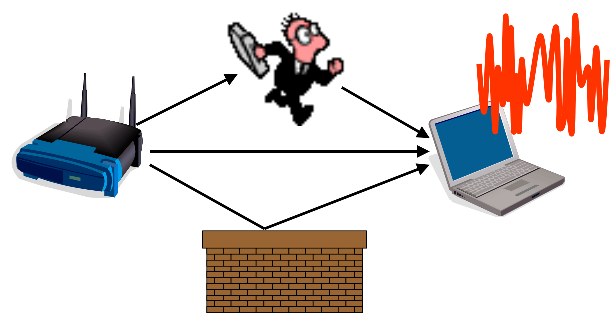




Why?

$$P(recv) = \frac{P(tran) \cdot A \cdot H}{4\pi d^2}$$

- Radio wave propagates (like your voice)
  - Decreasing signal strength
  - Radio waves lose energy due to absorption or scattering
  - Multi-path fading: reflections from multiple objects; time varying due to mobility



Path Loss / Path Attenuation

- Free Space Path Loss:

  d = distance

  λ = wave length

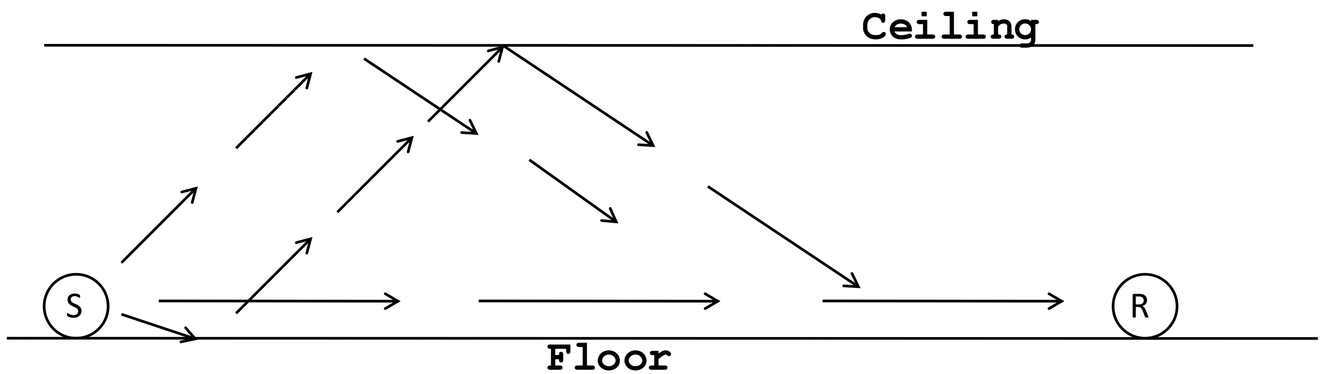
  f = frequency

  c = speed of light

$$\mathrm{FSPL} = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi d f}{c}\right)^2$$

- Reflection, Diffraction, Absorption
- Terrain contours (Urban, Rural, Vegetation).
- Humidity

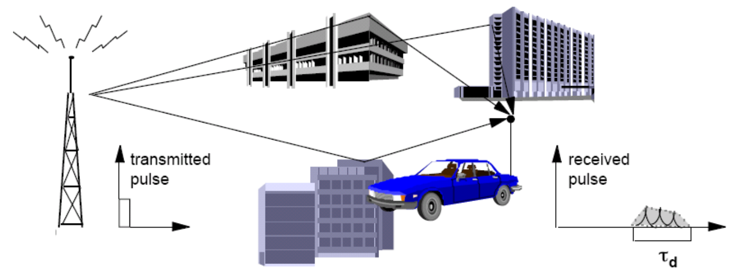
Multipath Effect



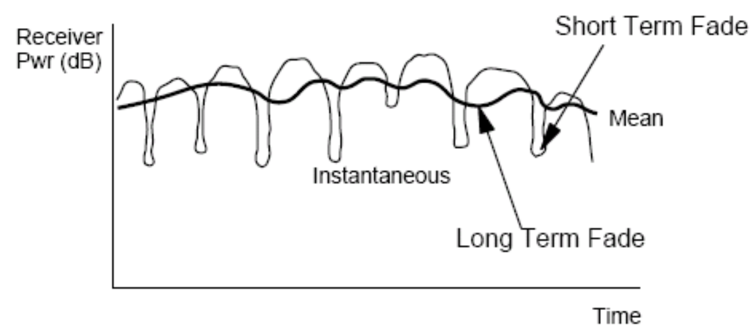
- Signals bounce off surface and interfere with one another
- Self-interference

Mobility Effect

- Mobility creates fluctuations of signal
- Large scale fades
  - Attenuation: in free space, power degrades by $1/d^2$
  - Shadows: signals blocked by obstructing structures

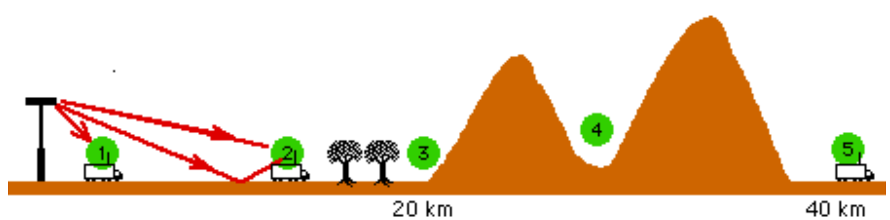


- Small scale fades
  - Multipath effects:
    - Rapid changes in signal strength over a small area or time interval
  - Movement of surrounding objects!

