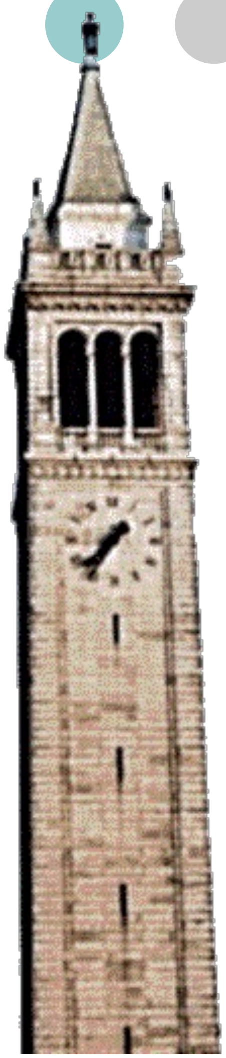

Wireless Communications and Networking

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UC Berkeley

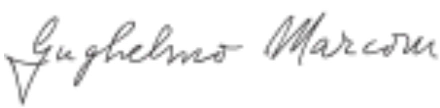
CS 168: Introduction to Computer Networks
Spring 2024

Early History of Wireless

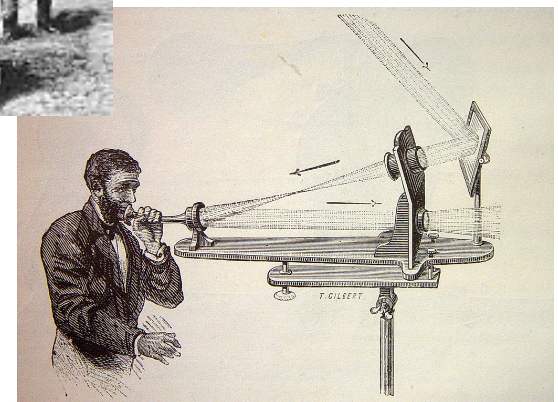
- ~1880: Photophone
  - Bell & Tainter

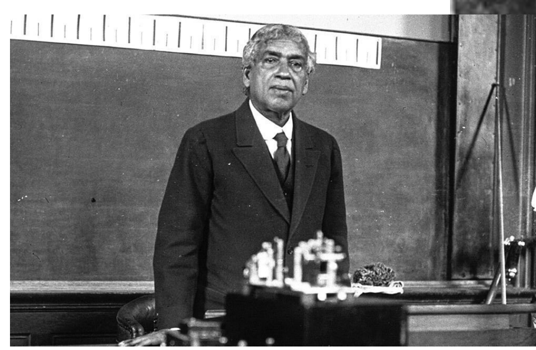
- ~1888: Radio Waves
  - Heinrich Hertz

- ~1894: Wireless Telegraph
  - Marconi



- ~1894: Millimeter Waves
  - Jagadish Chandra Bose



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Lufthansa Says
Track Checked
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Lufthansa Says Apple AirTags Are Once Again Allowed in Checked Bags
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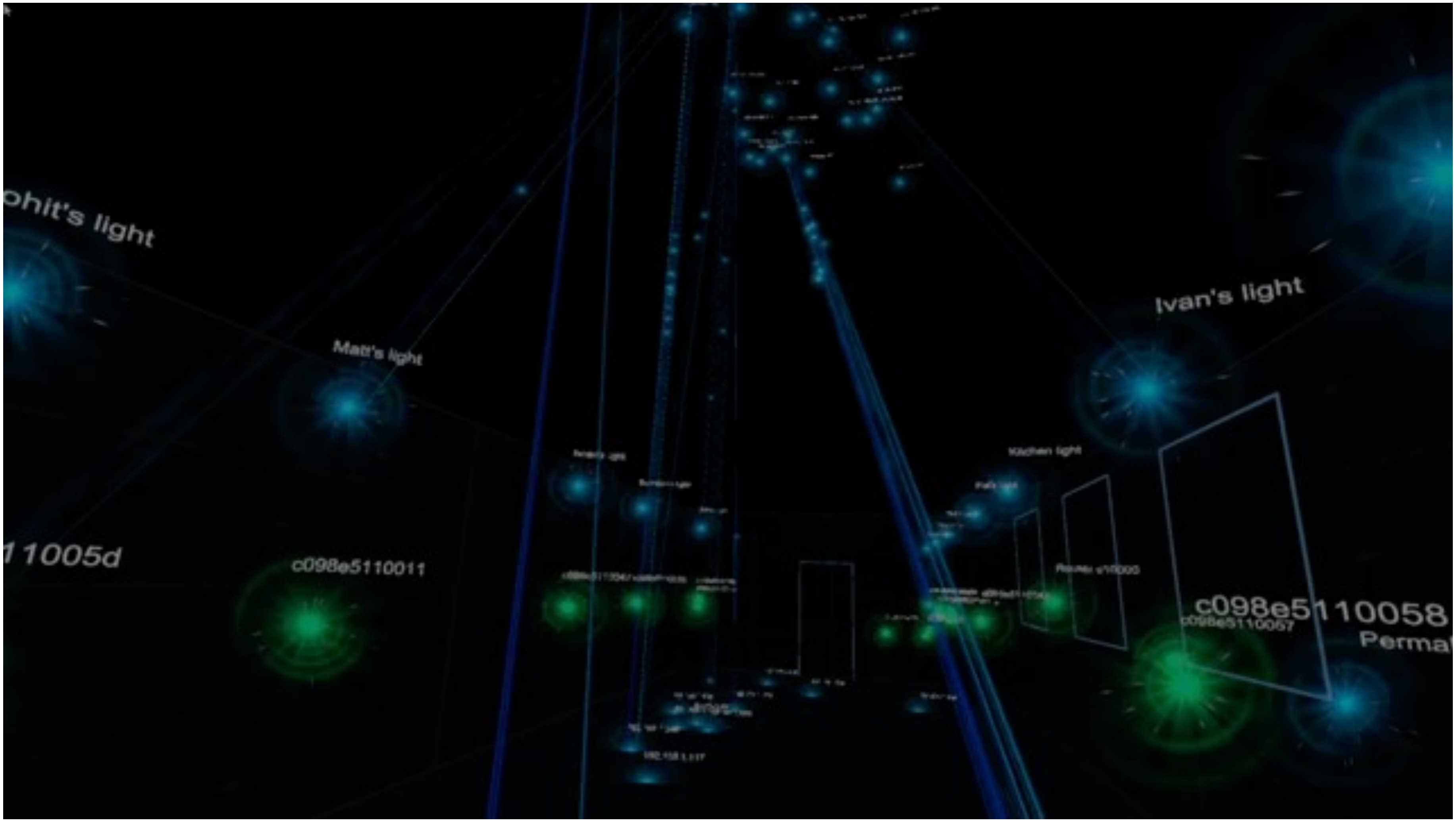
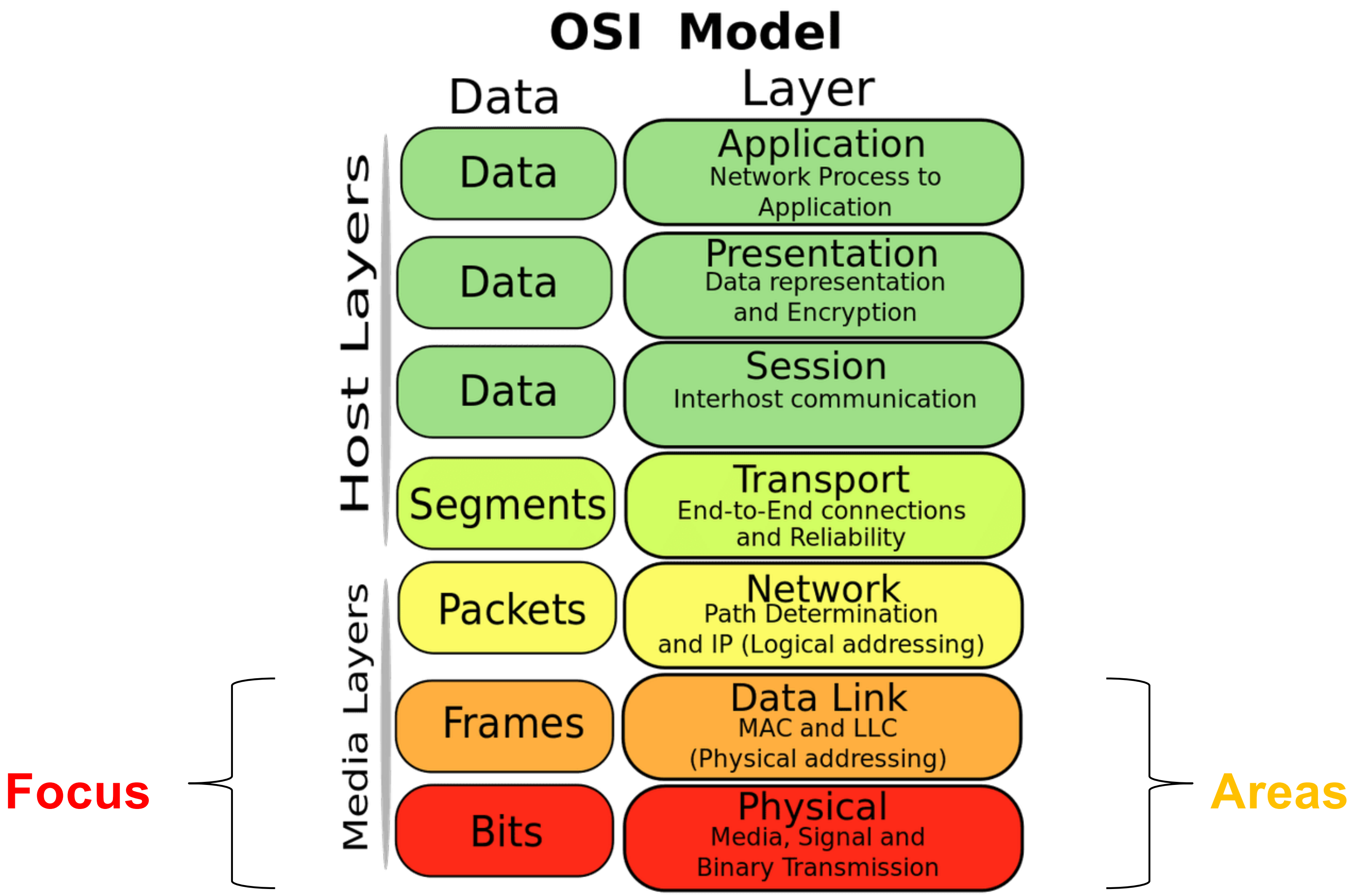
Artist's Conception of Wireless Networks



