Lecture 13
Wireless Communication

CE346 – Microcontroller System Design

Branden Ghena – Spring 2026

Some slides borrowed from:
Josiah Hester (Northwestern), Prabal Dutta (UC Berkeley)

Northwestern

Administrivia

- Heads up: office hours today are going to be *busy*
  - Quite a few groups still need Lab 6 checkoffs

- Project:
  - I’m still ordering more hardware if people need things, for another week or two
  - Be sure to create a private repo (see Ed post) for your project code

- How to get project help
  - Tips document on Ed
  - Make a post on Ed with questions
  - Office hours (including Fridays)
  - Find guides on the Internet

Today's Goals

- Explore important issues in wireless communication
  - Physical and Data Link layers particularly

- Describe several wireless networks that are very important to modern Internet of Things devices
  - Bluetooth Low Energy
  - Thread and Zigbee (802.15.4)
  - WiFi (802.11)
  - Low-Power Wide-Area Networks

nRF52833 supports BLE!
But our Microbit library doesn't (yet) 😢

Our Microbit library does support 802.15.4 communication though!

Outline

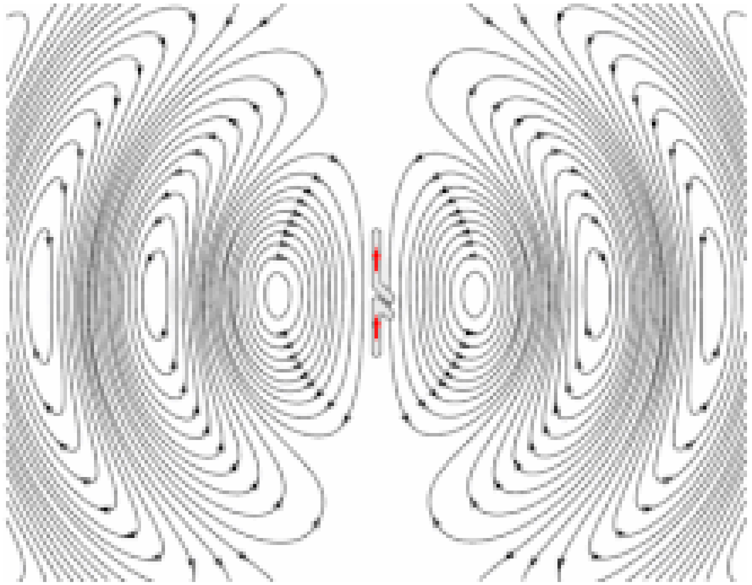
- **Wireless Communication Overview**

- Wireless Protocols
  - Overview
  - Bluetooth Low Energy
  - 802.15.4
  - WiFi
  - Low-Power Wide-Area Networks

Wireless: high-level idea

- Normally, we want to keep all electric signals contained in a wire
  - Don’t want to receive interference from other signals or cause interference

- Antennas are good at the opposite:
  - They spill electrical signals out into the world
  - They receive electrical signals from the world



- This means we can send information from one device to another without wires!

Why use wireless?

- There are no wires!

- No need to install and maintain wires
  - Reduces cost
  - Simplifies deployment – place devices wherever makes sense

- Supports mobile users
  - Move around office, campus, city
  - Move devices around home

What is hard about wireless?

- There are no wires!

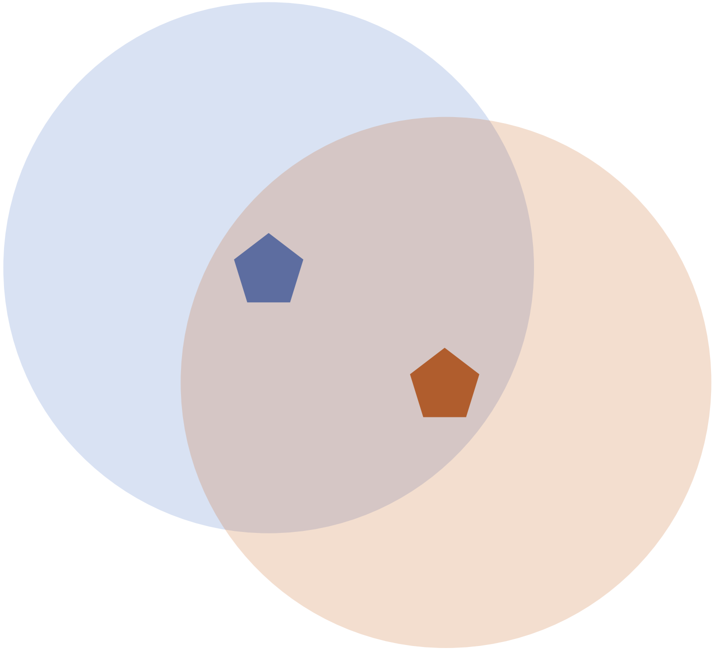
- Wired networks are constant, reliable, and physically isolated
  - Ethernet has the same throughput minute-to-minute
  - Bits sent through Ethernet or USB are (usually) received

- Wireless networks are variable, error-prone, and shared
  - WiFi throughput changes based on location and walls
  - Signals from nearby devices interfere with your signals
  - Individual bits might flip or never be heard at all

Wireless is a shared medium

- Wired communication has signals confined to a conductor
  - Copper or fiber
  - Guides energy to destination
  - Protects signal from interference

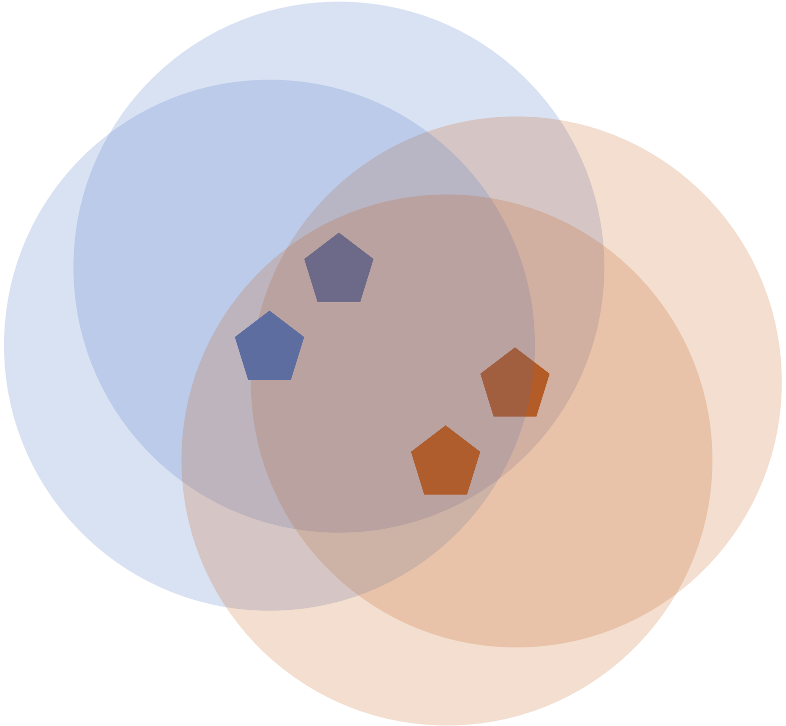
- Wireless communication is inherently broadcast
  - Energy is distributed in space
  - Signals must compete with other signals in same frequency band



Increasing network capacity is challenging

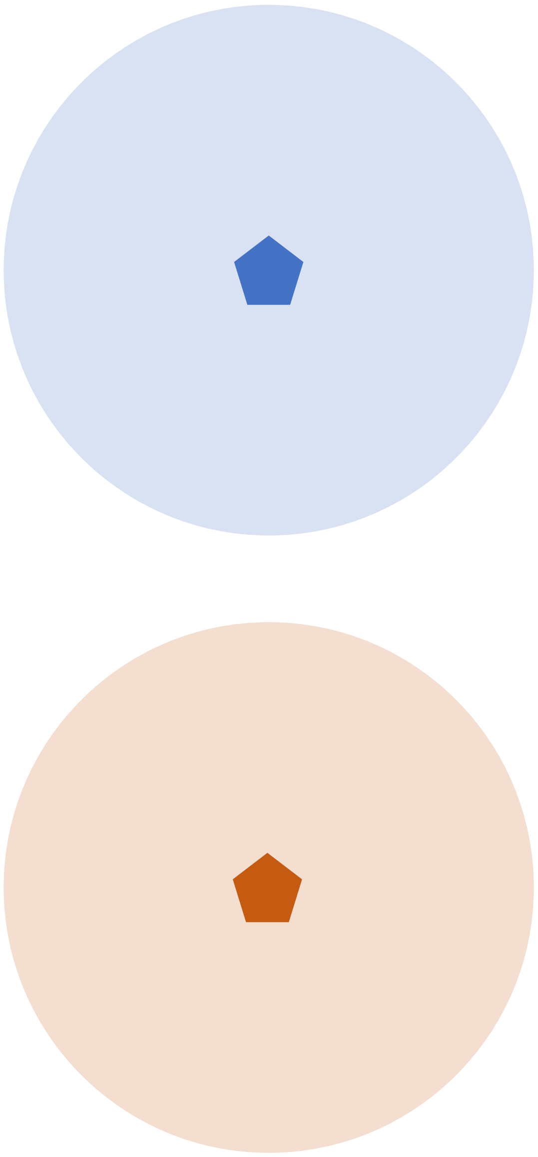
- Wired networks just add more wires
  - Buses are many signals in parallel to send more data

- Wireless networks are harder
  - Adding more links just increases interference
  - Need to expand to different frequencies
    - e.g., more *bandwidth*



Model of RF communication

- Energy that radiates spherically from an antenna at a "carrier frequency"
  - Good enough for understanding communication
- Attenuation with distance
  - Density of energy reduces over time, distance
  - Signal strength reduced, errors go up
- Two key features
  - Range and data rate affect error rates
  - Spatial reuse of frequencies