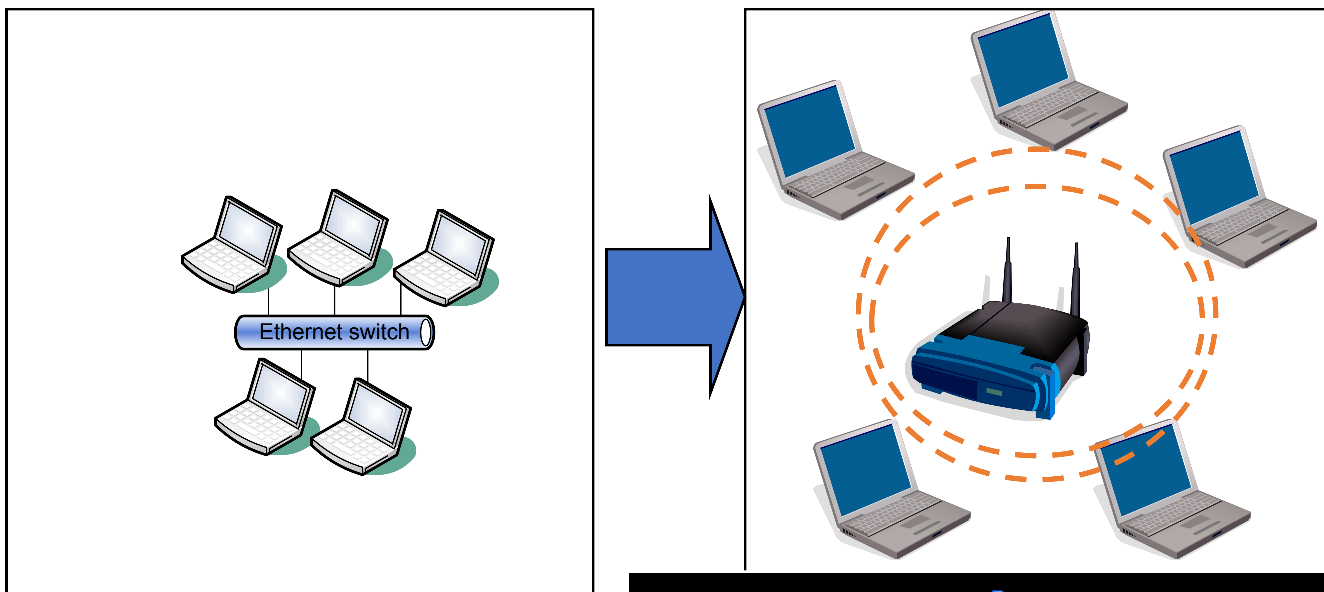


Radio Propagation 101

- Reflection
  - Propagating wave impinges on an object which is large compared to wavelength
  - E.g., the surface of the Earth, buildings, walls, etc.
- Diffraction
  - Radio path between transmitter and receiver obstructed by surface with sharp irregular edges
  - Waves bend around the obstacle
- Scattering
  - Objects smaller than the wavelength of the propagating wave
  - E.g., foliage, street signs, lamp posts



The Difference #2



Broadcast →interference

Why?

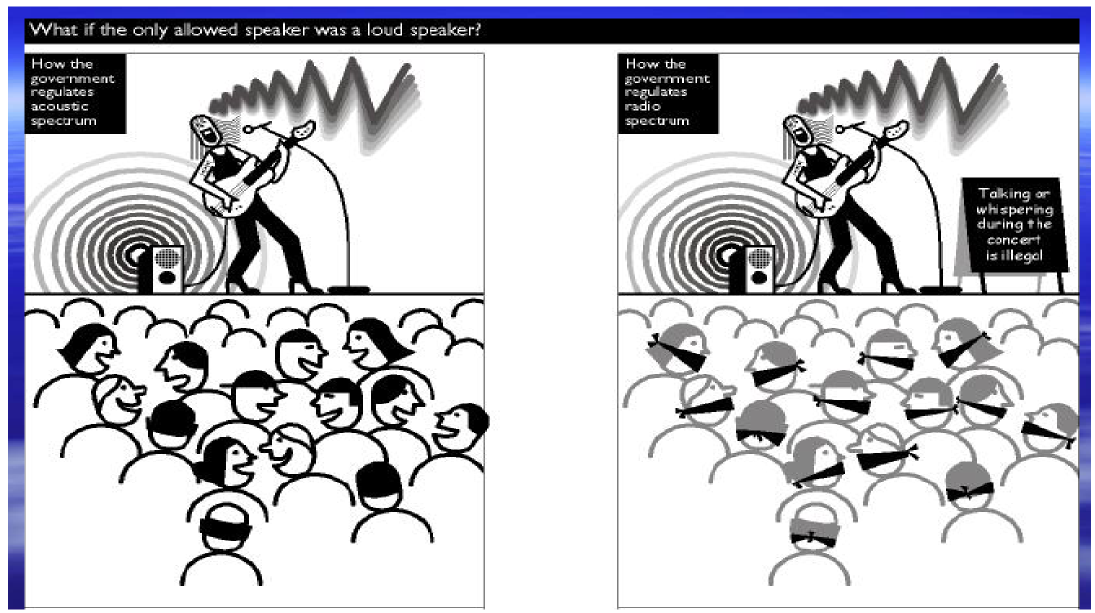
- Interference
  - Your signal is noise to others
  - Broadcast nature

$$\text{signal-to-noise-ratio}$$

$$SNR = \frac{P(recv)}{\text{noise} + \text{interference}}$$

$$rate \propto W \log(1 + SNR)$$

$$W : bandwidth$$



Interference from Other Sources

- External Interference
  - Microwave oven is turned on and blocks your signal
  - Would that affect the sender or the receiver?

- Internal Interference
  - Nodes (of the same network) within range of each other collide with one another's transmission

- We have to tolerate external interference and path loss, multipath, etc. but we can avoid internal interference!

Summary: What Makes Wireless Different?

- Broadcast medium…
  - Anybody in proximity can hear and interfere
- Cannot receive while transmitting…
  - Our own (or nearby) transmission is deafening our receiver
- Signals sent by sender don't always end up at receiver intact
  - Complicated physics involved

Artifact 1: Wireless Bit/Packet Errors

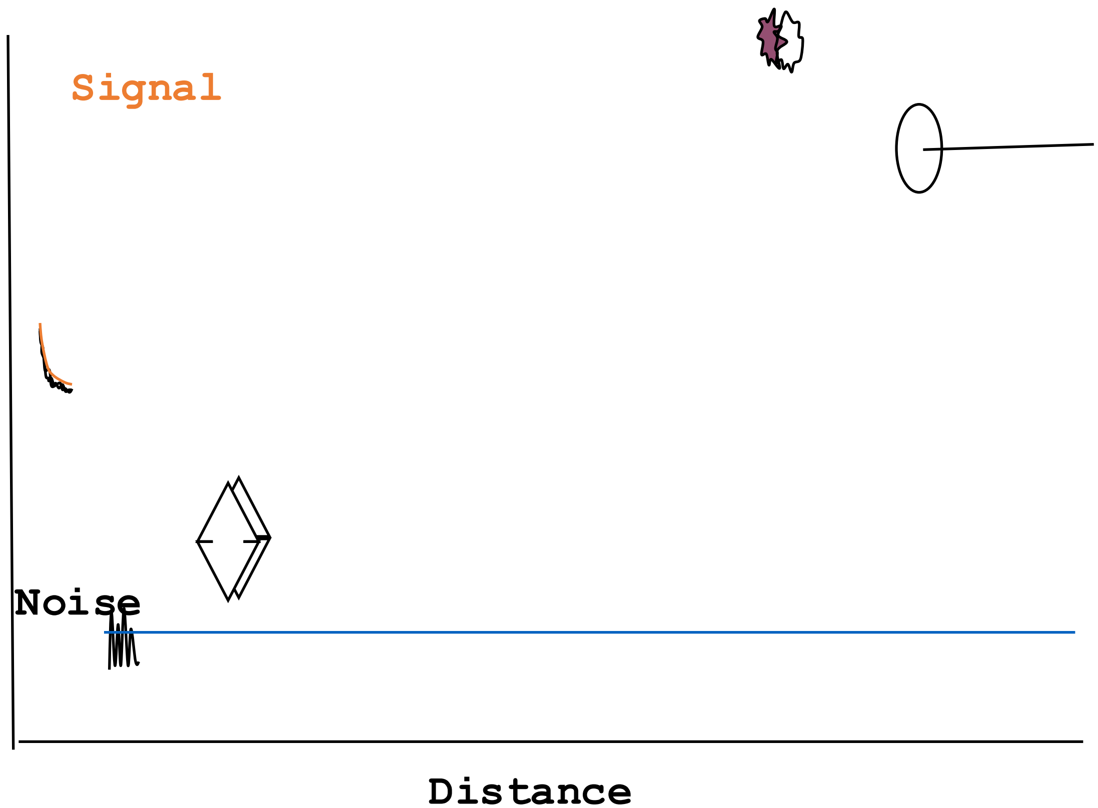
- The lower the SNR (Signal/Noise) the higher the Bit Error Rate (We could make the signal stronger…
- Why is this not always a good idea?
  - Increased signal strength requires more power
  - Increases the interference range of the sender, so you interfere with more nodes around you
    - And then they increase their power…….
- How would TCP behave in face of wireless losses?
- Local link-layer Error Correction schemes can correct some problems (should be TCP aware).