Wired vs Wireless: Some Crucial Differences

- Wireless is a fundamentally shared medium
  - Wired is not
- Wireless signals attenuate significantly with distance
  - Wired signals do not
- Wireless environments can change rapidly
  - Wired environments do not
- Wireless packet collisions are hard to detect
  - Wired packets collisions are not

Differences Mostly* Affect the PHY/DLC Layers



* Remember the End-to-End Principle?

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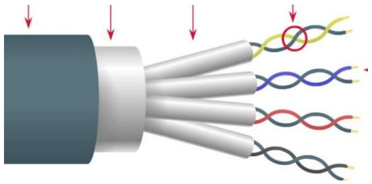
Wired Links

- Point to point (private), by default

- Creating multi-point buses requires work

- Fairly easy to shield from external interference

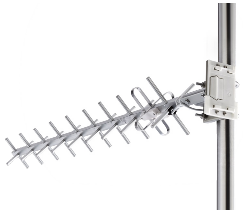


- Use electrical signals to transmit data

Wireless Links

- Are broadcast (shared), by default

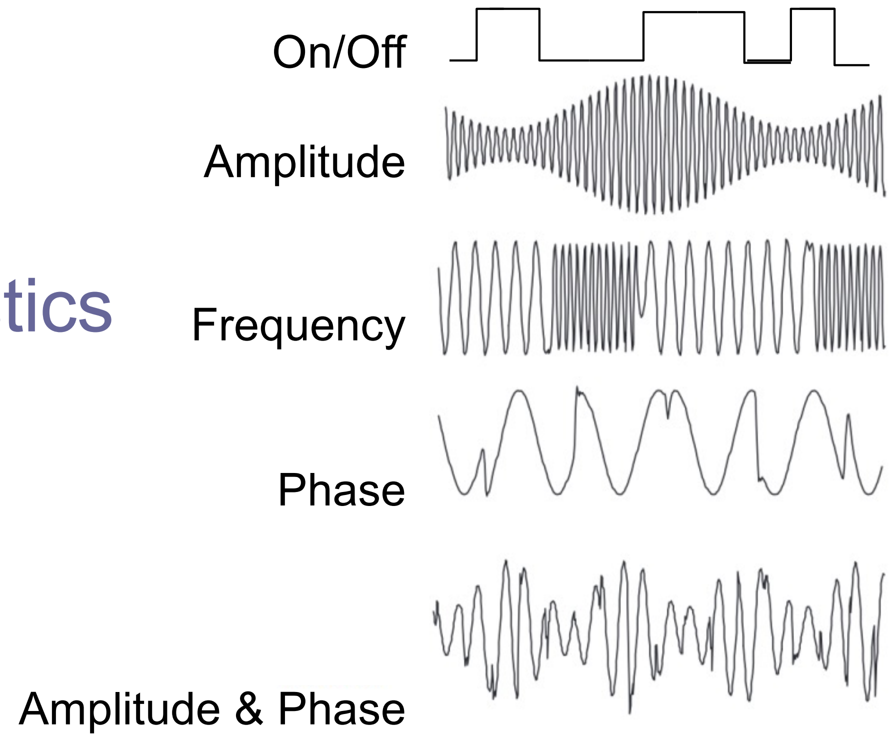
- Creating point-to-point “links” requires work



- Fairly hard to shield from external interference

- Modulate electromagnetic fields to transmit data

Physical Layer Modulation



Specifies electrical characteristics

- Voltages/Amplitudes
- Frequencies
- Phases
- Combination

Specifies how to map signals ⇔ data

- e.g. low voltage = 0 and high voltage = 1
- e.g. oscillation at a high frequency = 0, low freq = 1

Often specifies logical *network* topology too (star, mesh)

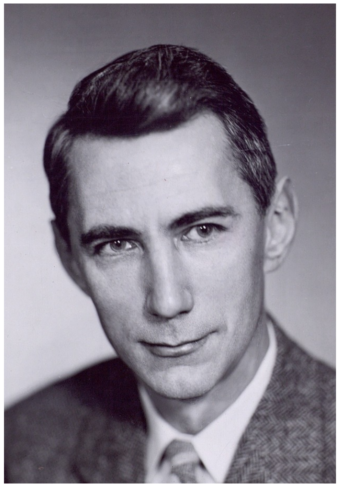
What about Noise and Interference?

- Noise & interference can corrupt the received signal!
- Noise *floor* is the ambient/background RF power
- Interference is usually other transmitters in same band

- SINR, or ratio of signal power to noise/interference power at receiver, is a key metric for communications
- SINR = $P_{signal} / P_{noise+interference}$
- $SINR_{dB} = 10 * \log_{10}(P_{signal} / P_{noise+interference})$

- If there's noise, need to transmit with more power!
- Or employ coding gain if signal *below* noise floor…

Noisy Channel Shannon Capacity



- Noise is unavoidable in reality
- Noise limits channel capacity

- Claude Shannon formulated the key relationship between Capacity (*C*), Bandwidth (*BW*), and Signal-to-Interference-and-Noise Ratio (*SINR*):

$$C = BW * \log_2(1 + SINR) \text{ bits/sec}$$

Example: Calculating Channel Capacity

$$C = BW * \log_2(1+SINR) \text{ bits/sec}$$

- Plain Old Telephone Systems (POTS) offered:
  - BW = 4 kHz bandwidth
  - $SINR_{dB}$ = ~20 dB

- What is the capacity of the POTS channel?
  - $SINR_{dB} = 10 * \log_{10}(SINR) \rightarrow SINR = 10\text{^}(SINR_{dB}/10)$
  - $C = 4000 * \log_2 (1 + 100)$ bps
  - C = 26.6 kbps

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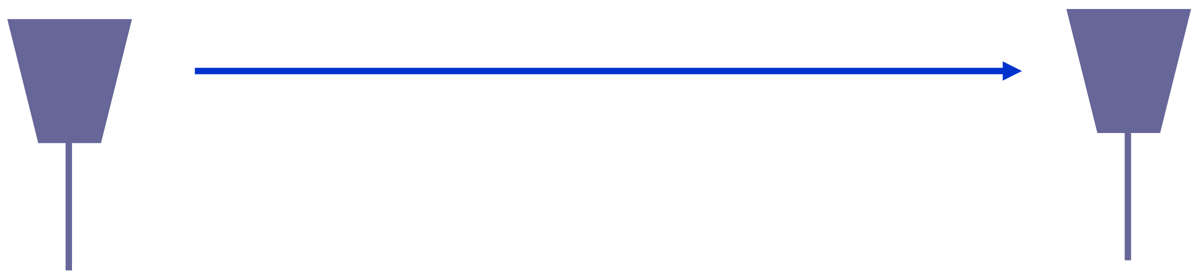
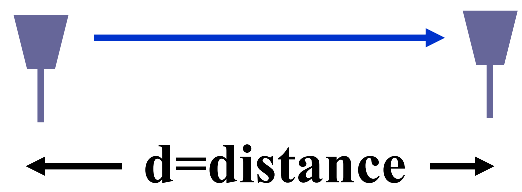
Basic Wireless Problem

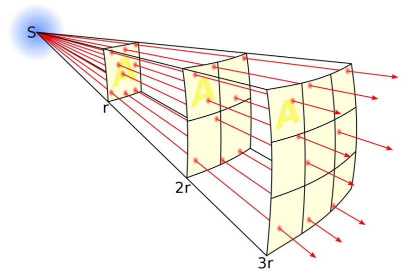


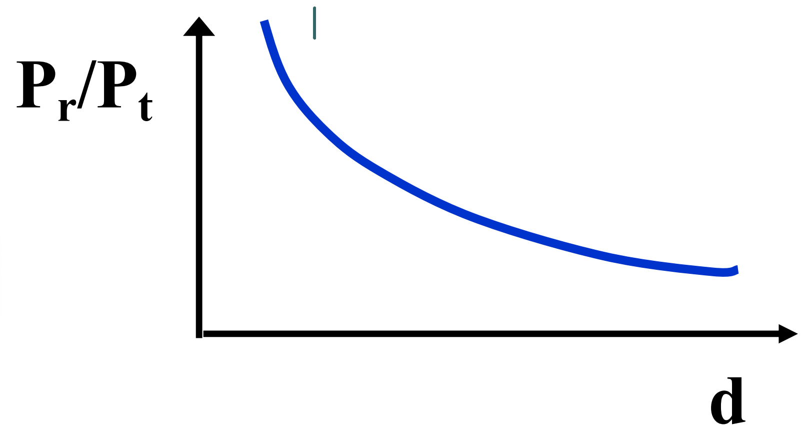
Transmit information

- From a transmitter to a receiver (e.g. sensor to phone)
- Using a non-contact medium (e.g. EM waves)
- Maximizing performance (e.g. accuracy, speed, range)
- Minimizing resource use (e.g. spectrum, energy)