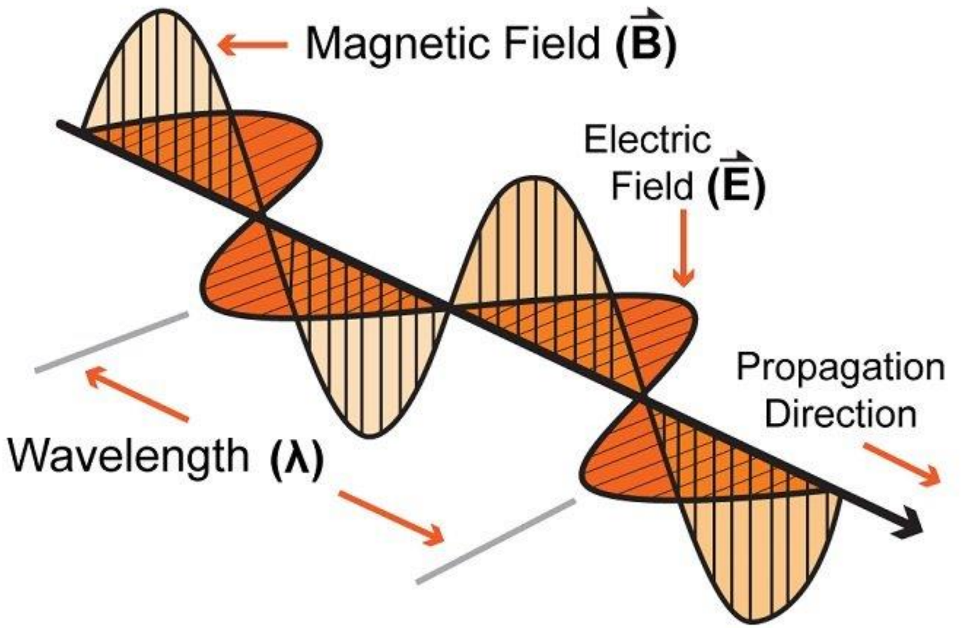


Signal qualities

1. Signal strength
   - The amount of energy transmitted/received

2. Signal frequency and bandwidth
   - Which "channel" the signal is sent on

3. Signal modulation
   - How data is encoded in the signal



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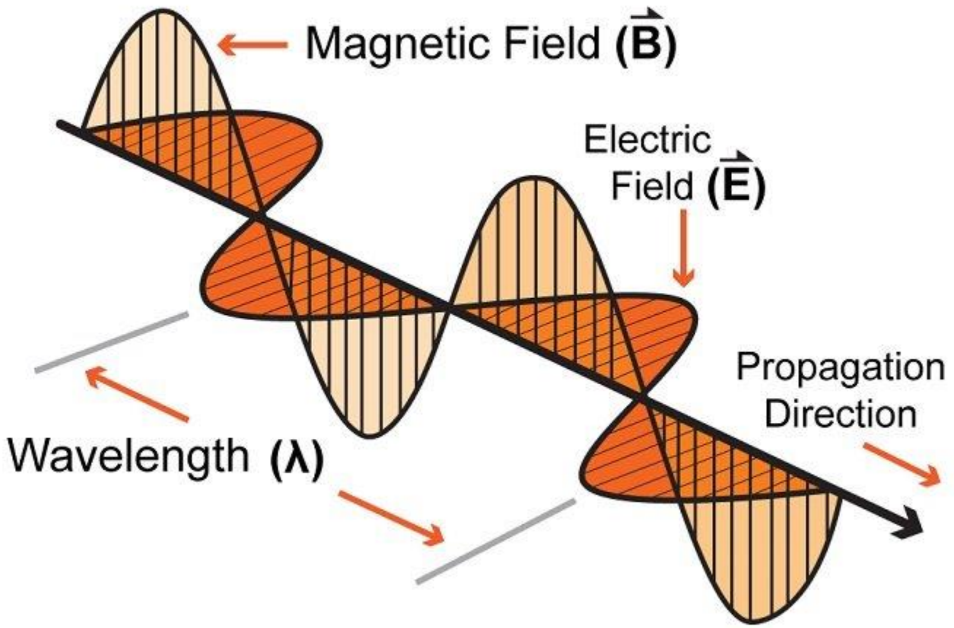

Wireless signals are incredibly low power

- Maximum BLE transmit power for the nRF52840:
  - 8 dBm -> 6.31 mW (10^{-3})
- Minimum BLE receive power for the nRF52840:
  - -95 dBm -> 316.2 fW (10^{-15})
- Signal strength decreases in energy spherically
  - Eventually the signal is too quiet to receive reliably

Some Intuitions for Signal Propagation, Power, Gain, etc.

- Popular nRF52840 development kit:
  - Max BLE transmit power for nRF52840: 8 dBm (6.31 mW)
  - Min BLE receive sensitivity for nRF52840: -95 dBm (316.2 fW)

6.31 mW

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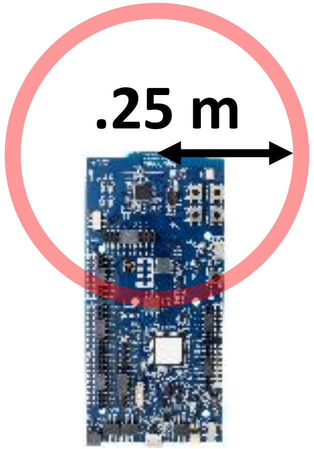

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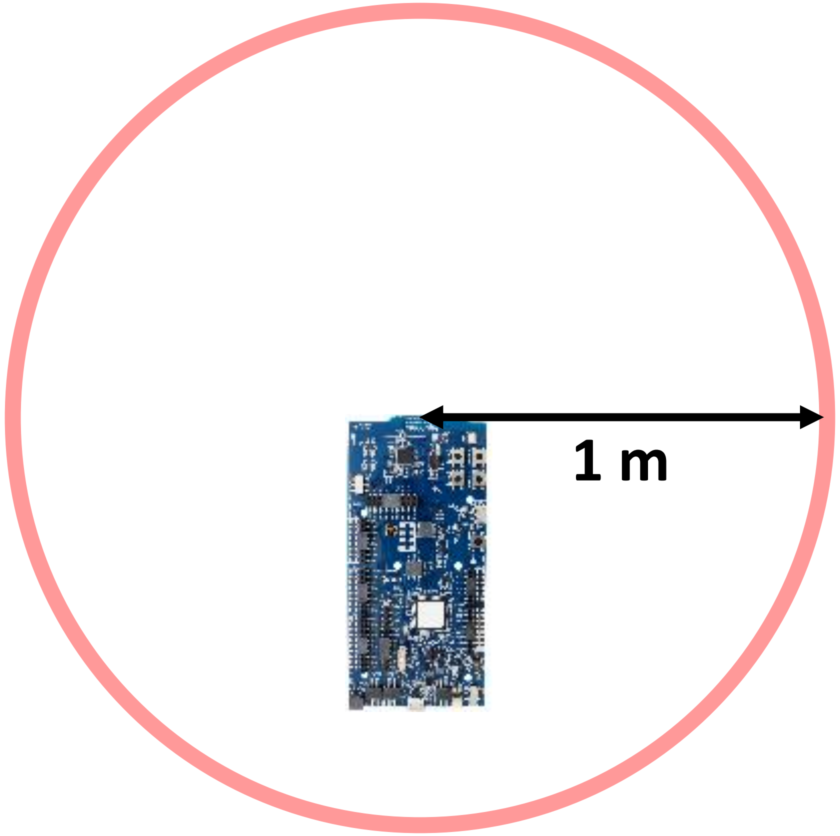

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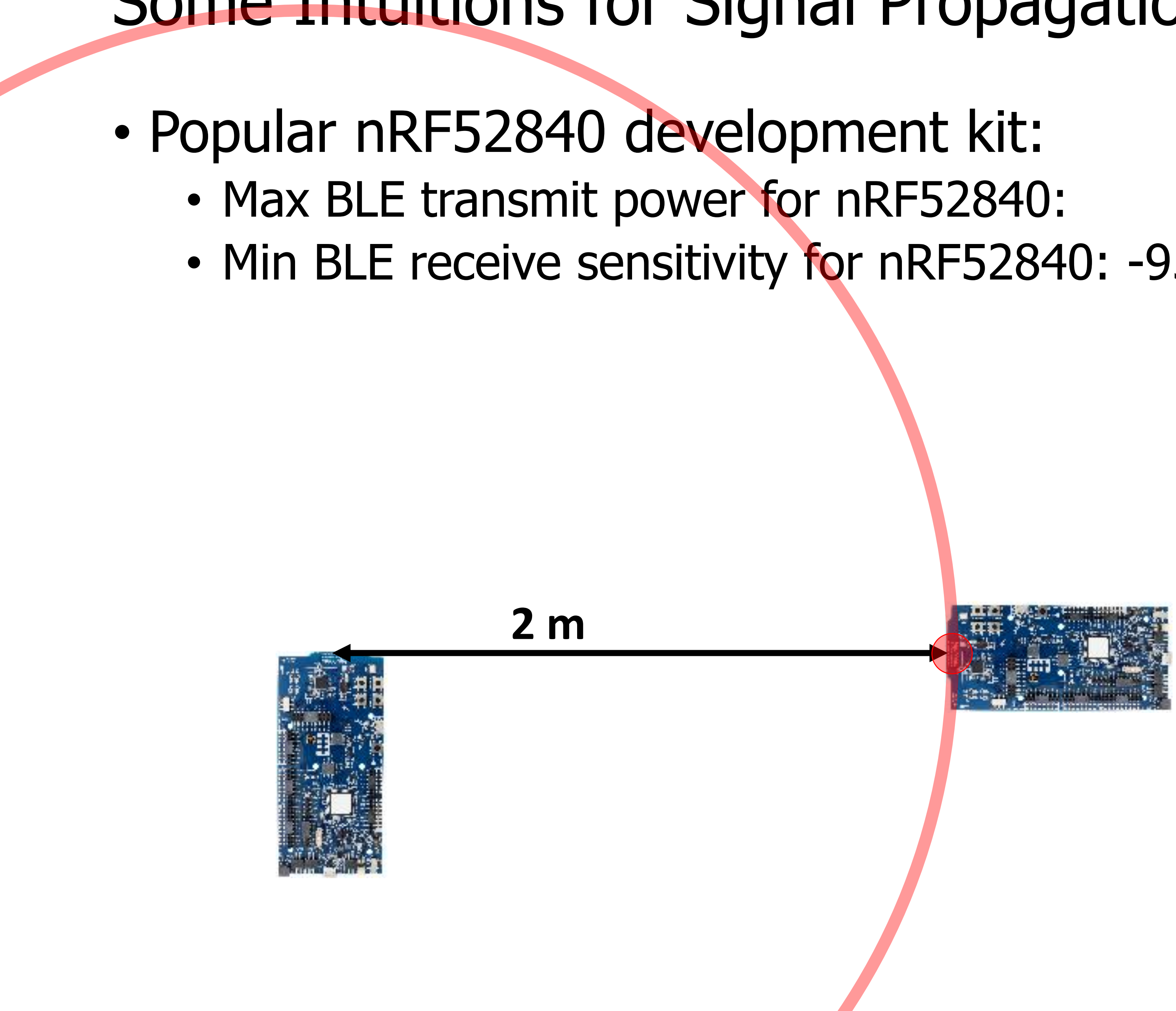

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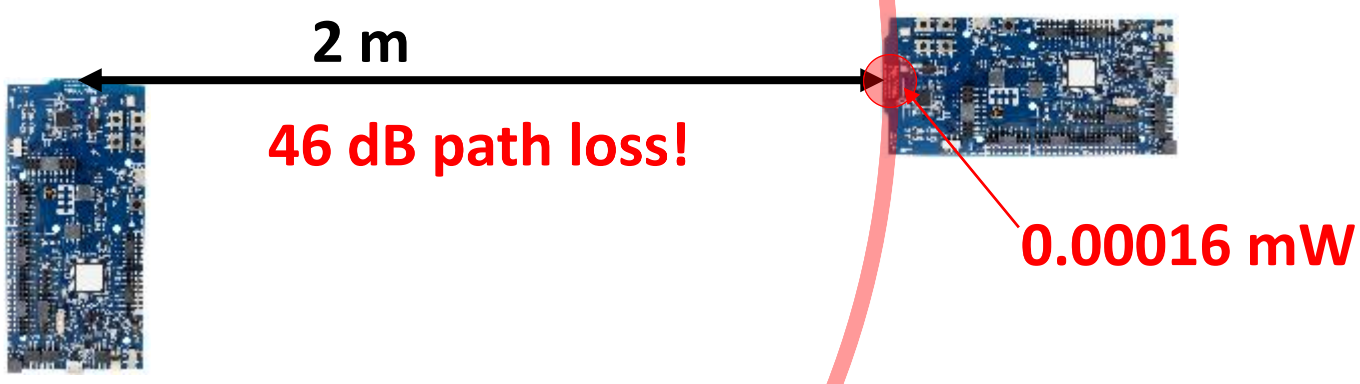