Artifact 2: Bitrate (aka data-rate)

- The higher the SNR (Signal to Noise Ratio) → the higher the (theoretical) bitrate.
- Modern radios use adaptive /dynamic bitrates.

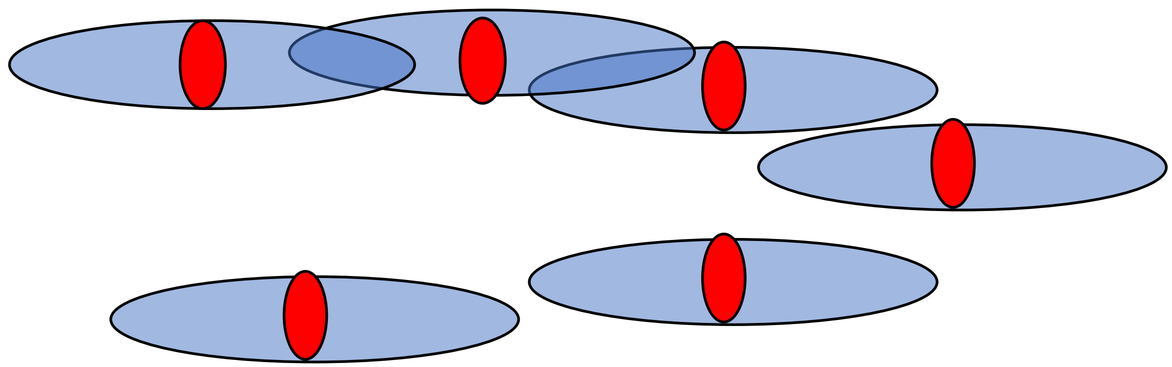
- Q: In face of loss,
  should we decrease or increase the bitrate?
- A:
  - If caused by free-space loss or multi-path fading, lower the bitrate.
  - If external interference - often higher bitrates (shorter bursts) are probabilistically better

The Amoeboed "cell"
(courtesy of David Culler, UCB)



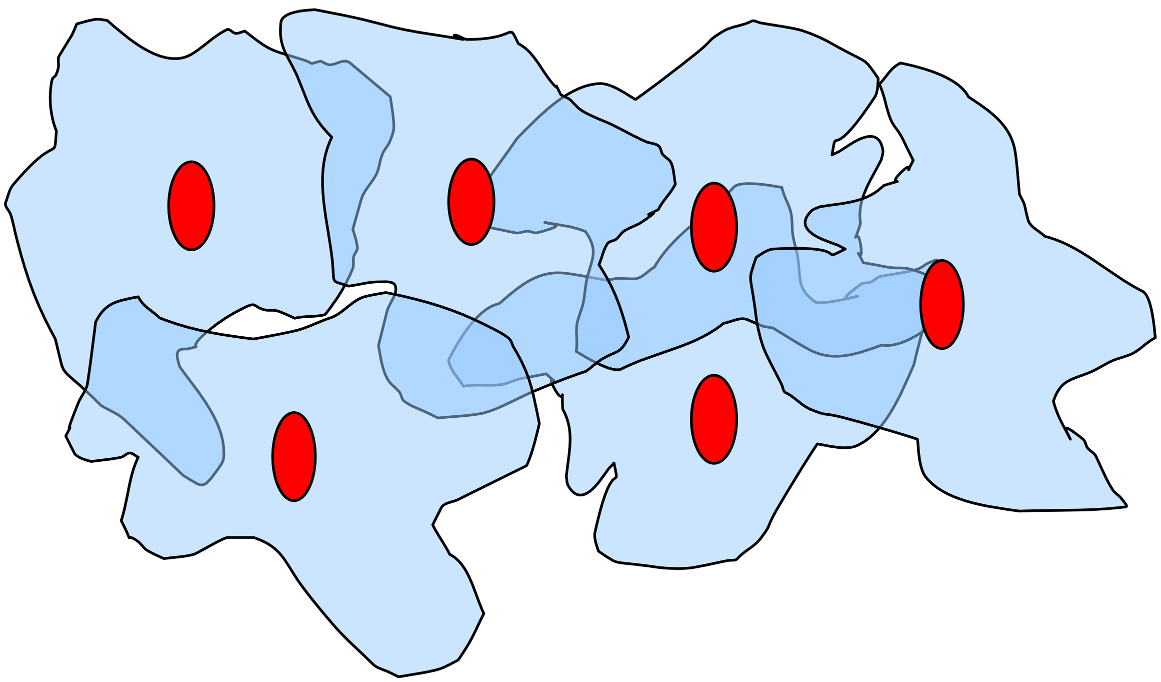
Ideal Radios

(courtesy of Gilman Tolle and Jonathan Hui, ArchRock)



Real Radios

(courtesy of Gilman Tolle and Jonathan Hui, ArchRock)



Metrics for evaluation / comparison of wireless technologies

- Bitrate or Bandwidth
- Range - PAN, LAN, MAN, WAN
- Stationary / Mobile
- Two-way / One-way
- Digital / Analog
- Multi-Access / Point-to-Point
- Applications and industries
- Operating environment

- Frequency - Wavelength

Frequency & Wave-Length

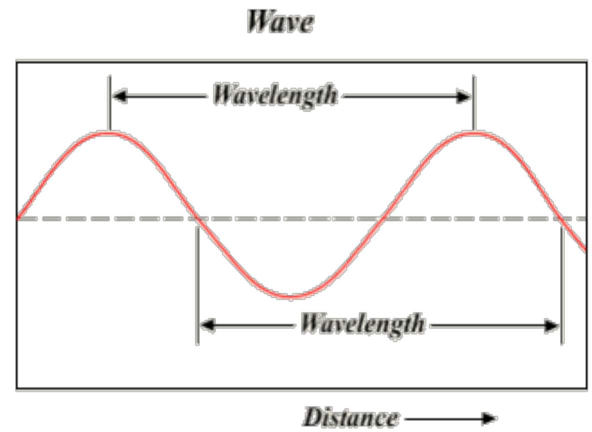
C is the speed of light
f is frequency
λ (lambda) is wavelength