Free Space (LOS) Model (and Friis Equation)







Friis Equation

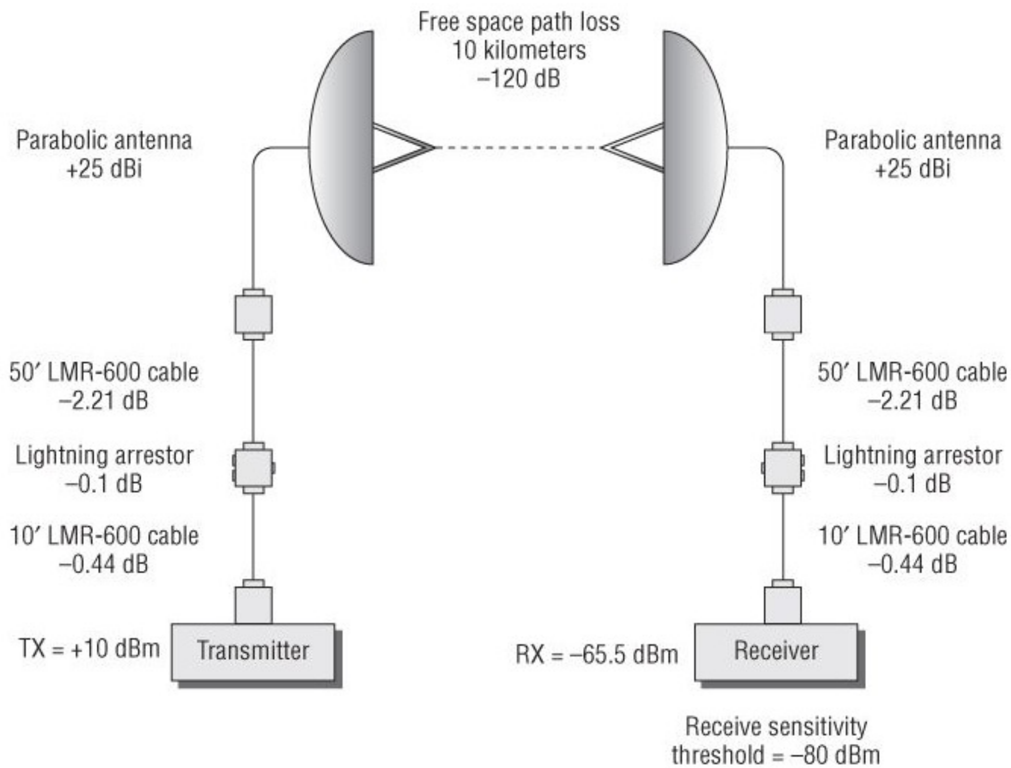
Linear Form: 1) $P_{rx} = P_{tx} G_{tx} G_{rx} \left(\frac{c}{4\pi D_r f_0} \right)^2$

Log Form: 2) $P_{rx}(dB) = P_{tx} + G_{tx} + G_{rx} + 20\log_{10}\left(\frac{\lambda}{4\pi D_r} \right)$

- Path loss for unobstructed LOS path
  - Both linear (mW, W) and log (dBm, dBW) forms
- Power falls off :
  - Proportional to $1/d^2$
  - Proportional to λ^2 (inversely proportional to f^2)
    - This is due to the effective aperture of the antenna!

Credit: Adapted from Andrea Goldsmith, https://en.wikipedia.org/wiki/Inverse-square_law

Link Budget: Accounting of All Gains and Losses Experienced by a Communications System



- LB = ∑ gains, losses → Check if LB > RX sensitivity
  - If link budget is positive, you might be in business
  - If link budget is negative, you're really in trouble

Image Credit: https://sellugsk.live/product_details/47078787.html

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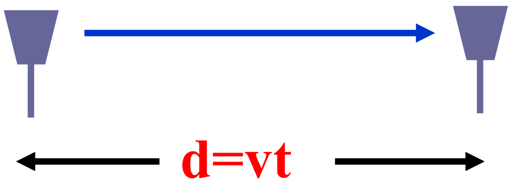
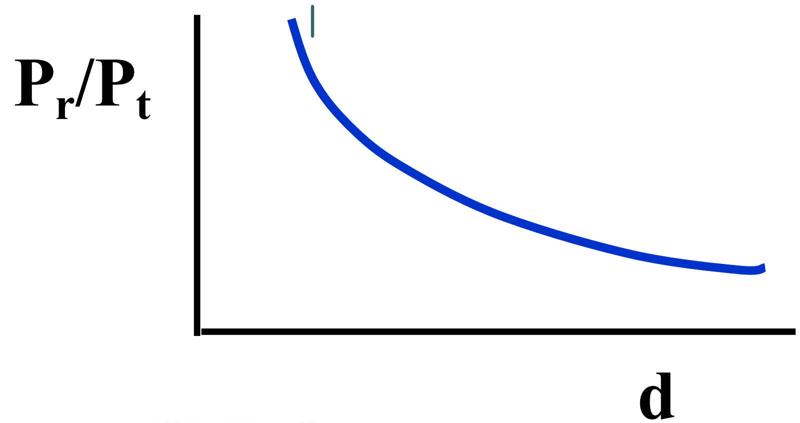


What if we're moving?



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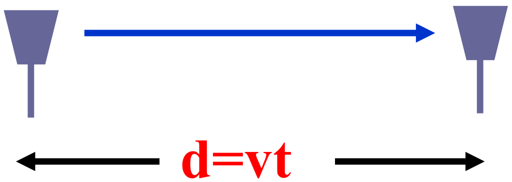

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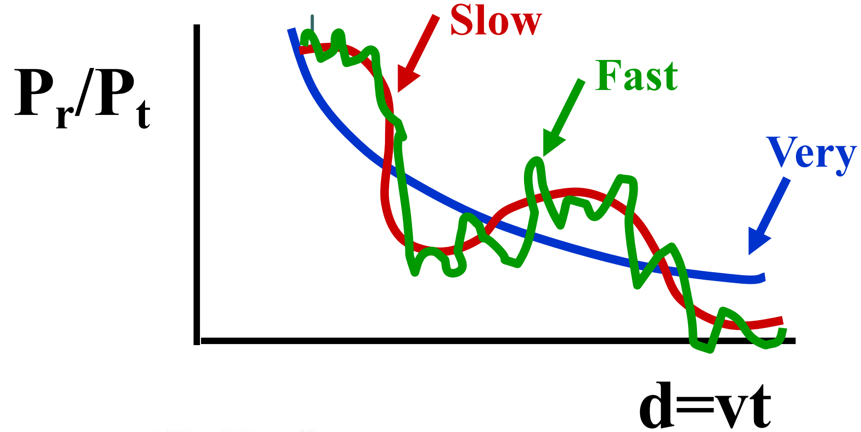

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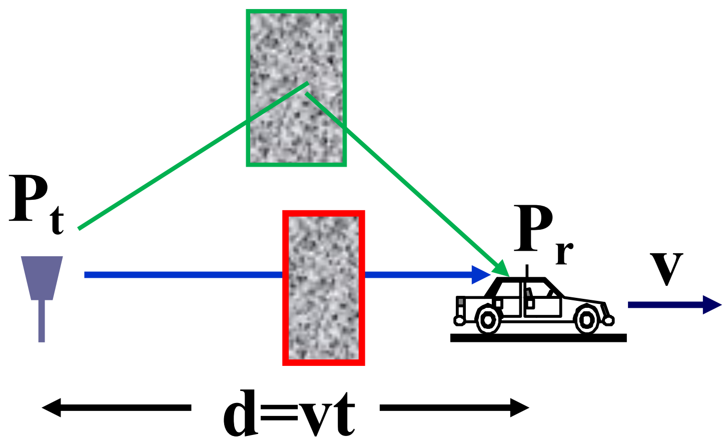
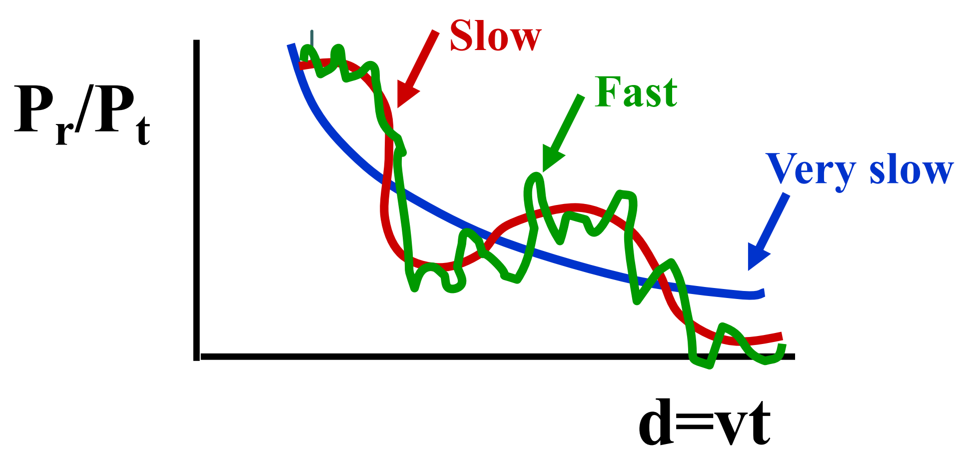
    - This is due to the effective aperture of the antenna!