Signal strength varies significantly across technologies

- Bluetooth Low Energy (local area)
  - nRF52840 transmit power: 8 dBm (6.31 milliwatt)
  - nRF52840 receive sensitivity: -95 dBm (316.2 femtowatt)

- LoRa (wide area)
  - SX127X LoRa transmit power: 20 dBm (100 milliwatt)
  - SX127X LoRa receive sensitivity: -148 dBm (1.6 attowatt)

Signal qualities

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   - Which “channel” the signal is sent on

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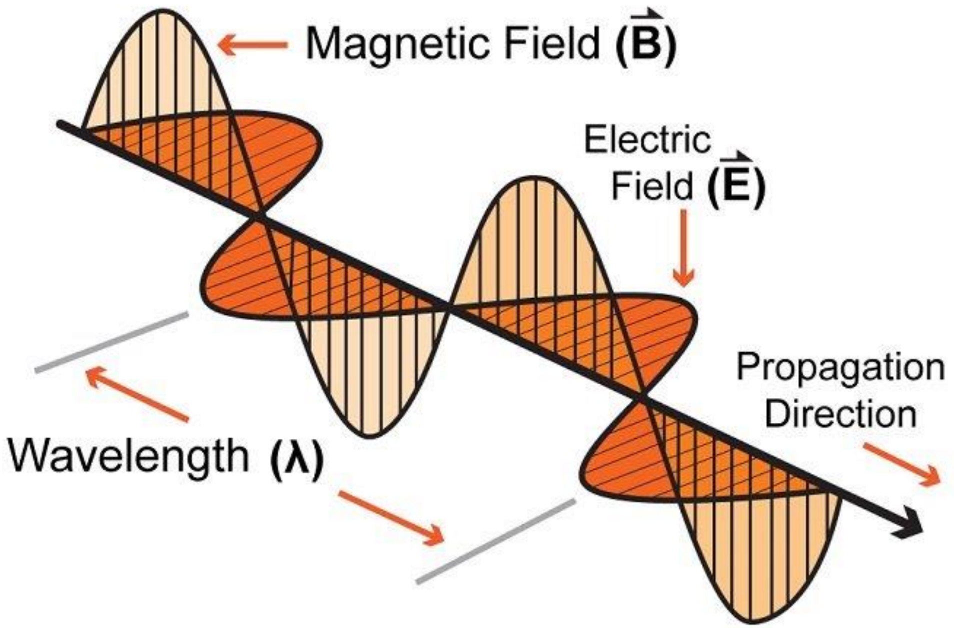
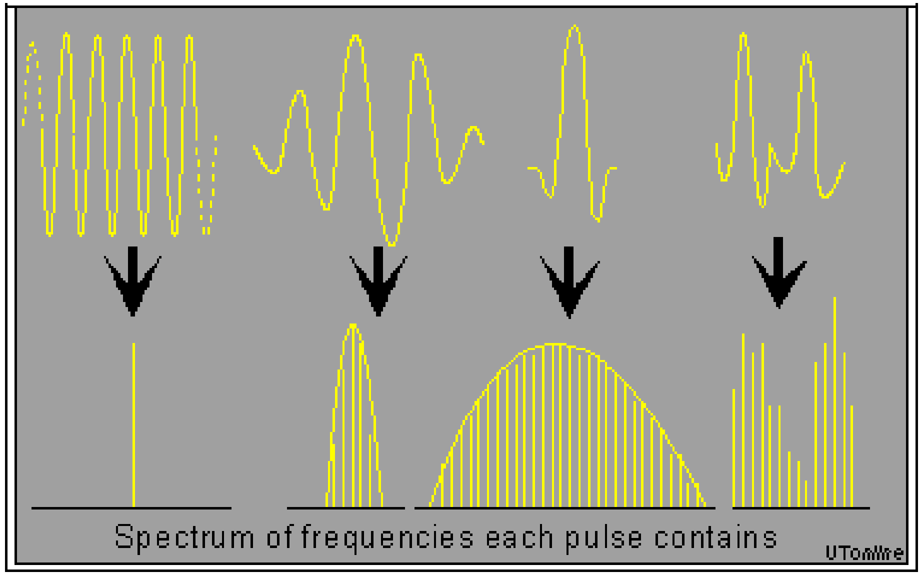


Complex waveforms have a center frequency and a width

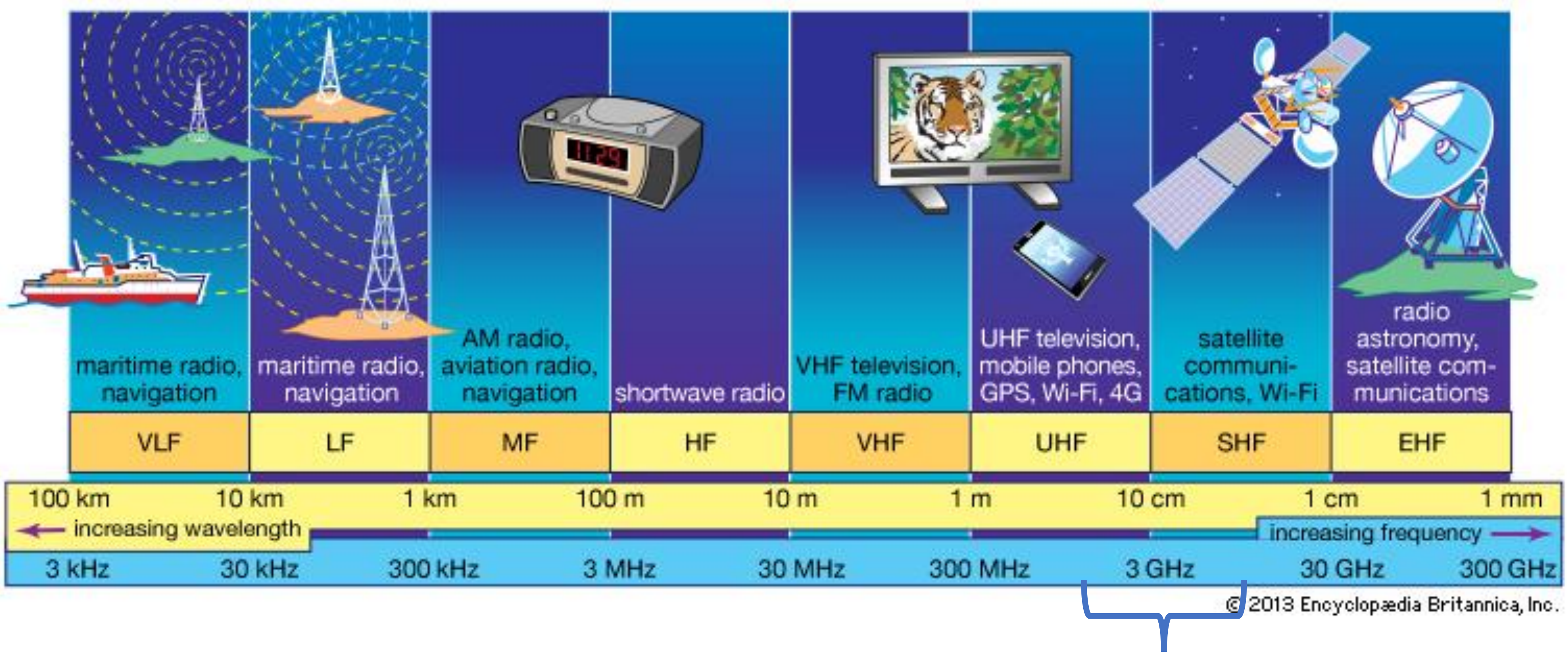
- A pure sinusoid is energy at exactly one frequency
- A messy sinusoid with data layered on top of it has nearby energy
  - There's a center of the signal energy
  - Plus some amount of width, which depends on how complicated the data layered on top is



How do radio stations work?

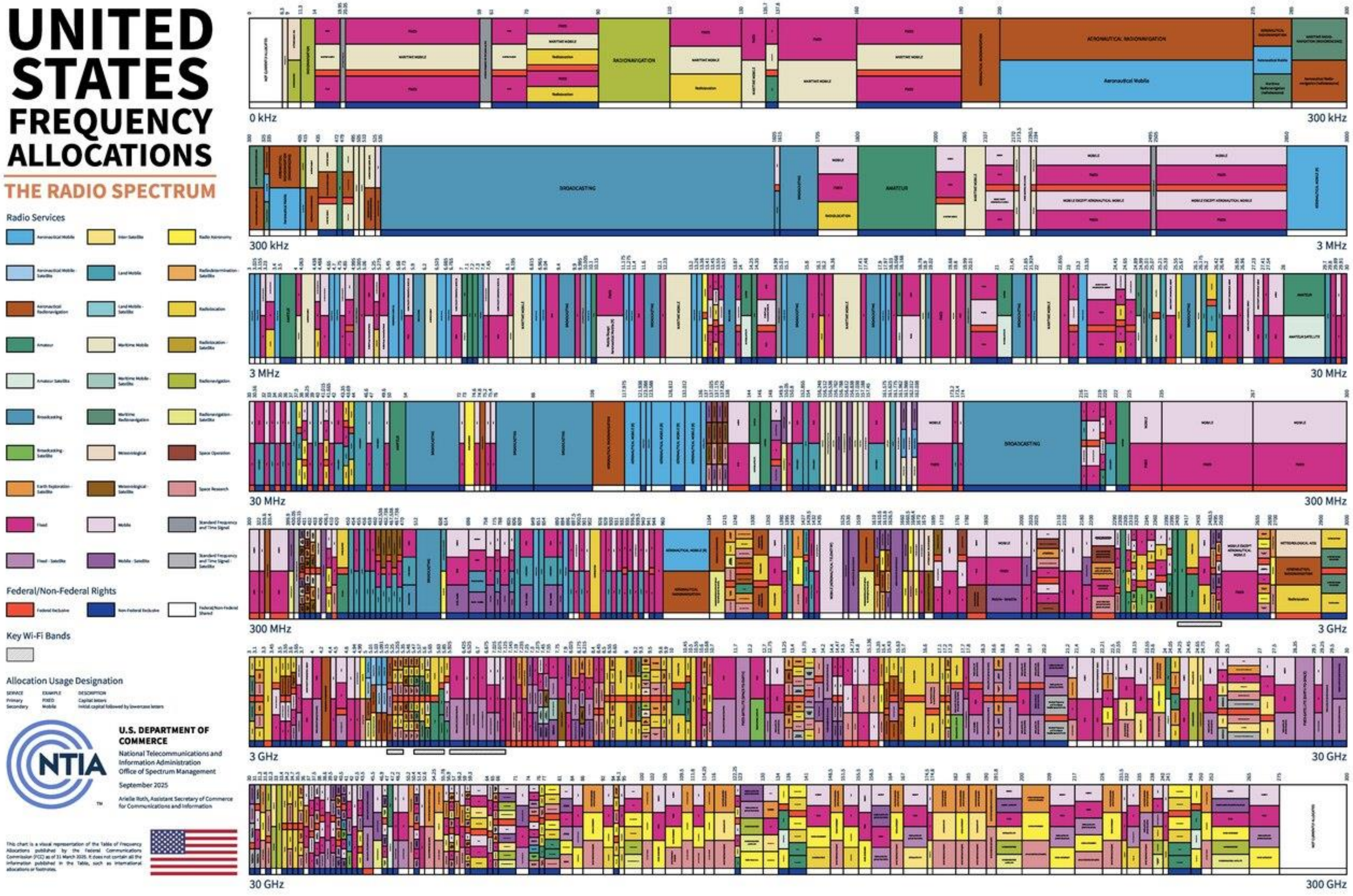
- FM radio in cars is a good example of frequencies
  - All of FM radio has an allocation of 87.5 to 108.0 MHz
  - Each station takes has up to ~200 kHz of bandwidth
- First station is 87.7 MHz +/- 100 kHz
  - Ranges from 87.6 to 87.8
- Second station is 87.9 MHz +/- 100 kHz
  - Ranges from 87.8 to 88.0
- What if they overlapped? They interfere with each other
  - You’d possibly hear both. Or get junk data that’s neither.