Wavelength

$$\lambda = \frac{C}{f}$$

Frequency

$$f = \frac{C}{\lambda}$$

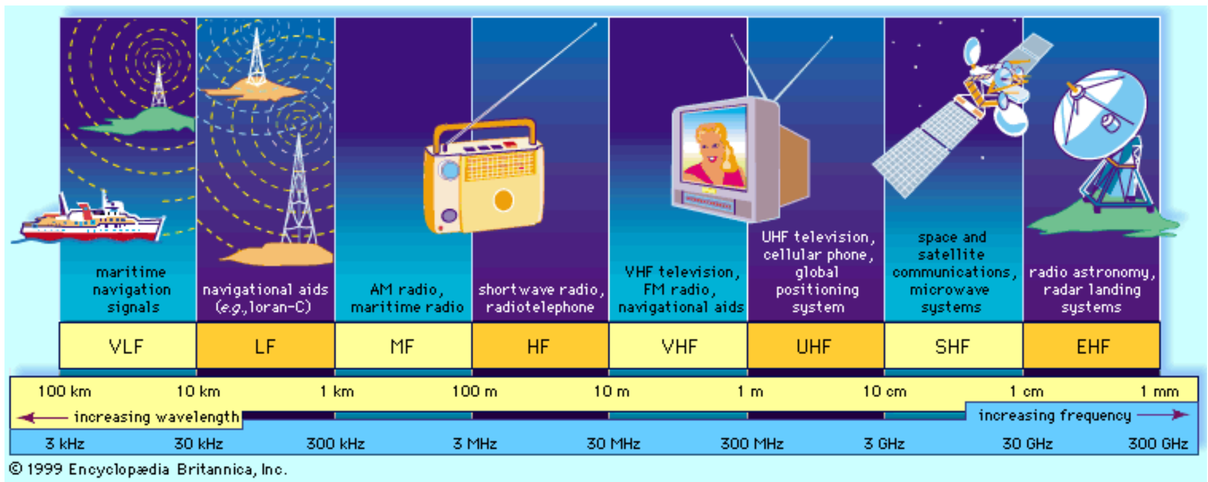


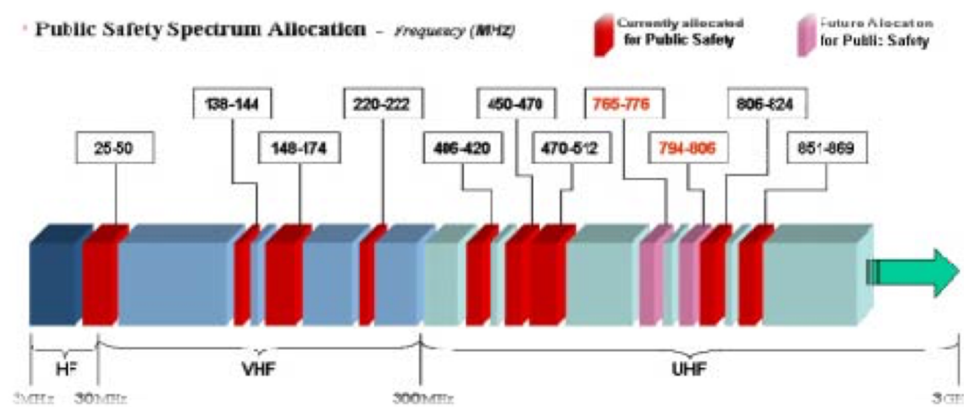
- Frequency: the number of cycles per second.
- Wavelength: the length of each cycle(in meters).

- Affects most physical properties:
  Distance (free-space loss)
  Penetration, Reflection, Absorption
  Size of antenna
  Energy proportionality

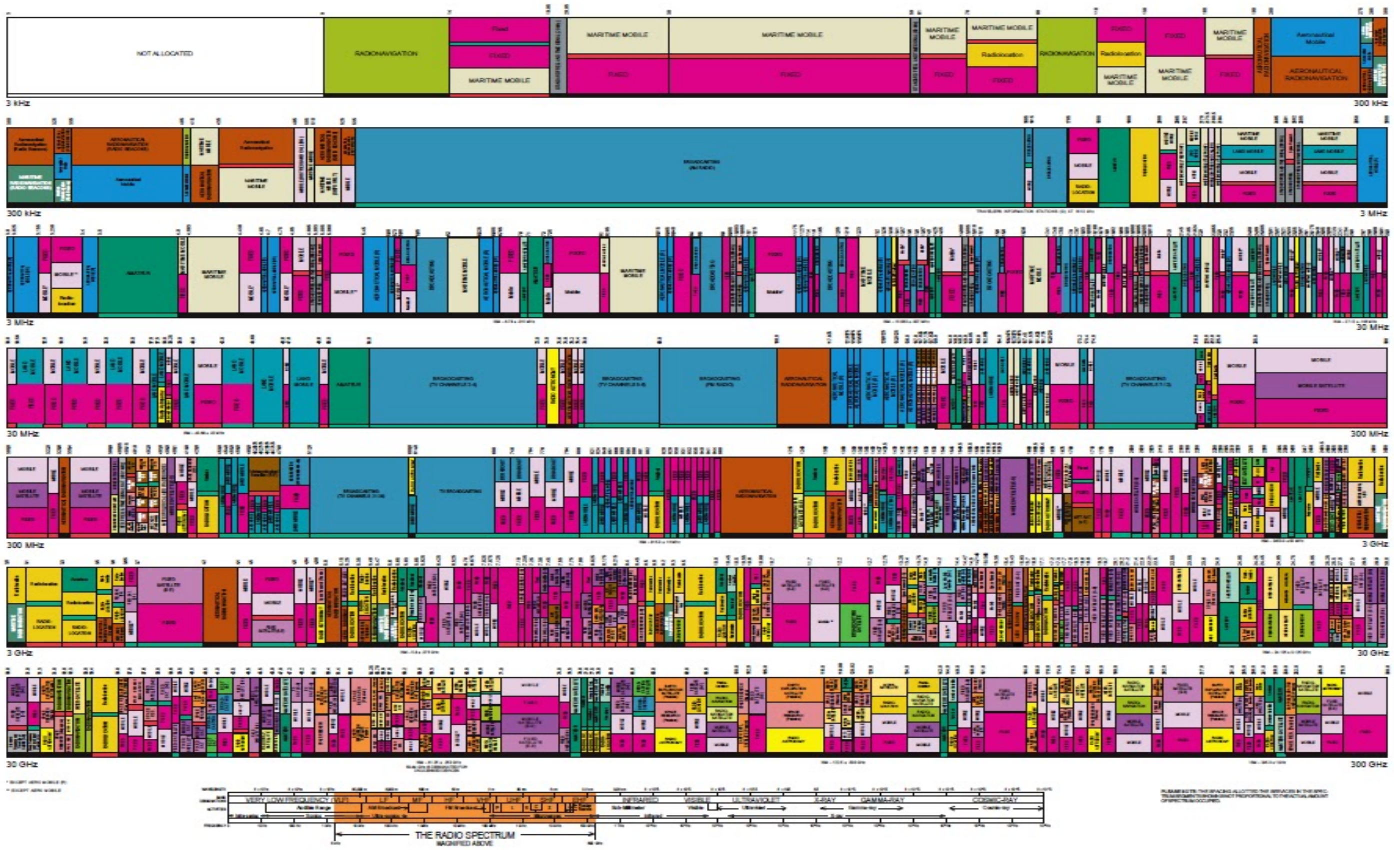
- Policy & law: Licensed / Deregulated

The Wireless Spectrum





United States Frequency Allocations



The wireless spectrum

- Allocated to license holders.
- Occasionally (rarely) a chunk gets auctioned – for billions of dollars.