Radio Propagation Characteristics

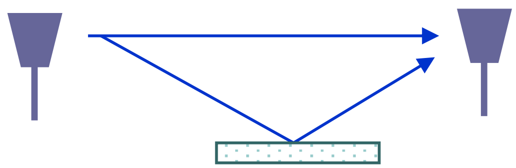
- Path Loss (includes average shadowing)
- Shadowing (due to obstructions)
- Multipath Fading





Credit: Andrea Goldsmith

Two Ray Model

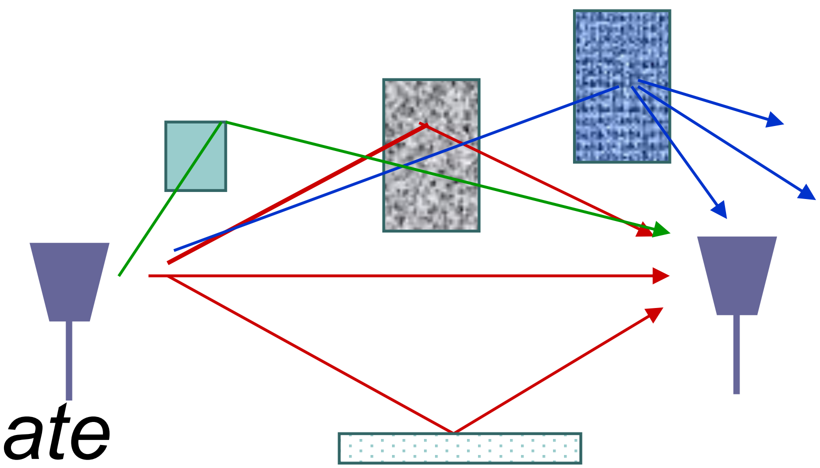


- Path loss for one LOS path and 1 ground (or reflected) bounce
- Ground bounce approximately cancels LOS path above critical distance
- Power falls off
  - Proportional to d^2 (small d)
  - Proportional to d^4 ($d>d_c$)
  - Independent of λ (f_c)

General Ray Tracing

Models signal components as particles

- Reflections
- Scattering
- Diffraction



Reflections generally dominate

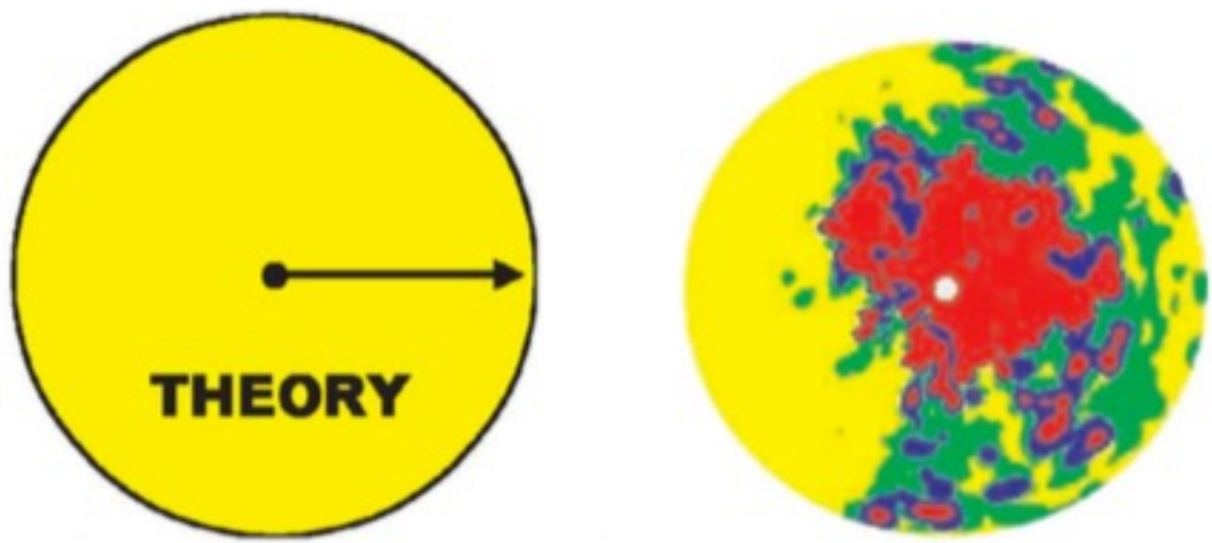
- Requires site geometry and dielectric properties
  - Easier than Maxwell (geometry vs. differential eqns)
- Computer packages often used

Simplified Path Loss Model

- Used when path loss dominated by reflections.
- Most important parameter is the path loss exponent γ, determined empirically.

$$P_r = P_t K \left[\frac{d_r}{d} \right]^{\gamma}, \qquad 2 \le \gamma \le 8$$

Wireless propagation is messy



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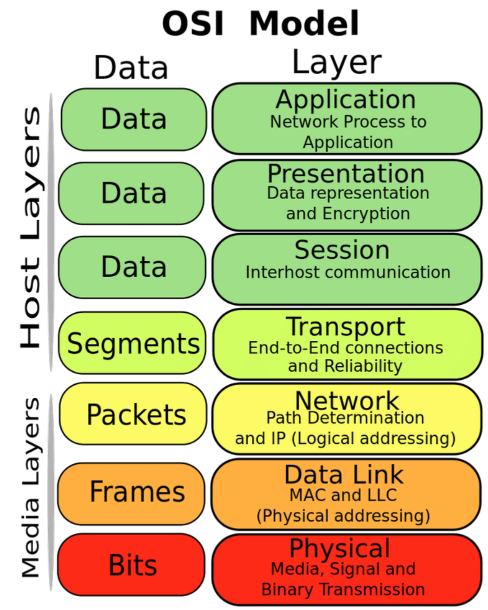
Collision Detection vs Collision Avoidance

- Wired frame collisions often easy to detect
  - May not happen at all (e.g. for point-to-point links)
  - Can often detect collisions by sensing the medium
  - If collision detected, retry transmission with backoff

- Wireless frame collisions much harder to detect
  - There is a spatial aspect to collisions
  - Transmitter may not be able to detect a collision at all
  - Might not matter, if there's no collision at the receiver!
  - Conversely, two transmitters might not even be in range

Medium Access Controls

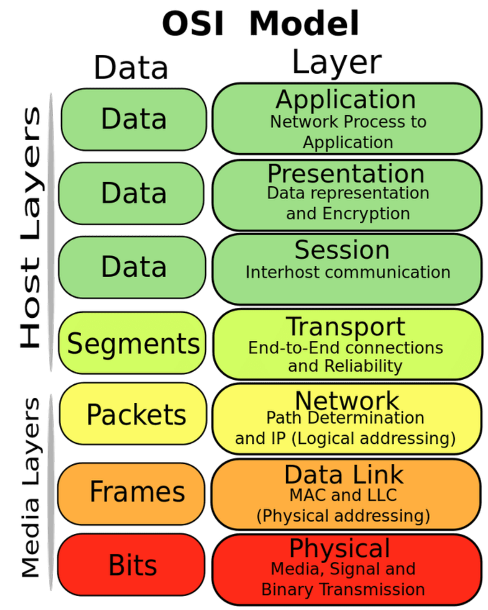


Question:

How do multiple devices share the same transmission technology?

- Don't worry about it, let collisions happen
- Listen for others and don't transmit if they are
- Coordinate with others and transmit at different times
- Transmit at different frequencies

Medium Access Controls



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How do multiple devices share the same transmission technology?

- Don't worry about it, let collisions happen
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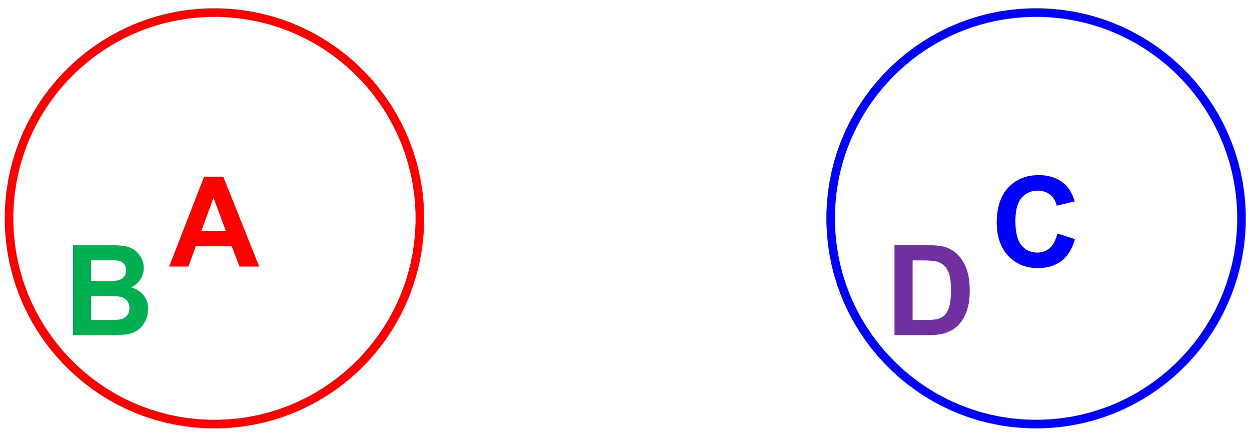
- Coordinate with others and transmit at different times
- Transmit at different frequencies

Listen for Others and Don’t Transmit If They Are (aka CSMA—Carrier Sense Multiple Access)