RF communication



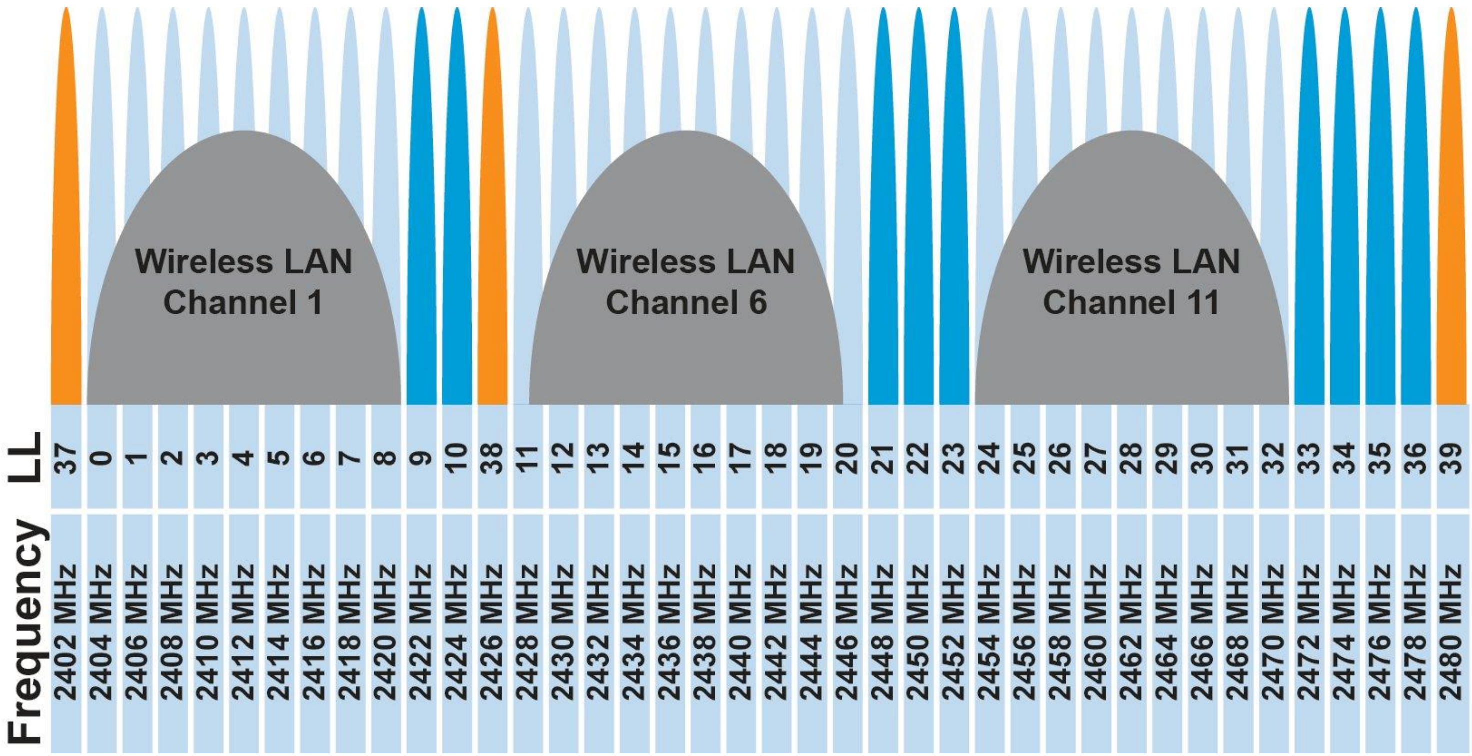
IoT focus

Wireless spectrum is allocated to specific uses



Unlicensed bands are where IoT thrives

- 902 MHz – 928 MHz
  - LPWANs
- 2.4 GHz to 2.5 GHz
  - WiFi, BLE, Thread
- 5 GHz
  - Faster WiFi



- Cellular uses licensed bands at great cost
  - **Why pay?**

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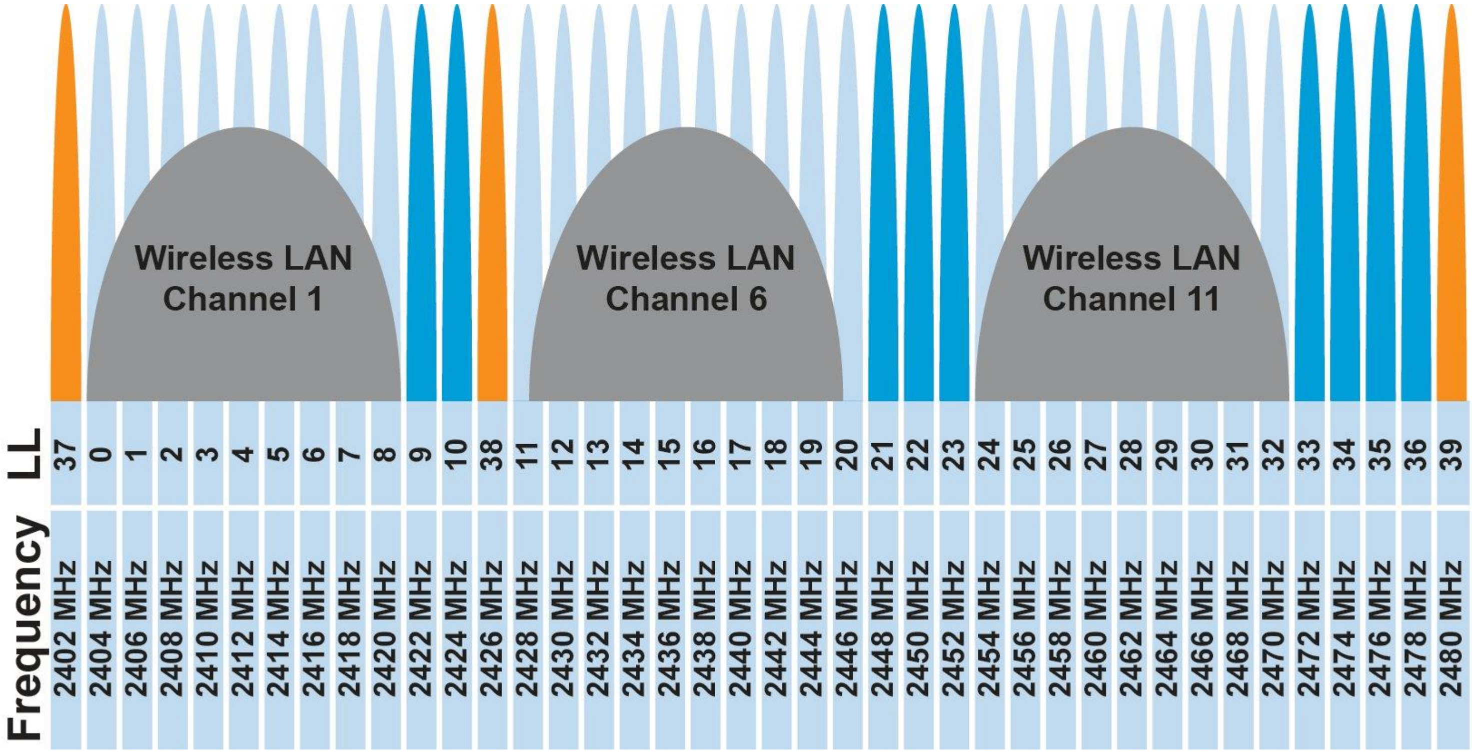

- Cellular uses licensed bands at great cost
  - **Why pay? No interference from other users**