- Q: Is spectrum a scarce resource?
  - Reclaim spectrum from old analog broadcasters.
  - White-spaces / Cognitive radios.
  - Tiered use policy.
  - Enable roaming (technically and commercially).

Part 2:
Why so many wireless technologies and standards?

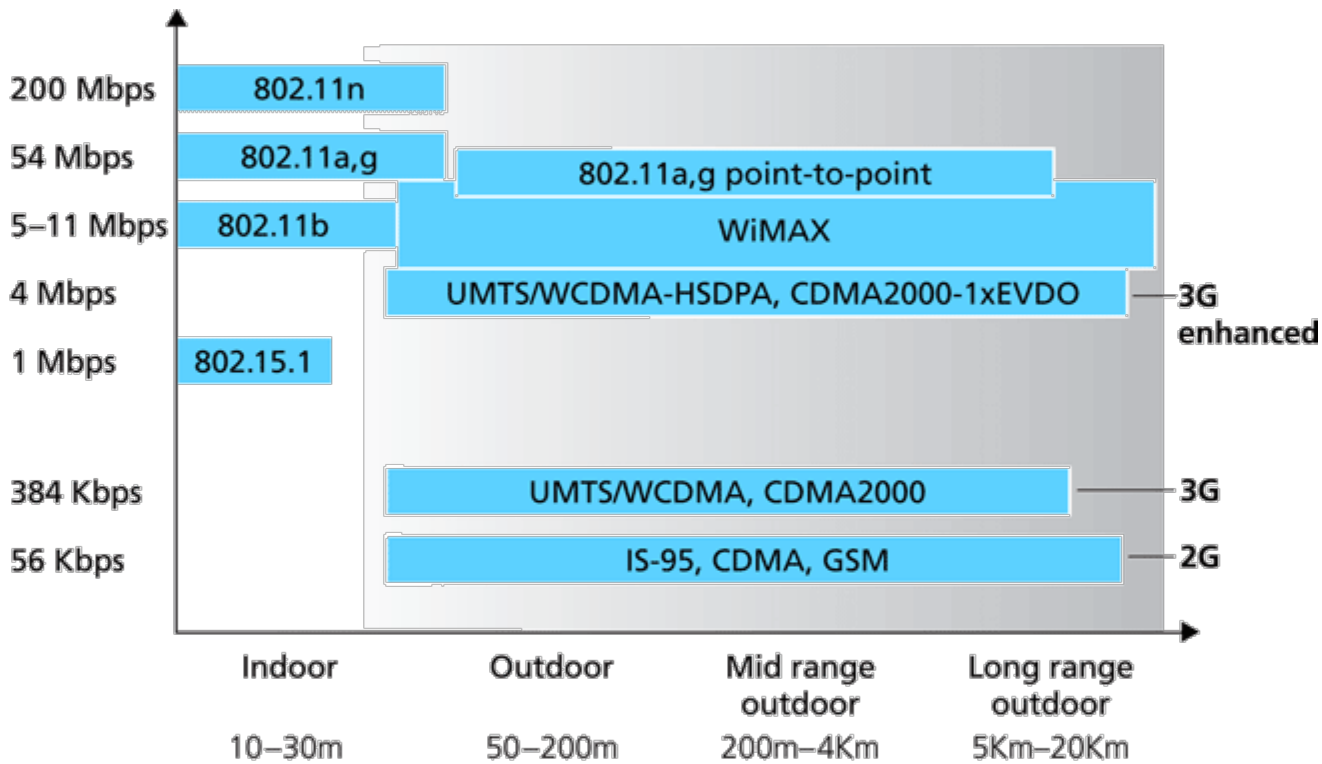
Common Wireless Standards

- Cellular (Typically 800/900/1800/1900Mhz):
  - 2G: GSM / GPRS /EDGE / CDMA / CDMA2000/
  - 3G: UMTS/HSDPA/EVDO
  - 4G: LTE, WiMax
  - 5G: mmWave LTE

- IEEE 802.11 (aka WiFi):
  - b: 2.4Ghz band, 11Mbps (*~4.5 Mbps operating rate*)
  - g: 2.4Ghz, 54-108Mbps (*~19 Mbps operating rate*)
  - a: 5Ghz band, 54-108Mbps (*~19 Mbps operating rate*)
  - n: 2.4/5Ghz, 150-600Mbps (4x4 mimo).
  - ac: 2.4/5Ghz, >1Gbps (4x4 mimo) (wide channels)
  - ad: 2.4/5Ghz/60GHz, >4Gbps (mmWave) (wide channels)

- IEEE 802.15 – lower power wireless:
  - 802.15.1: 2.4Ghz, 2.1 Mbps (Bluetooth)
  - 802.15.4: 2.4Ghz, 250 Kbps (Sensor Networks)

Wireless Standards



Antennas / Aerials

- An electrical device which converts electric currents into radio waves, and vice versa.

Gain: 2-3dB 8-12dB 15-18dB 28-34dB

Q: What does “higher-gain antenna” mean?

Q: What are omni-directional antennas?

How many wireless radios on your phone?

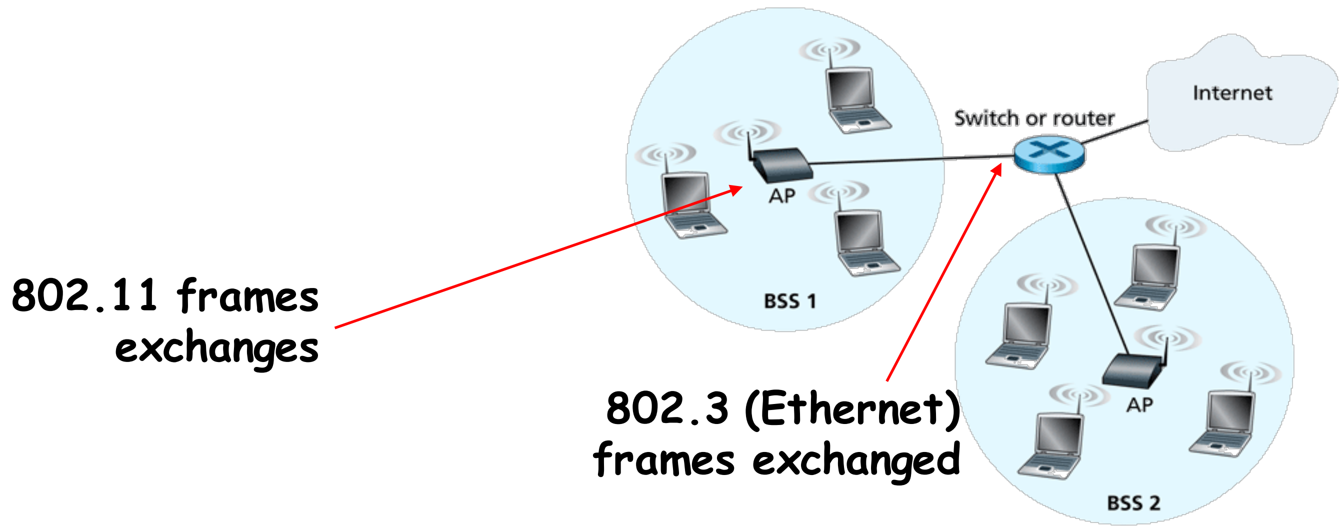
- WiFi 802.11n - 2.4 & 5Ghz (MiMo?)
- 2G – GSM "Quad band" 800/900 & 1800/1900mhz
- 3G – HSDPA+
- 4G – LTE
- Bluetooth
- NFC
- GPS Receiver
- FM-Radio receiver (antenna is the headphones cable)

Part 3:
802.11

aka - WiFi …
What makes it special?