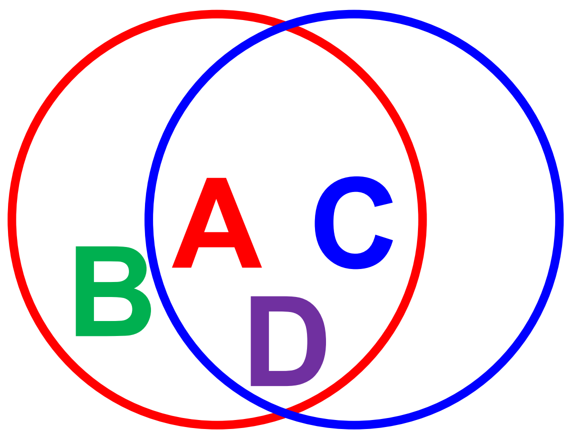
- Sounds simple, but how does CSMA work?
- Let’s start with Carrier Sense part
  - If a carrier is sensed (i.e. P_{rx} > threshold), don’t transmit
- This works when two pairs are well separated



- A transmits to B while C transmits to D, concurrently
- Assume a uniform disc communications range

CSMA in Close Quarters

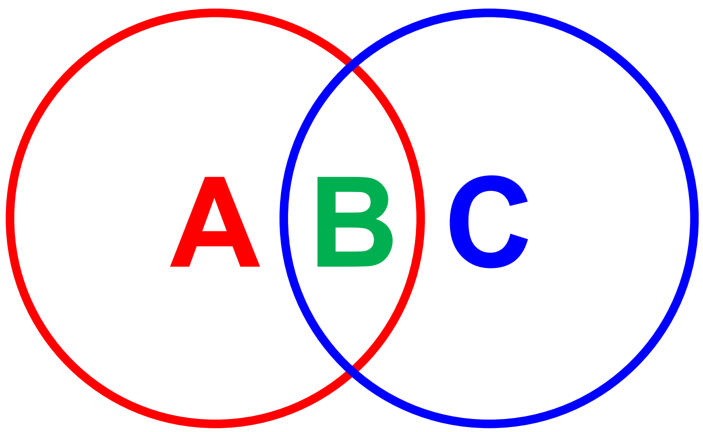
- Carrier sense also works well transmitters are in range of each other, e.g. A and C



- Again, A transmits to B while C transmits to D
- A and C will (nominally) take turns transmitting

CSMA and the Hidden Terminal Problem

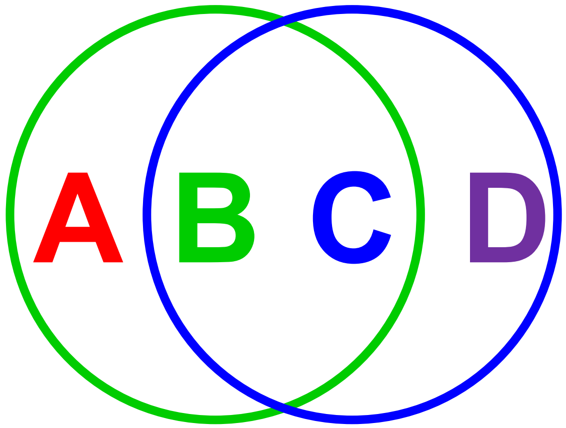
- But what if two transmitters are out of range of each other but are sending to the same receiver?
- They can't hear each other so CSMA/CA fails!
- A's transmissions collide with C's transmissions at B



- If both A and C could individually saturate the link, and are received with similar signal strength at B, the transmissions will likely collide and likely be lost!
- Issue illustrates the spatial aspect of collisions

CSMA and the Exposed Terminal Problem

- Now imagine that there's data from B → A and C → D



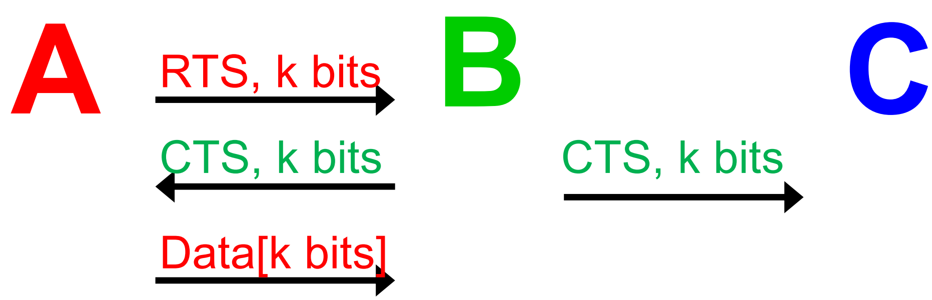
- There wouldn't be any collisions at A or D, however…
- CSMA dictates that B and C can't both send
- Issue again illustrates the spatial aspect of collisions

Multiple Access with Collision Avoidance (MACA)

- Carrier sense was adopted in early packet radios
- Connected Hawaiian islands together over long range
- Unfortunately, many hidden and exposed terminals
- Led to new designs for collision avoidance
- Key idea is to incorporate receiver conditions into transmitter's calculus

Use RTS/**CTS** to Inform Transmission Decision

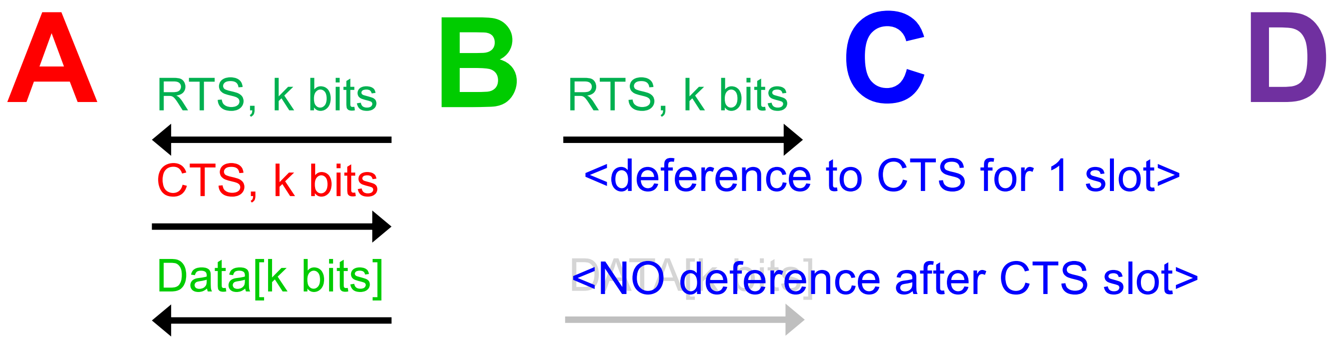
- Transmit request-to-send (RTS) and receive a clear-to-send (CTS) before transmitting the data



- A sends RTS with information about data size
- B sends CTS if it is clear to receive
- C receives the CTS message and defers for k bits
- A sends the data
- This solves the **hidden terminal** problem

Use **RTS**/CTS to Inform Transmission Decision

- Receiving a request-to-send (RTS) causes all other nodes (except intended receiver) to defer for one CTS time slot and frees those other nodes to transmit if a corresponding CTS is not received

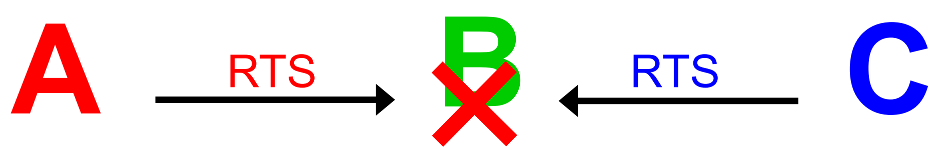


- This (**could**) solve the **exposed terminal problem**
- Caveat #1: Don't do carrier sense anymore (why?)
- Caveat #2: D's CTS must be received over B's data

Credit: Adapted from Kyle Jamieson

What about (RTS) Collisions?

- If two nodes want to transmit to the same receiver at the at the same time, their RTS transmissions collide!



- When A and C's RTS messages collide, B does not send a CTS response
- What should A and C do if they don't receive at CTS?

Binary Exponential Backoff (BEB) in MACA

- What should a transmitter do if its RTS transmission doesn’t result in a corresponding CTS reception?
  - Randomly backoff and then resend the RTS again.

- From what distribution should we select the backoff?
  - A distribution of integers that represent backoff “slots”

- How long should a backoff slot be?
  - Length of an RTS transmission

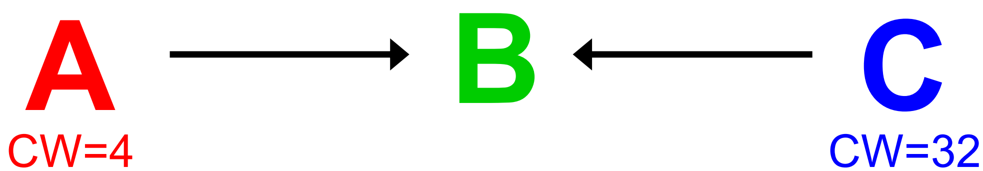
- How should we determine the distribution?

Determining the Contention Window (CW)

- CW := current contention window (units of RTS time)
- MACA Sender:
  - CW_0 = 2 and CW_M = 64
  - Upon successful RTS/CTS, $CW \leftarrow CW_0$
  - Upon failed RTS/CTS, $CW \leftarrow \min[2CW, CW_M]$
- Before retransmission, wait a uniform random number of RTS lengths (30 bytes, 240 us in MACA) in [0, *CW*]
- Is this fair?