Signal qualities

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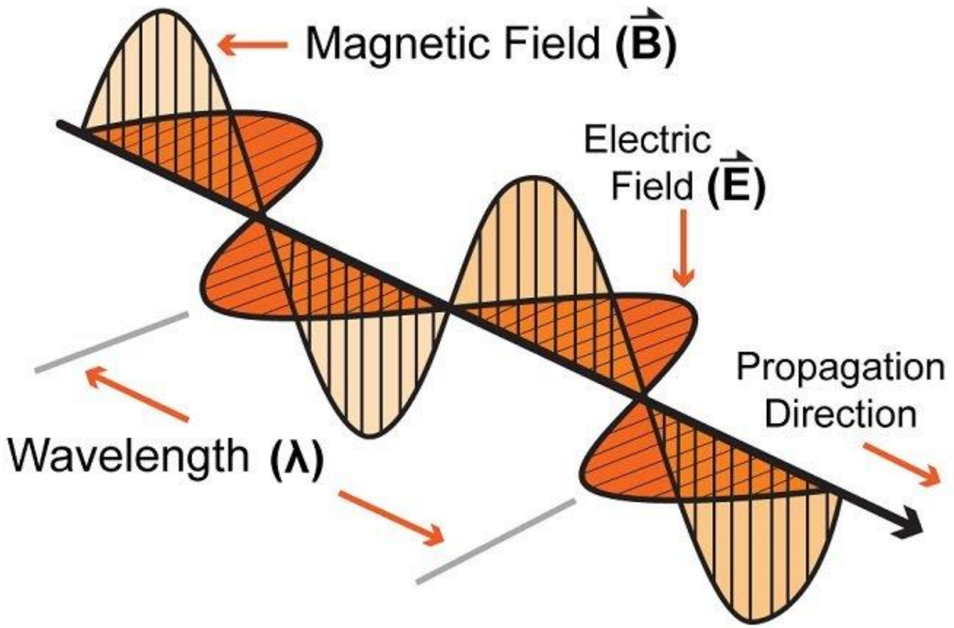
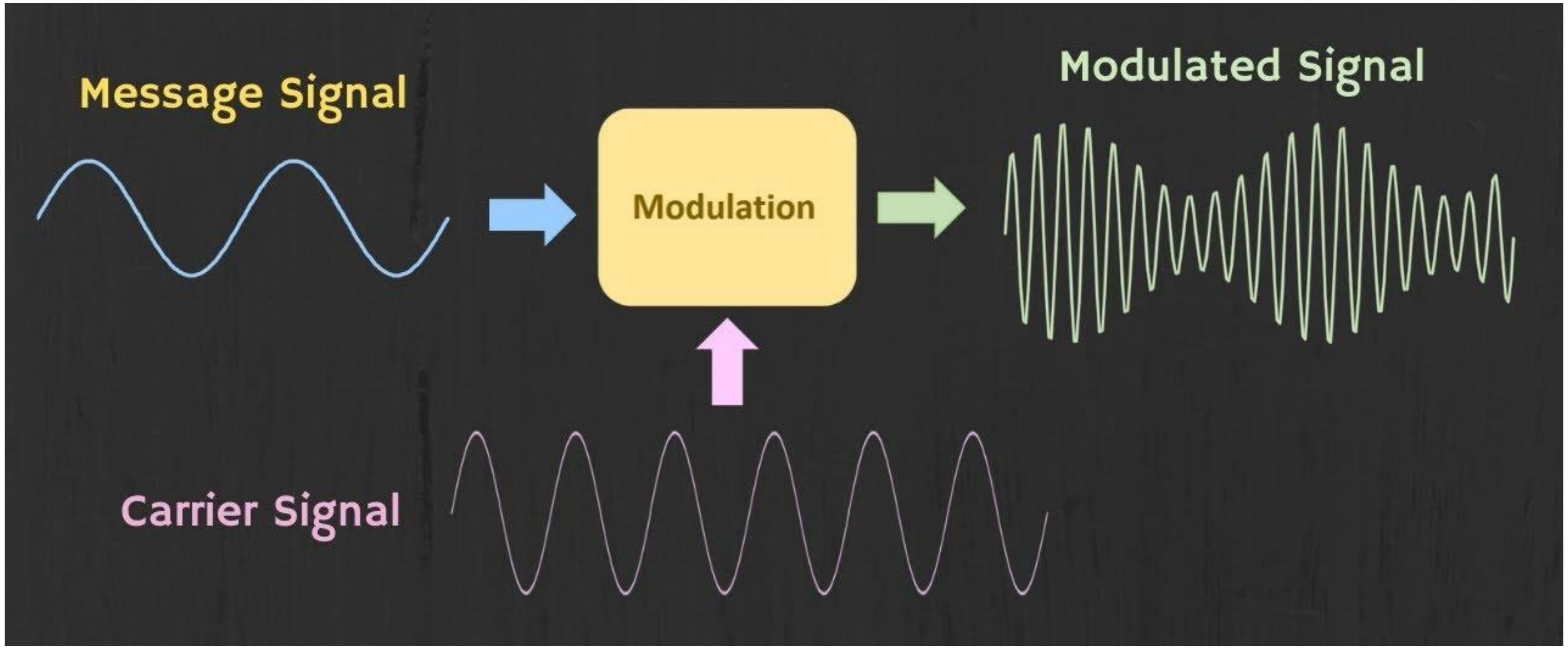
3. **Signal modulation**
   - How data is encoded in the signal



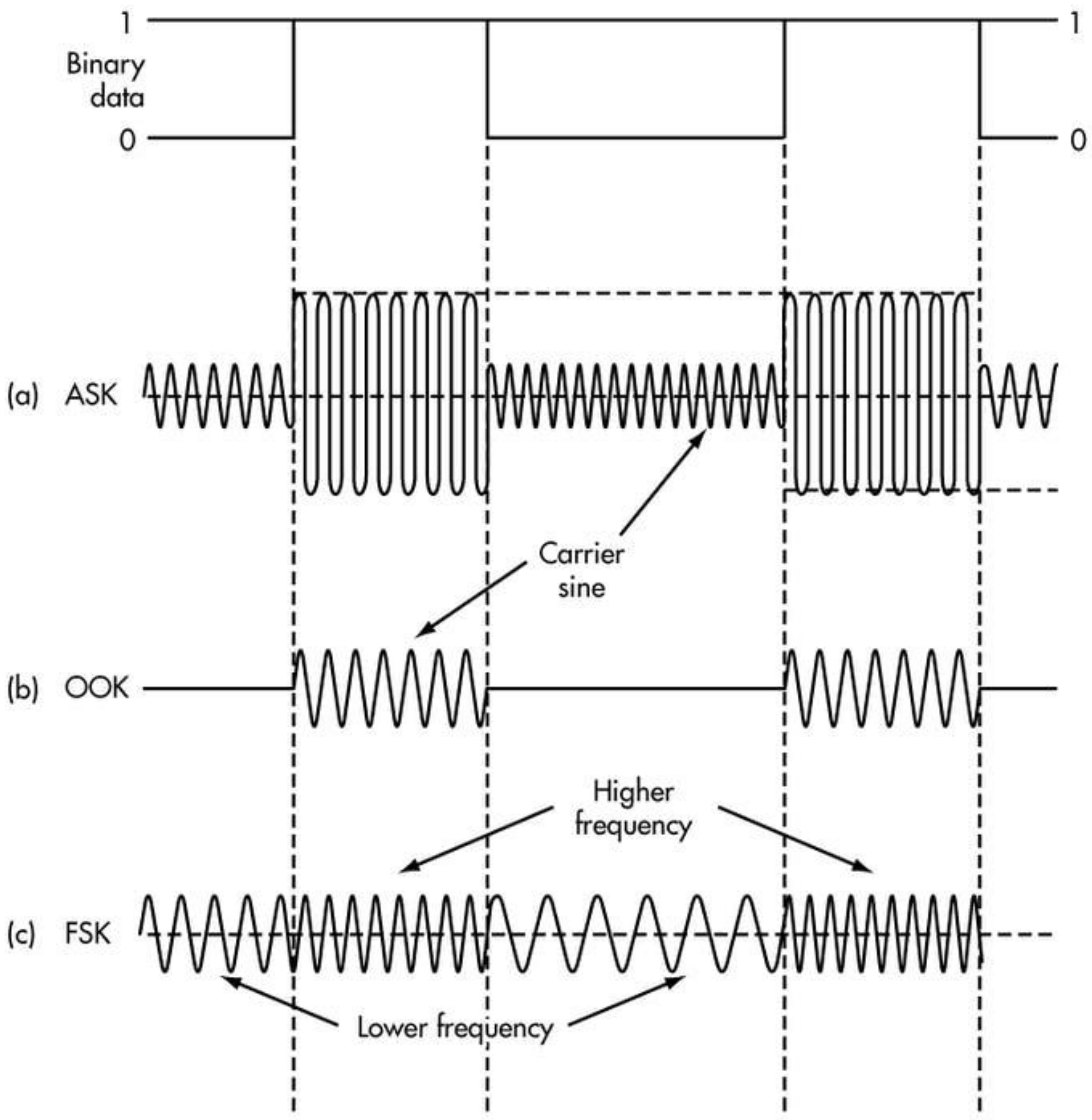
Modulation

- Encoding signal data in an analog “carrier” signal
  - Carrier signal defines the frequency
  - Modulation scheme + data define bandwidth required



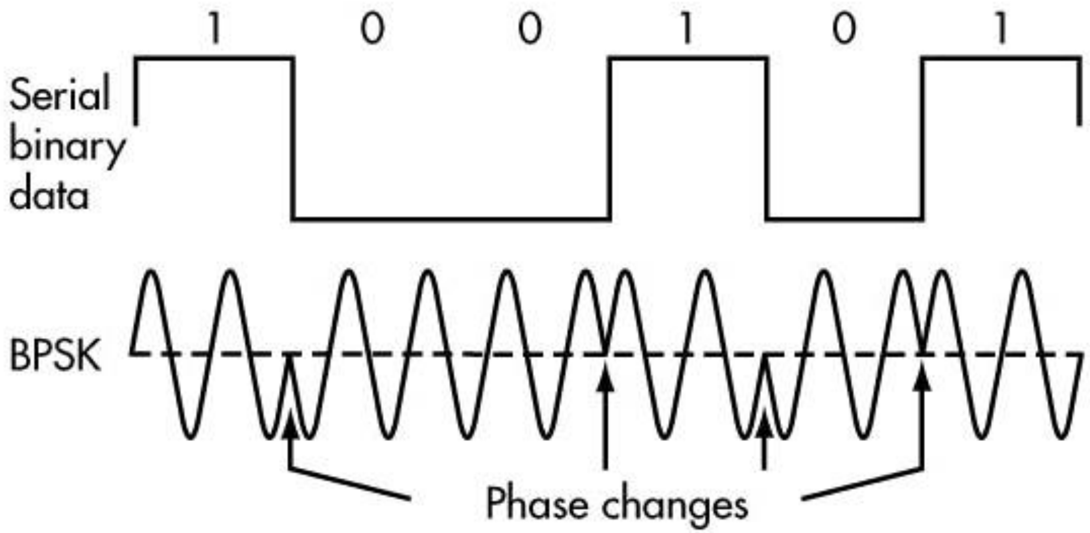
Common modulation types

- Encoding binary data on a signal
- Amplitude-shift Keying (ASK)
  - Modify amplitude of carrier signal
  - On-Off Keying (OOK) is an extreme example
- Frequency-shift Keying (FSK)
  - Modify frequency of carrier signal



Modulation types

- Phase-shift keying (PSK)
  - Modify phase of carrier signal
  - Often differential:
    the change signifies data



- More complicated possibilities exist
  - QAM (Quadrature Amplitude Modulation) combines amplitude and phase shift keying
    - Allows for more than one bit per “symbol”

Break + Open Question

- **What lets some protocols travel further than others?**
  - WiFi is about 100 meters
  - Cellular is more than 1000 meters

Break + Open Question

- **What lets some protocols travel further than others?**
  - WiFi is about 100 meters
  - Cellular is more than 1000 meters

- Multiple different parameters affect this
  - More transmit power
  - More receive sensitivity (receive at a lower power)

  - Modulation that makes it easier to recover bits without errors
  - Bandwidth can also affect error rates, which in turn affects distance

  - Frequency kinda-sorta, but not as much as people think

Outline

- Wireless Communication Overview
- **Wireless Protocols**
  - **Overview**
  - Bluetooth Low Energy
  - 802.15.4
  - WiFi
  - Low-Power Wide-Area Networks

What is the role of a wireless protocol?

- Multiple methods exist for sending bits wirelessly

- Protocols make choices about how to use them
  1. Select exact configurations for bit communication (Physical Layer)

  2. Determine how to send packets of data (Data Link Layer)
     - What are the fields within a packet?
     - Which device sends a packet and when can it do so?

  3. Organize communication between devices (Network Layer)
     - How are devices named?
     - How is communication directed between those devices?

Framing

- Typical packet structure
  - Preamble - Existence of packet and synchronization of clocks
  - Header - Addresses, Type, Length
  - Data - Payload plus higher layer headers (e.g. IP packet)
  - Trailer - Padding, CRC

Preamble	Destination Address	Source Address	Type and Length	Data	CRC

- Wireless considerations
  - Control information for Physical Layer
  - Ensure robustness for header
  - Possibly different data rates for different parts of packet

Medium Access Control

- How does a network determine which transmitter gets to transmit?

- Remember: the wireless medium is inherently broadcast
  - Two simultaneous transmitters may lose both packets

Analogy: wireless medium as acoustic

- **Activity: How do we determine who gets to speak?**
  - Two simultaneous speakers also lose both “transmissions”
  - How many different methods can you come up with?