Deregulation > Innovation > Adoption > Lower cost = Ubiquitous technology

802.11 Architecture



- Designed for limited area
- AP's (Access Points) set to specific channel
- Broadcast beacon messages with SSID (Service Set Identifier) and MAC Address periodically
- Hosts scan all the channels to discover the AP's
  - Host associates with AP

Wireless Multiple Access Technique

- Collision Detection
  - Where do collisions occur?
  - How can you detect them?

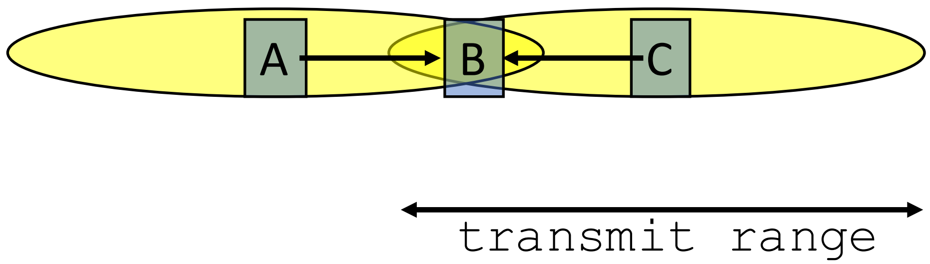
- Carrier Sense
  - Sender can listen before sending
  - What does that tell the sender?

Wireless Multiple Access Technique

- Collision Detection (Receiver)
  - Where do collisions occur?
  - How can you detect them?

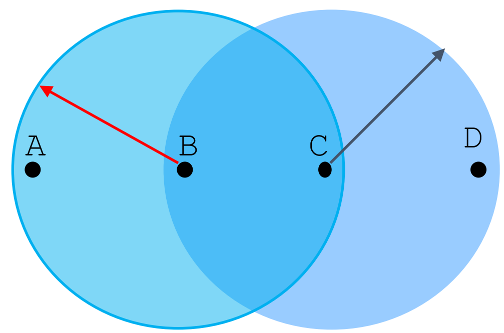
- Carrier Sense (Transmitter)
  - Sender can listen before sending
  - What does that tell the sender?

Hidden Terminals



- A and C can both send to B but can't hear each other
  - A is a *hidden terminal* for C and vice versa
- Carrier Sense will be ineffective

Exposed Terminals



- Exposed node: B sends a packet to A; C hears this and decides not to send a packet to D (despite the fact that this will not cause interference)!
- Carrier sense would prevent a successful transmission.

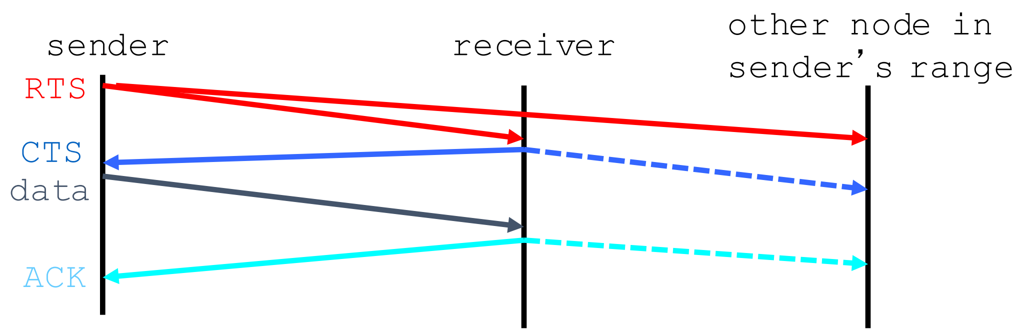
Key Points

- No concept of a global collision
  - Different receivers hear different signals
  - Different senders reach different receivers
- Collisions are at receiver, not sender
  - Only care if receiver can hear the sender clearly
  - It does not matter if sender can hear someone else
  - As long as that signal does not interfere with receiver
- Goal of protocol:
  - Detect if receiver can hear sender
  - Tell senders who might interfere with receiver to shut up

Basic Collision Avoidance

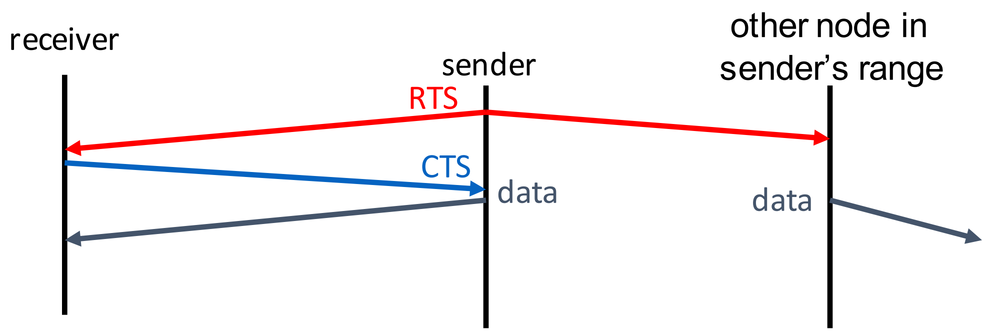
- Since can't detect collisions, we try to *avoid* them
- Carrier sense:
  - When medium busy, choose random interval
  - Wait that many **idle** timeslots to pass before sending
- When a collision is inferred, retransmit with binary exponential backoff (like Ethernet)
  - Use ACK from receiver to infer "no collision"
  - Use exponential backoff to adapt contention window

CSMA/CA - Collision Avoidance



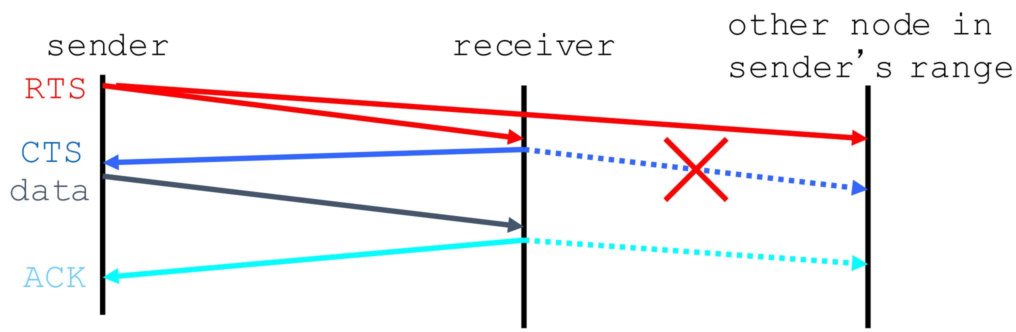
- Before every data transmission
  - Sender sends a Request to Send (RTS) frame containing the length of the transmission, and the destination.
  - Receiver respond with a Clear to Send (CTS) frame
  - Sender sends data
  - Receiver sends an ACK; now another sender can send data
- When sender doesn't get a CTS back, it assumes collision