Unfairness in MACA

- MACA's BEB can lead to unfairness because backed-off sender had decreasing chances to acquire medium
  - Winners keep winning
  - Losers keep losing
- Example where both A and C could saturate B:



- A more likely to win backoff and set min CW = 2
- C more likely to defer (maintain CW)

MACAW: Fixing the Unfairness in MACA

- MACAW proposal
  - Transmitters write their CW into packets
  - Upon receiving a packet, copy and adopt its CW

- Results: Disseminates congestion level of winning transmitter to other contenders

- Is this a good idea?

- What are the downsides?

Determining the Contention Window in MACAW

- Integrates with MACAW's ACK mechanism
- Multiplicative Increase, Linear Decrease (MILD)
- MACAW Sender:
  - $CW_0 = 2$ and $CW_M = 64$
  - Upon failed RTS/CTS, $CW \leftarrow \min[1.5CW, CW_M]$
  - Upon successful RTS/CTS, but failed ACK, **no change**
  - Upon successful RTS/CTS/DATA/ACK, $CW \leftarrow CW - 1$

Increasing Reliability with ACK messages

- MACAW uses an ACK packet after a DATA packet
  - Note: MACA does not do this

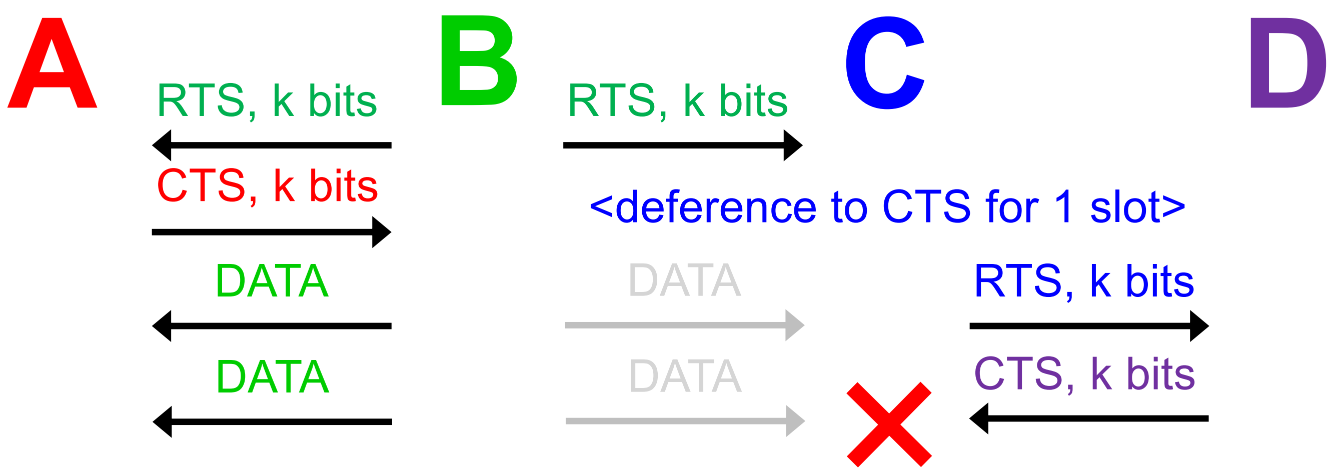
- Sender resends if RTS/CTS succeeds, but no ACK

- Sender resends RTS. Two Cases:
  - Case #1: DATA was lost
    - Receiver sends CTS, sender sends DATA
  - Case #2: Receiver got the DATA (reverse-link ACK loss)
    - Receiver sends ACK

ACK Considerations

- ACKs enable quick retransmission of lost DATA
  - Avoid TCP window reductions under interference
  - Here, ACKs are for performance, not correctness (E2E)
- ACKs are useful if there is-band noise/interference
  - Other types devices on the channel (esp. ISM bands)
  - Other sources of noise (microwave ovens)
- Sequence numbers are needed in DATA packets

MACAW and Exposed Terminals

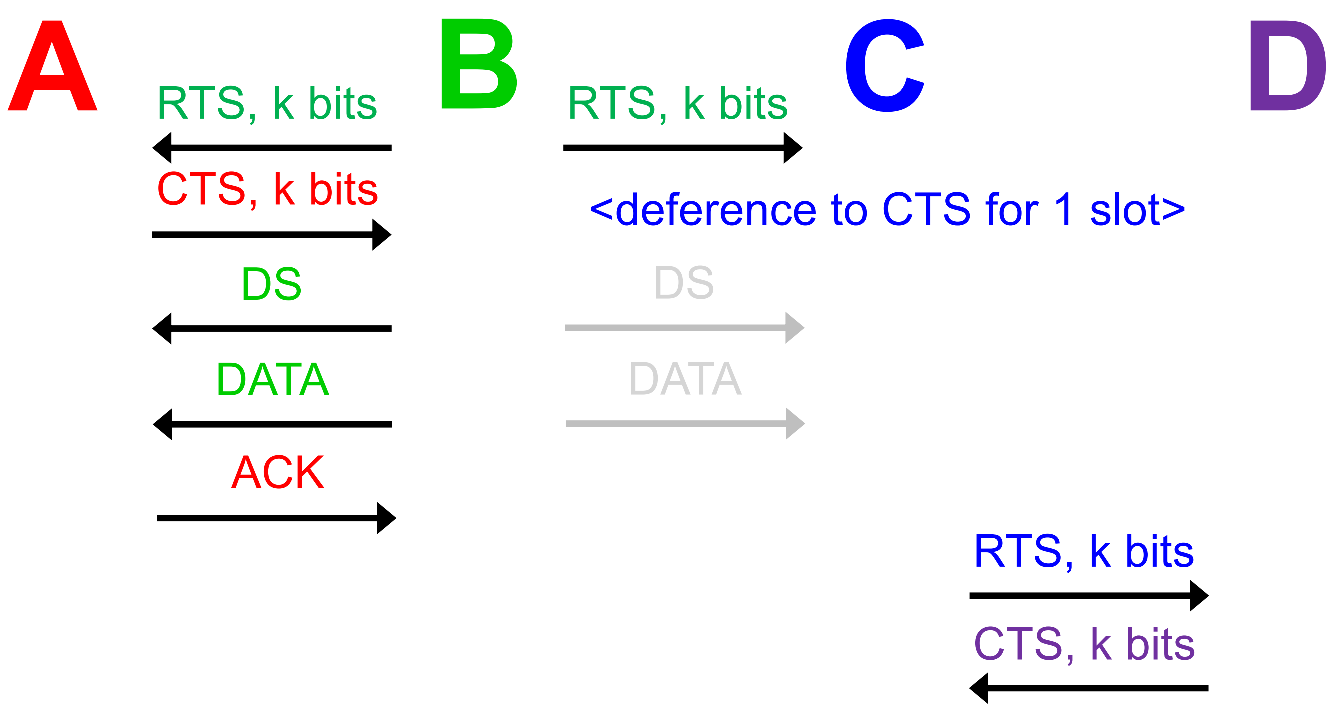


- Recall, C can only proceed only if it gets D's CTS
  - But B's DATA will likely collide with D's CTS

- What do we do now?

MACAW and Exposed Terminals

- Have B send a Data Sending (DS) packet after CTS
  - This way, C knows that B received a CTS
  - And C defers until after A's ACK



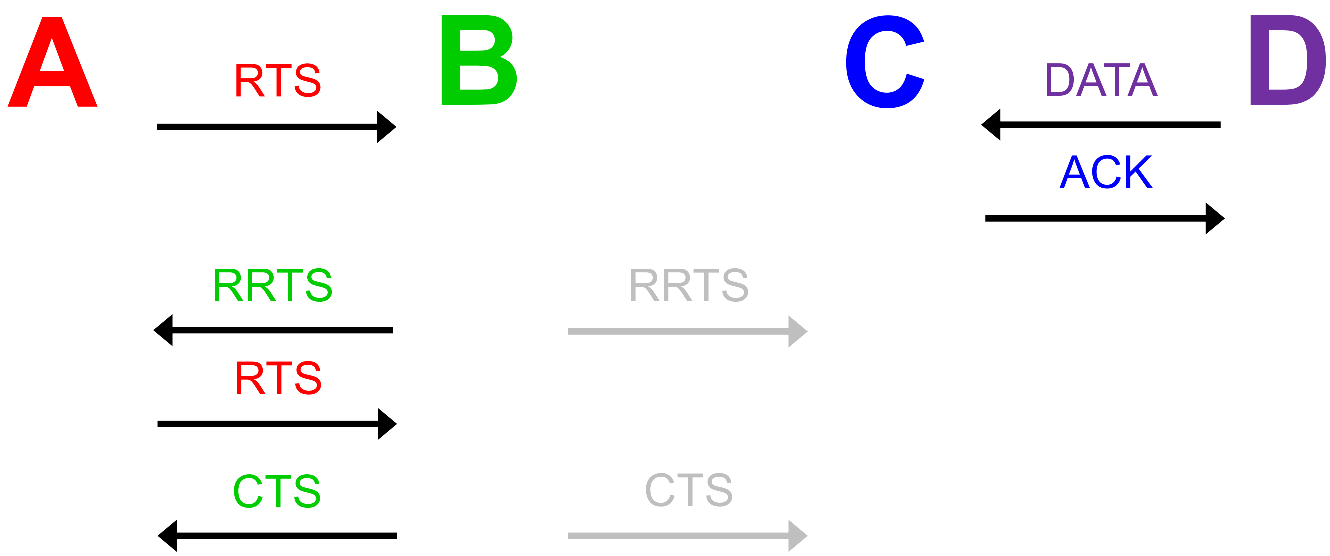
Need for Synchronization

- Suppose D has a smaller CW, ongoing transmission
- B cannot reply to A's RTS
- A doesn't know when the contention periods are
  - So, A's backoff will increase (unfairly)