Analogy: wireless medium as acoustic

- **Activity: How do we determine who gets to speak?**
  - Two simultaneous speakers also lose both “transmissions”
  - How many different methods can you come up with?

- Eye contact (or raise hand) -> out-of-band communication
- Wait until it’s quiet for some time -> carrier sense multiple access
- Strict turn order -> time division multiple access
- Just speak and hope it works -> ALOHA
- Everybody sing at different tones -> frequency division multiple access (stretching the metaphor)

- Others?

ALOHA

- ALOHAnet (1971)
  - University of Hawaii – Norman Abramson
  - First demonstration of wireless packet network

- Rules
  1. If you have data to send, send it

- Two (or more) simultaneous transmissions will collide and be lost
  - Wait a duration of time for an acknowledgement
  - If transmission was lost, try sending again "later"
    - Want some kind of exponential backoff scheme here

CSMA/CA – Carrier Sense Multiple Access with Collision Avoidance

- First listen for a duration and determine if anyone is transmitting
  - If idle, you can transmit
  - If busy, wait and try again later

- "listen before send"

- More expensive than Aloha, but far more reliable
  - Higher energy and lower data rate due to time spent listening
  - Don't mess up messages that have already started
    - Collisions can only occur if there are multiple waiting devices

TDMA – Time Division Multiple Access

- Split transmissions in time
  - Devices share the same channel

- Splits time into fixed-length windows
  - Each device is assigned one or more windows
  - Can build a priority system here with uneven split among devices

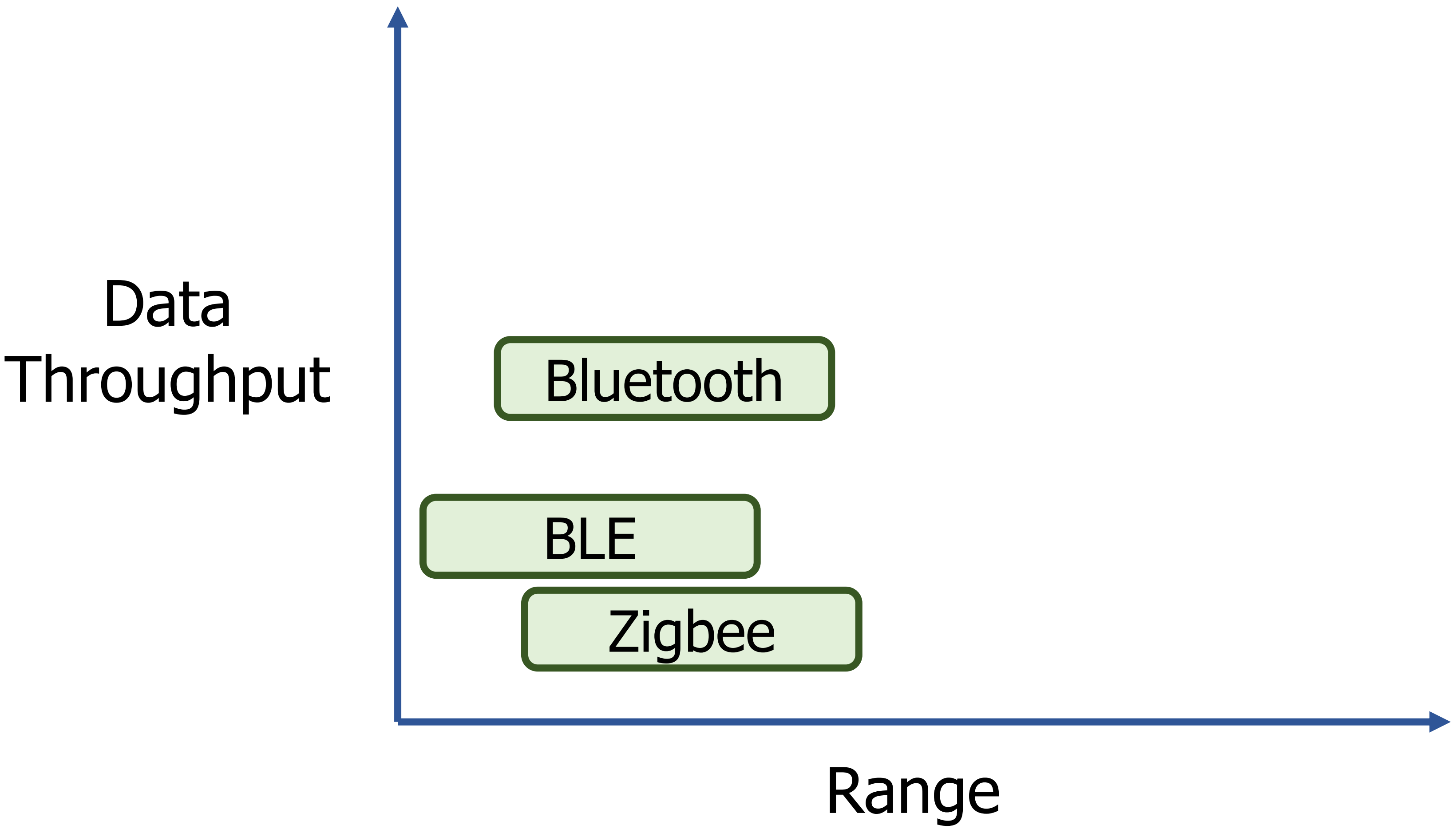
- Requires synchronization between devices
  - Often devices must listen periodically to resynchronize
  - Less efficient use of slots reduce synchronization
    - Large guard windows. E.g., 1.5 second slot for a 1 second transmission

Outline

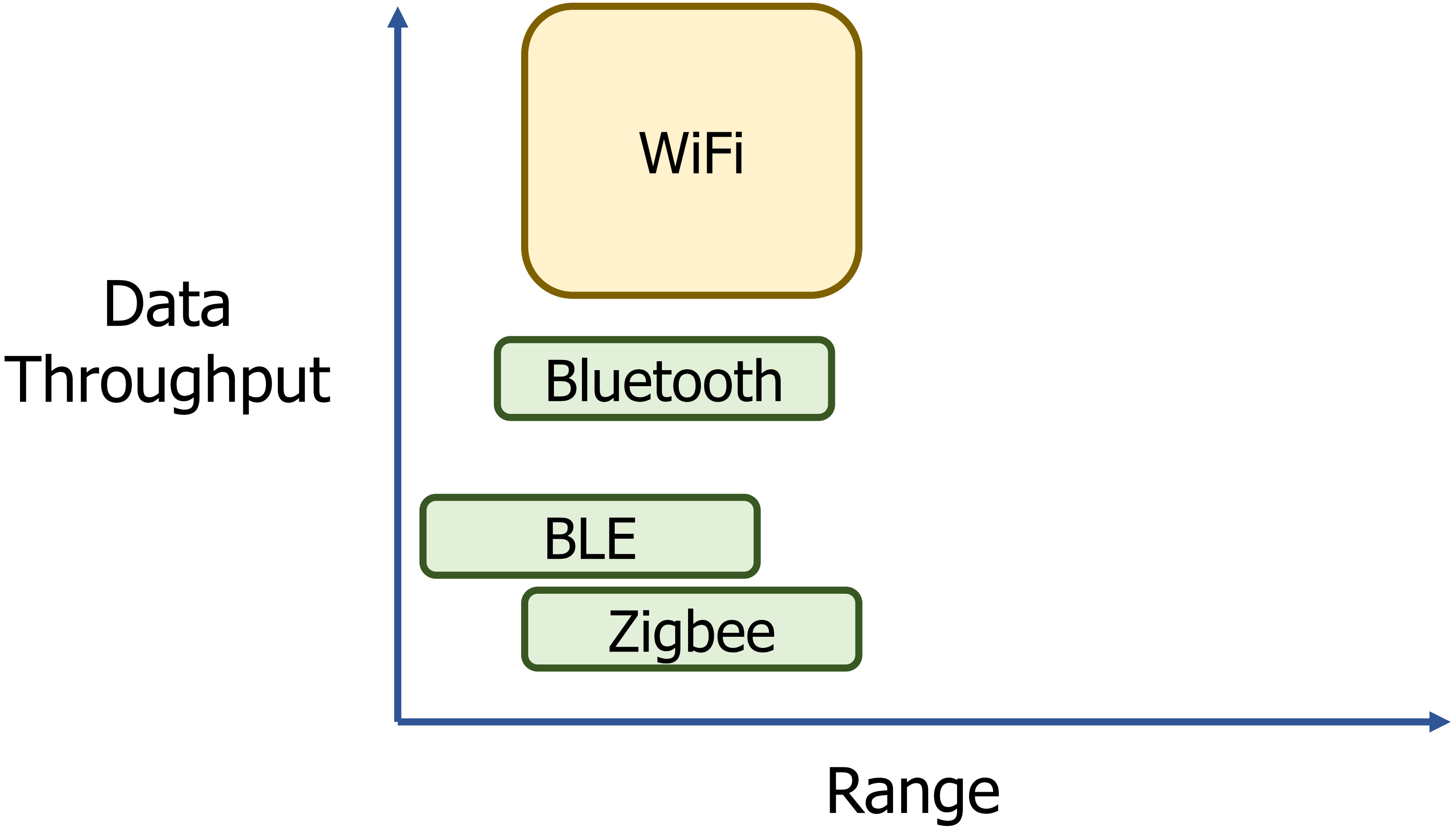
- Wireless Communication Overview

- **Wireless Protocols**
  - Overview
  - **Bluetooth Low Energy**
  - **802.15.4**
  - **WiFi**
  - **Low-Power Wide-Area Networks**