CSMA/CA - Collision Avoidance



- If other nodes hear RTS, but not CTS: send
  - Presumably, destination for first sender is out of node's range …

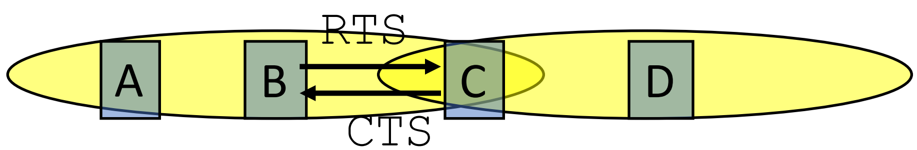
CSMA/CA -MA with Collision Avoidance



- If other nodes hear RTS, but not CTS: send
  - Presumably, destination for first sender is out of node's range …
  - … Can cause problems when a CTS is lost
- When you hear a CTS, you keep quiet until scheduled transmission is over (hear ACK)

RTS / CTS Protocols (CSMA/CA)

B sends to C

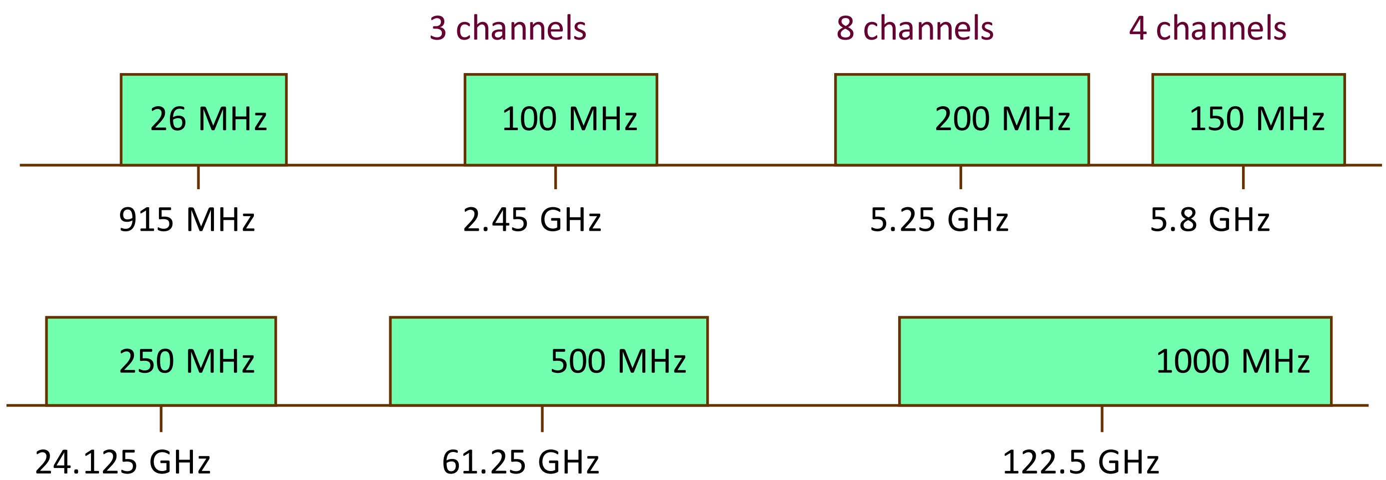


Overcome hidden terminal problems with contention-free protocol

1. B sends to C Request To Send (RTS)
2. A hears RTS and defers (to allow C to answer)
3. C replies to B with Clear To Send (CTS)
4. D hears CTS and defers to allow the data
5. B sends to C

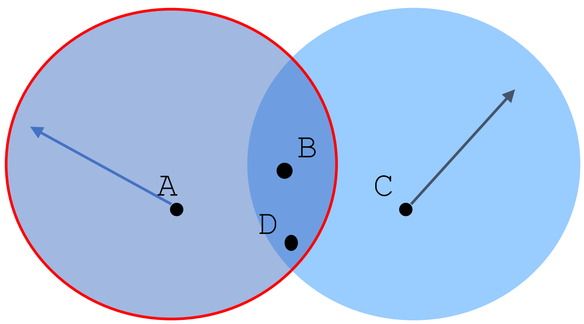
Channelization of spectrum

- Typically, available frequency spectrum is split into multiple channels
- Some channels may overlap



Preventing Collisions Altogether

- Frequency Spectrum partitioned into several channels
  - Nodes within interference range can use separate channels



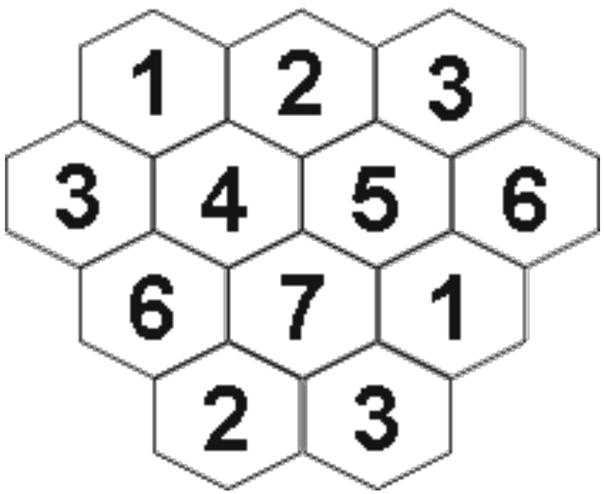
  - Now A and C can send without any interference!
  - Aggregate Network throughput doubles

Using Multiple Channels

- 802.11: AP's on different channels
  - Usually manually configured by administrator
  - Automatic Configuration may cause problems
- Most cards have only 1 transceiver
  - **Not Full Duplex: Cannot send and receive at the same time**
- Multichannel MAC Protocols
  - Automatically have nodes negotiate channels
    - Channel coordination amongst nodes is necessary
    - Introduces negotiation and channel-switching latency that reduce throughput