- MACAW's approach: Let B contends "on behalf of" A

MACAW: RRTS

- But B knows when the gaps for contention are
- B sends a request-for-RTS (RRTS) to A when DATA completes (hears an ACK from C)
- C defers transmission for two slot periods
- A sends an RTS immediately without backoff



A Challenging Scenario for MACAW's RRTS

- What happens in this scenario?
  - Assume C is successful with ongoing transmissions
  - When A sends RTS to B, B just can't hear it
  - So RRTS doesn't solve this problem

802.11's MAC – A Topic for a Different Day, But…

- Adopts MACAW's MAC from a high level
  - Same RTS/CTS/DATA/ACK
    - RTS/CTS optional
  - Different contention window control

- Adopts CS and Deference from Ethernet
  - But not collision detection
    - Transmit Signal Power >> Receive Signal Power

- Adds design elements for high data rates, TCP above

Outline

- Early History
- Wireless Fundamentals
- Design Space Challenges
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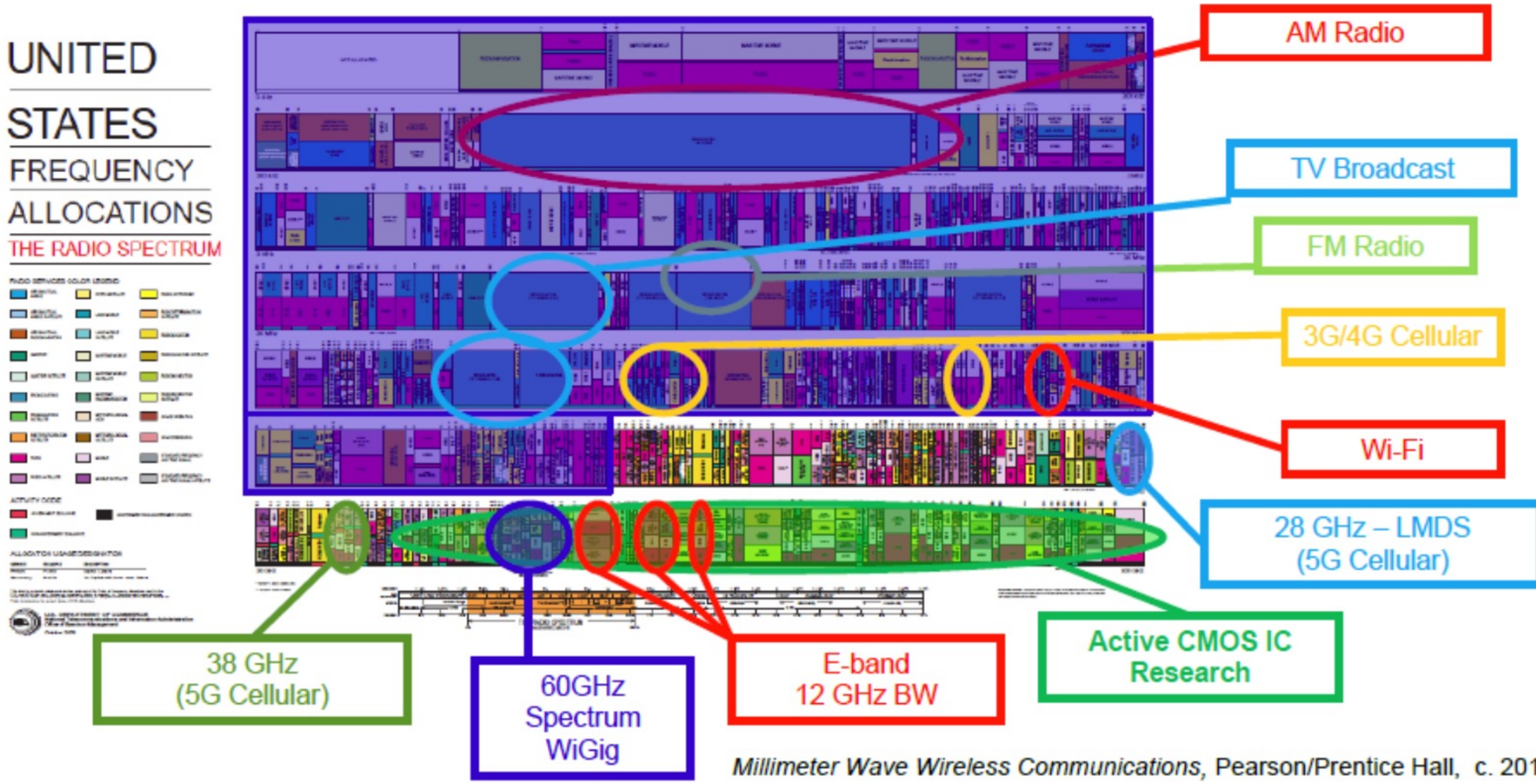
Spectrum, and its allocation