Comparison of wireless protocols



Comparison of wireless protocols



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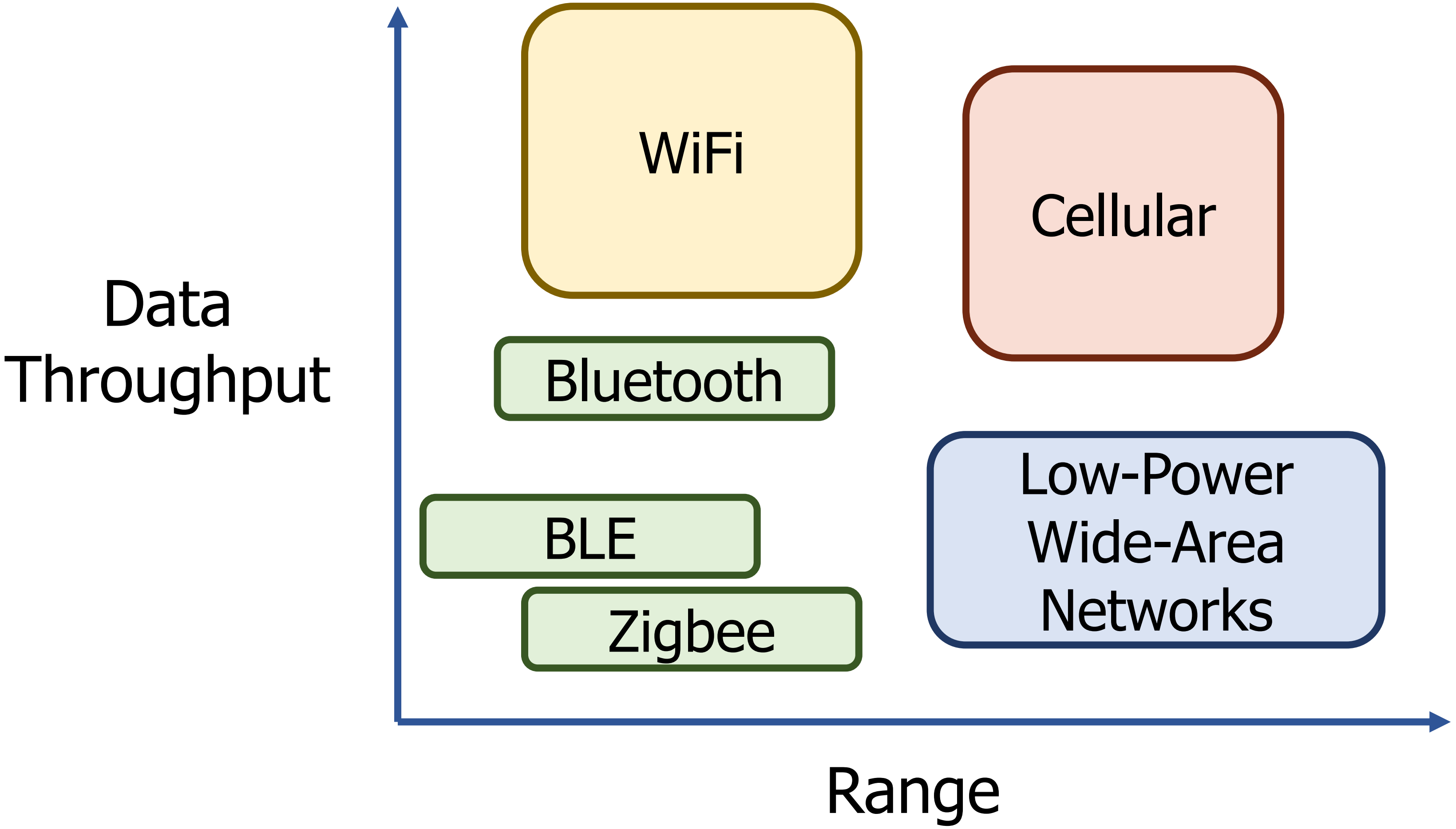

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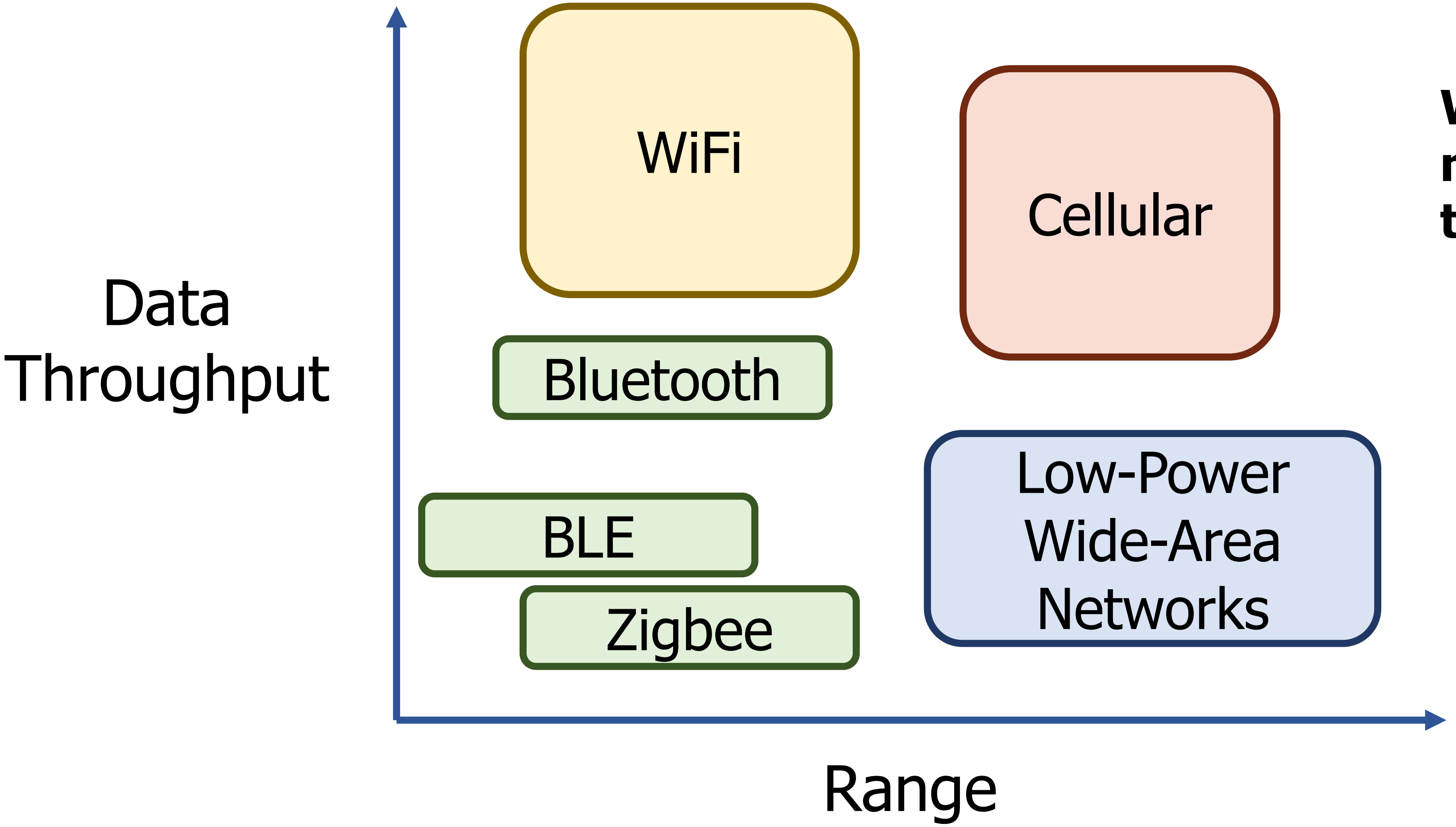
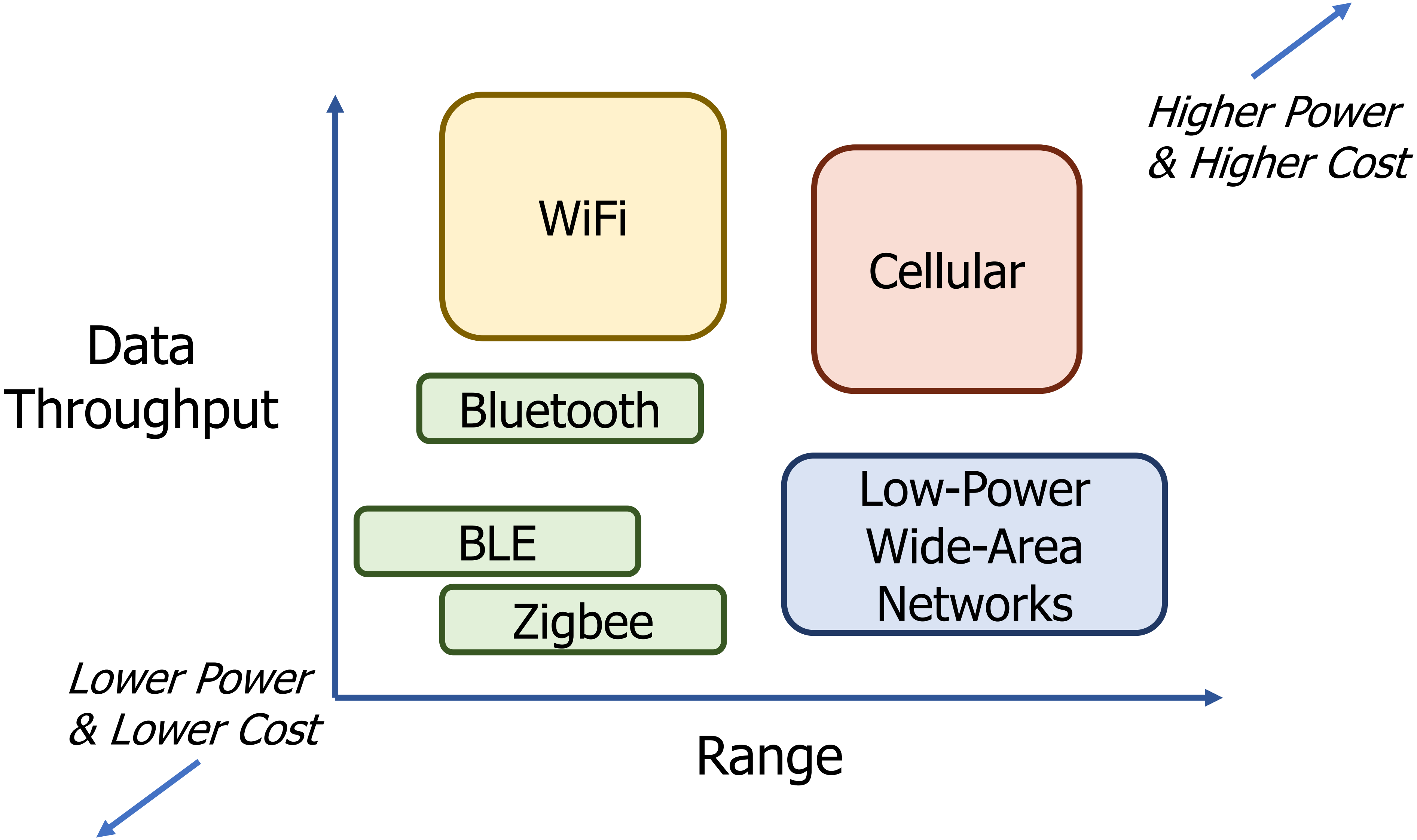


Why don’t we always max out range and throughput?