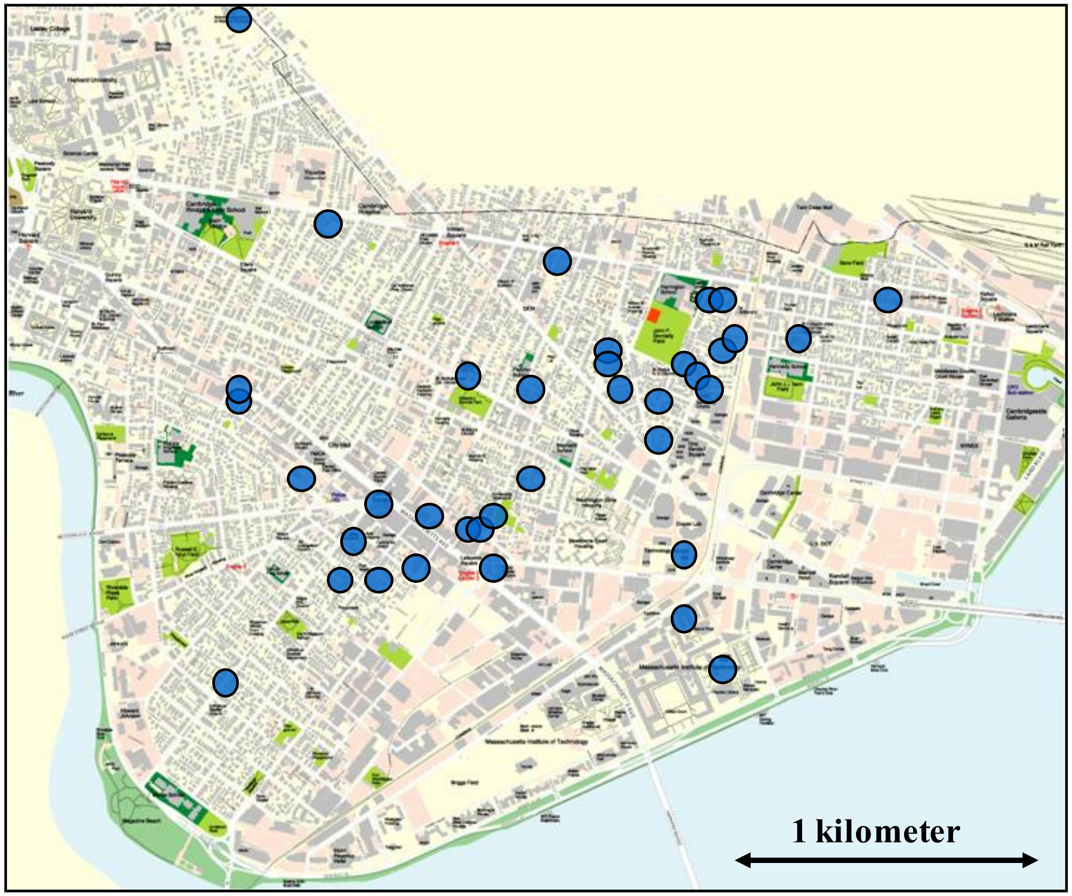
Preventing Collisions Altogether

Partition space into non-overlapping cells.

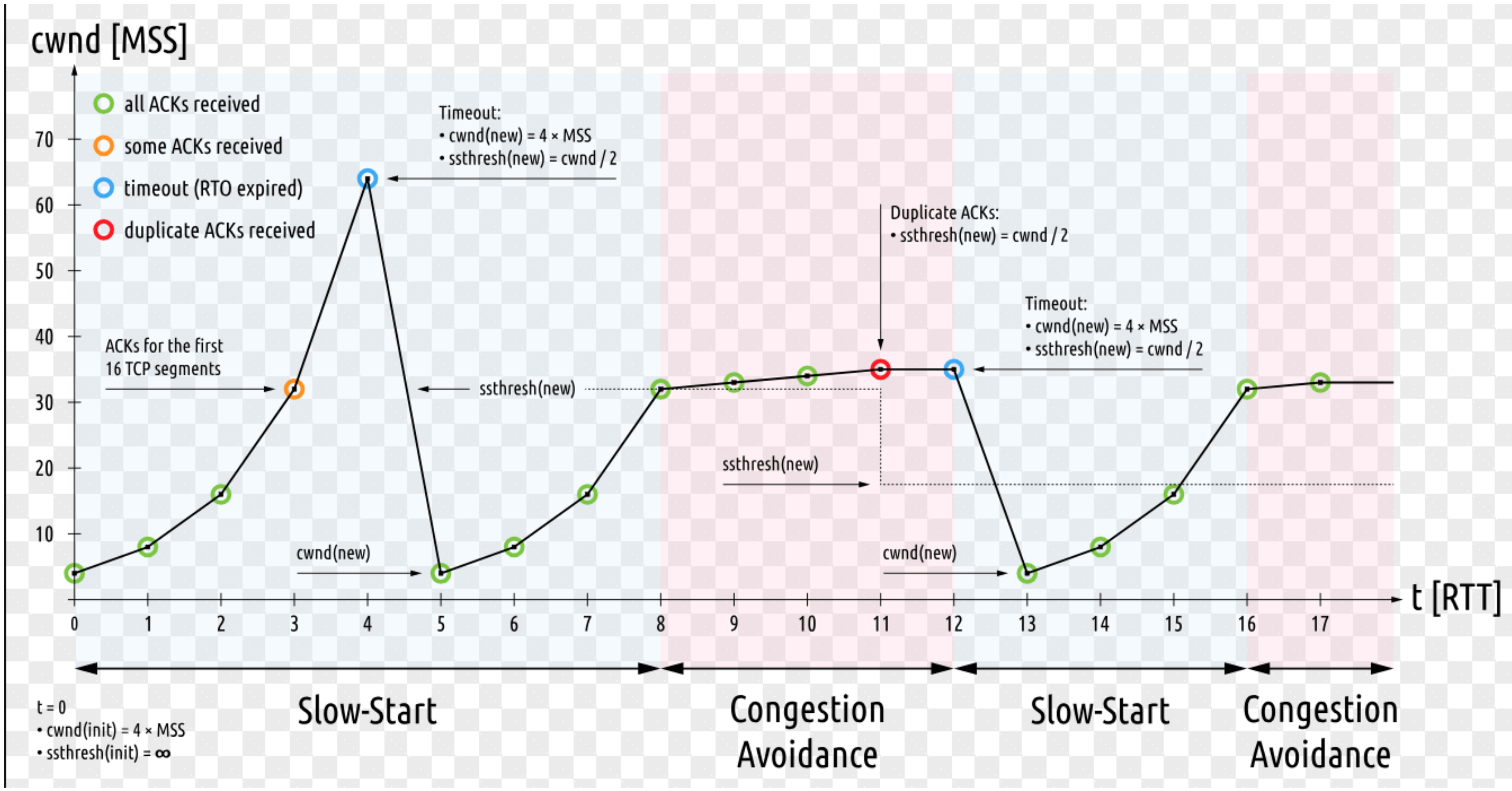


Large Multihop Network

(courtesy of Sanjit Biswas, MIT)



Quick Quiz



cwnd [MSS]
all ACKs received
some ACKs received
timeout (RTO expired)
duplicate ACKs received
Timeout:
• cwnd(new) = 4 × MSS
• ssthresh(new) = cwnd / 2
Duplicate ACKs:
• ssthresh(new) = cwnd / 2
Timeout:
• cwnd(new) = 4 × MSS
• ssthresh(new) = cwnd / 2
ACKs for the first
16 TCP segments
ssthresh(new)
ssthresh(new)
cwnd(new)
cwnd(new)
70
60
50
40
30
20
10
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
t [RTT]
Slow-Start
Congestion Avoidance
Slow-Start
Congestion Avoidance
t = 0
• cwnd(init) = 4 × MSS
• ssthresh(init) = ∞