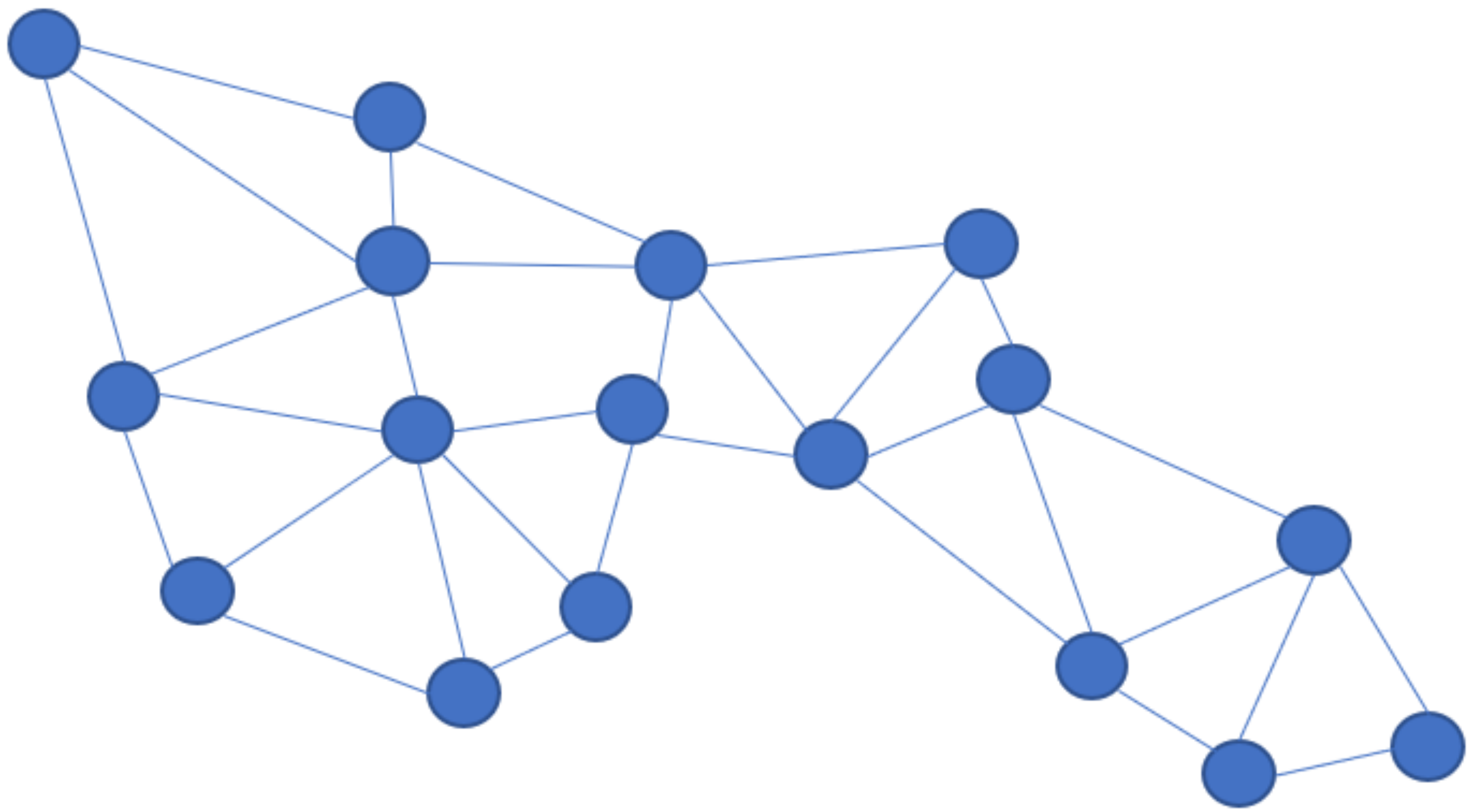


Millimeter Wave Wireless Communications, Pearson/Prentice Hall, c. 2015

All existing commercial systems fit into a small fraction of the mmWave band

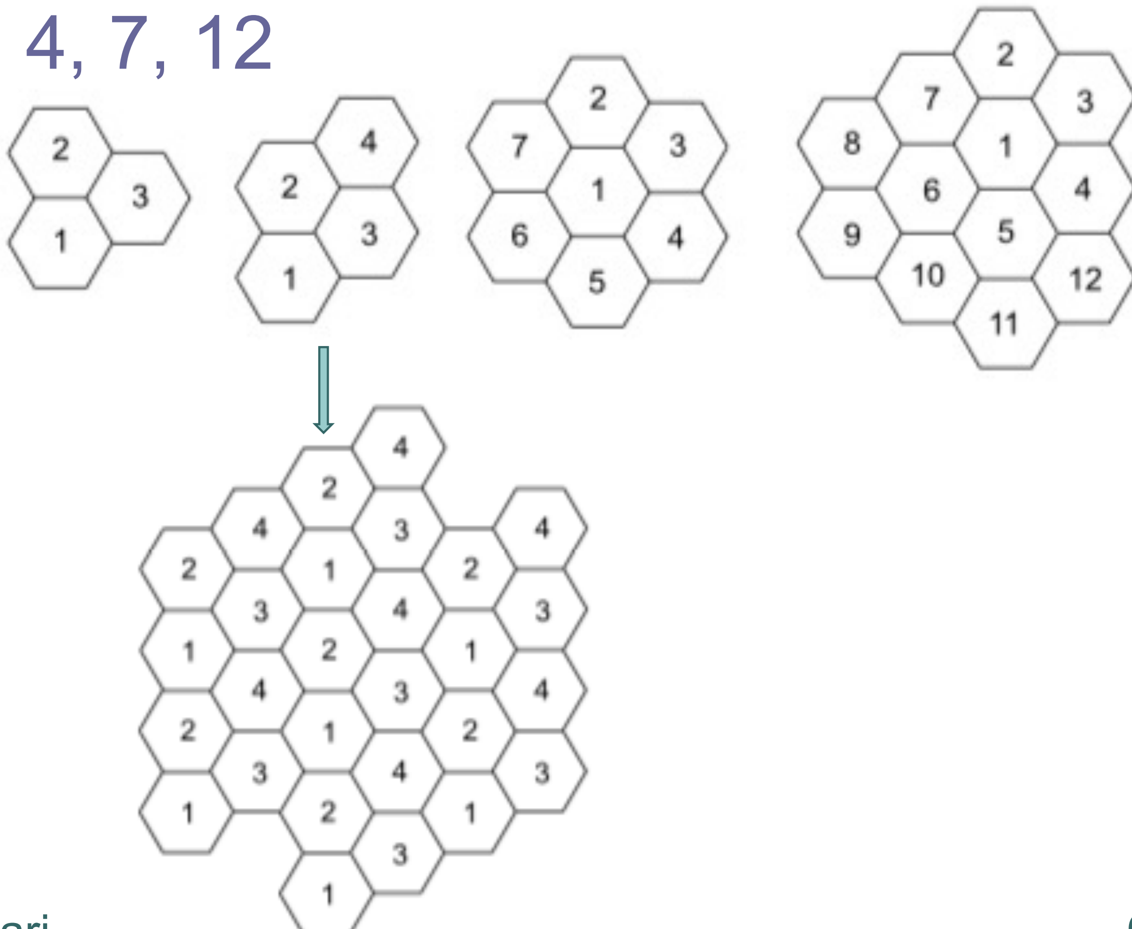
Should we use mesh networks?

- Shorter range, lower interference
- More hops, more complexity



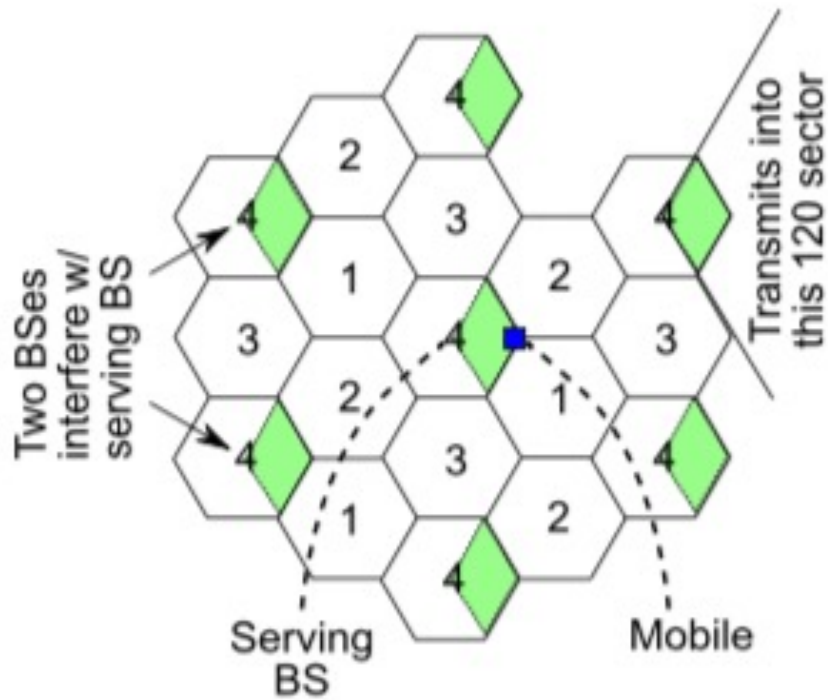
Should we allocate channels/frequencies?

- Avoids interference
- Allocations vs # of channels
- N = 3, 4, 7, 12



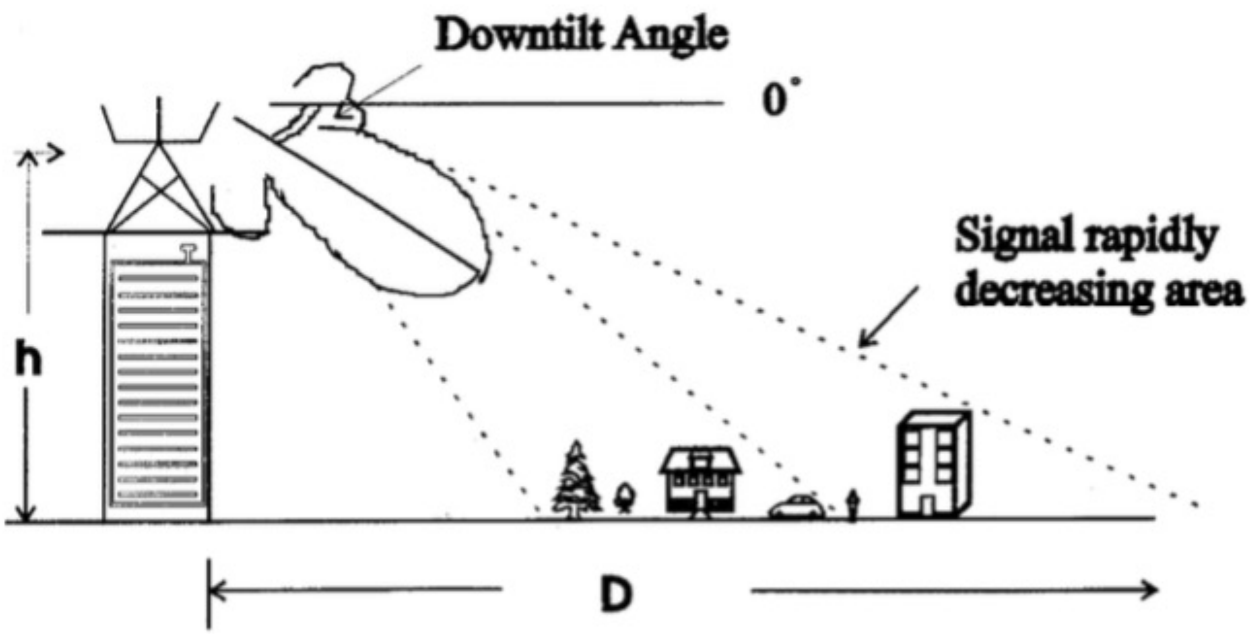
Should we use directional antennas?

- Avoids interference
- Requires more complexity



Where should we place the infrastructure?

- Up high, with a wide field of view and long range?
- Down low, close to the action?



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Common IoT Wireless Options

- Personal Area Networks (PANs)
  - Bluetooth, BLE
- Local Area Networks (LANs)
  - WiFi (IEEE 802.11*)
  - Zigbee, et al. (IEEE 802.15.4*) – arguably PAN
- Wide Area Networks (WANs)
  - GSM (for voice, some data)
  - LTE and 5G (for audio, video)
  - Sigfox, Lora, LTE-M (for Machine-to-Machine, M2M, IoT)

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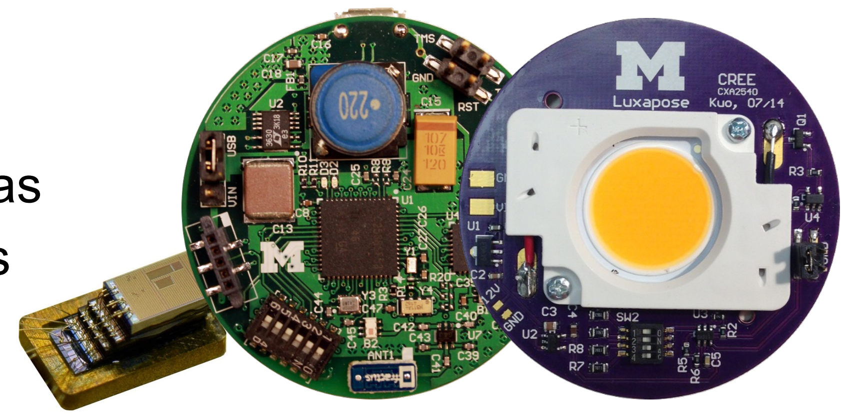
Emerging set of proximal communication interfaces

Visible Light

- Enabled by pervasive LEDs and cameras
- Supports indoor localization and comms
- Easy to modify existing LED lighting



Ultrasonic

- Small, low-power, short-range
- Supports very low-power wakeup
- Can support pairwise ranging of nodes

Vibration

- Pervasive accelerometers
- Pervasive vibration motors
- Bootstrap desktop area context