Comparison of wireless protocols



Protocols

- **Bluetooth Low Energy**
- 802.15.4 – Zigbee and Thread
- WiFi
- Low-Power Wide-Area Networks

Bluetooth Low Energy

- Bluetooth Classic was good for enabling device to device communication
  - But not particularly fast discovery or low energy operation

- Bluetooth Low Energy was developed to improve this
  - Focuses on low-energy interactions
  - Much lower throughput that Bluetooth

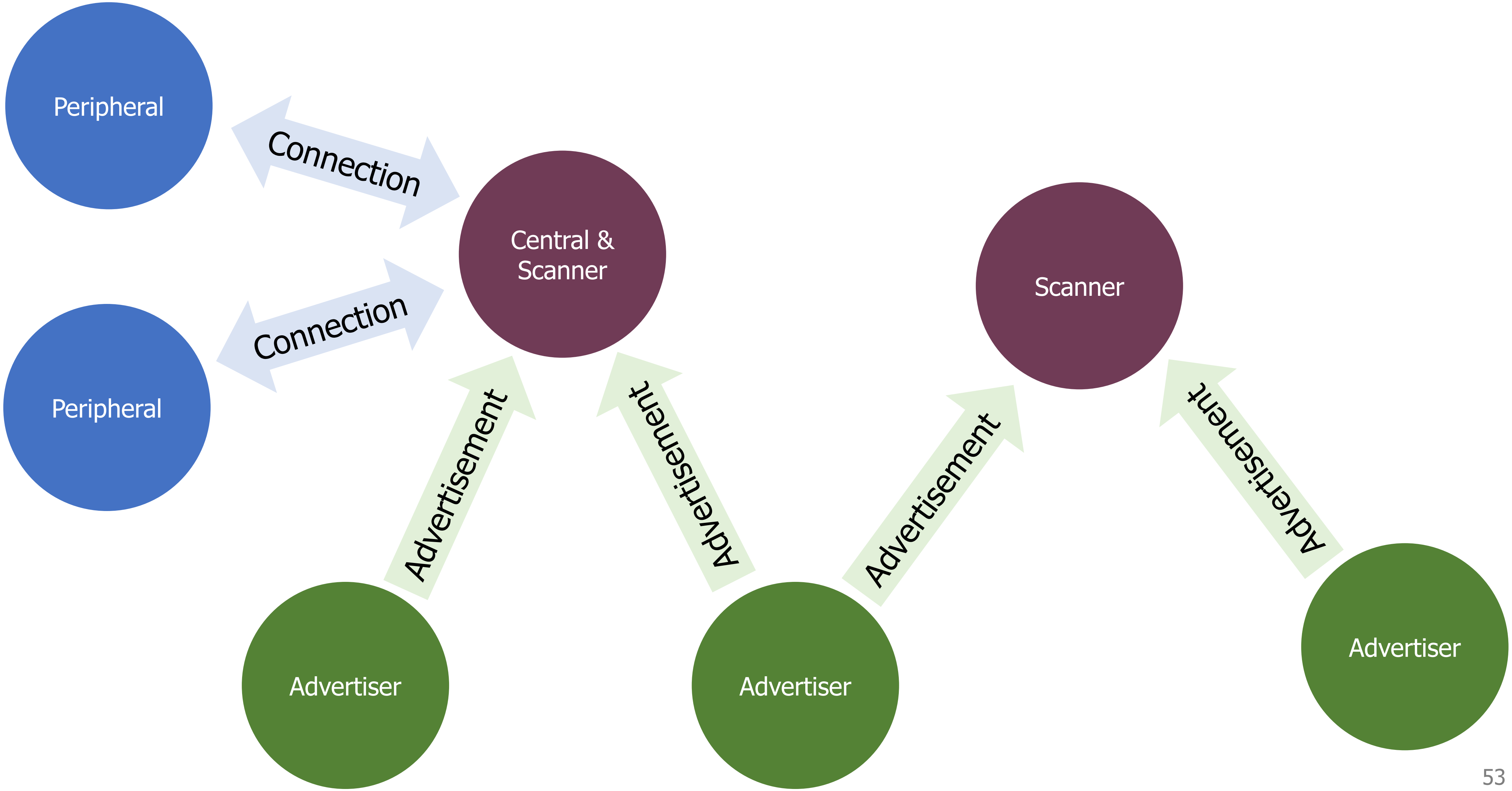
- Supported by hardware devices already in smartphones
  - Humans can interact directly with nearby devices!!

BLE mechanisms

- Advertising
  - Discovery
  - Advertisements – broadcast messages indicating device details
  - Ephemeral, uni-directional communication from Advertiser to Scanner(s)
  - ALOHA access control

- Connections
  - Interaction
  - Bi-directional communication between Peripheral and Central
  - Maintained for some duration
  - TDMA access control

BLE network topology



Protocols

- Bluetooth Low Energy
- **802.15.4 – Zigbee and Thread**
- WiFi
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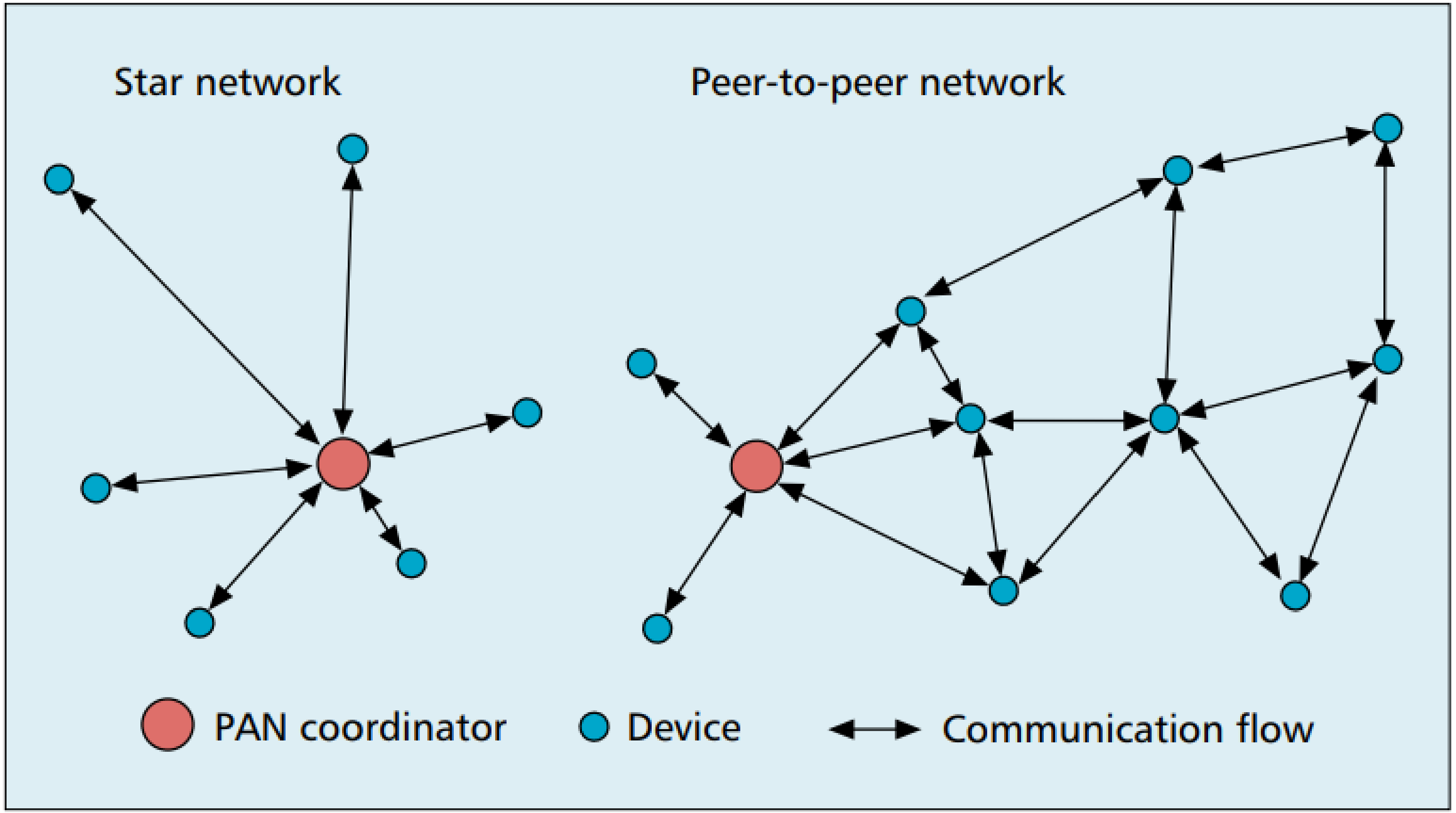
802.15.4 & Thread & Zigbee

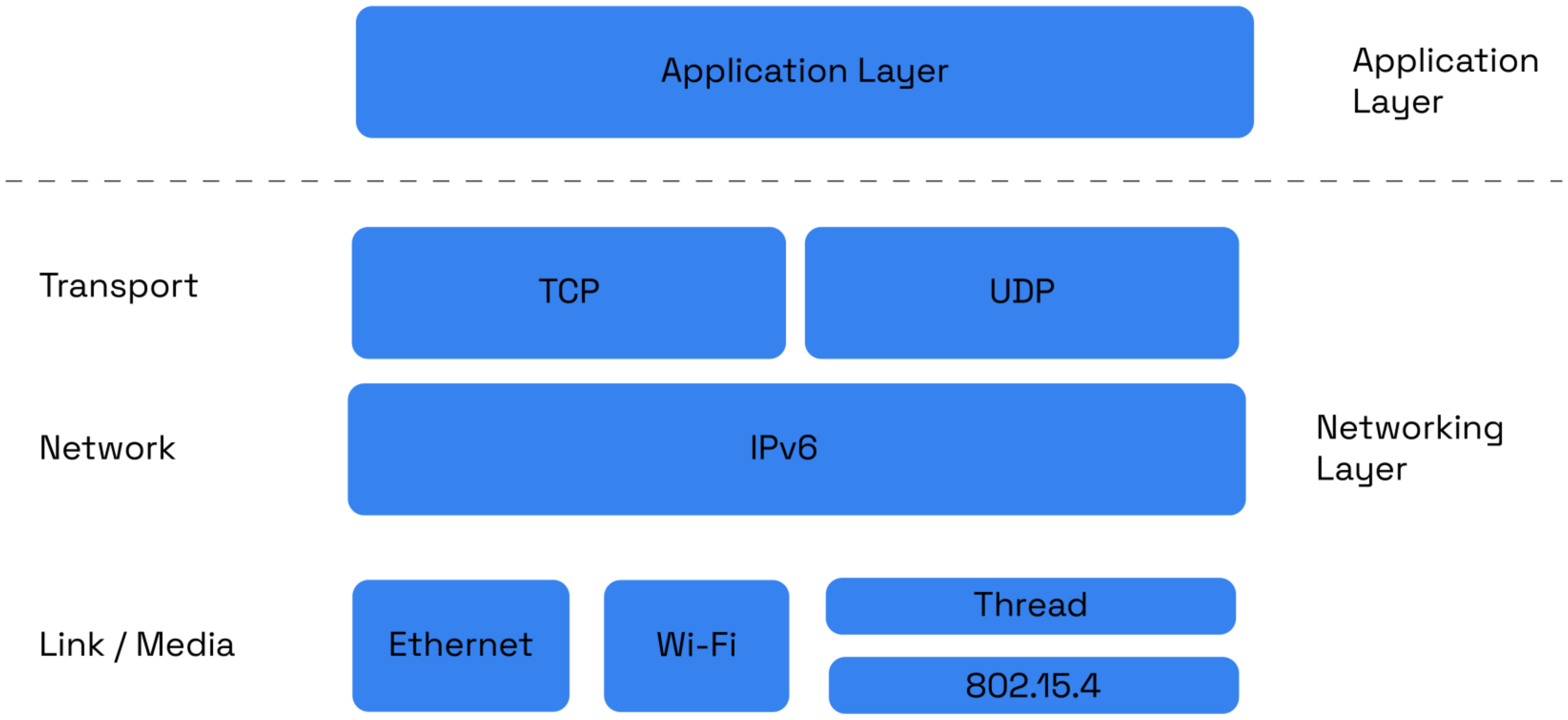
- 802.15.4 is a low-energy method for transmitting bits (physical layer)
  - Radio chips have been widely available for 15-20 years
- *Significant* amounts of sensor network research have focused on building layers on top of 802.15.4
  - Access control layers (CSMA)
  - Network layers
- Thread is a selection of these possibilities to make a network
  - Uses IPv6 networking!!
- Zigbee makes slightly different selections
  - Focuses on automatic interpretation and discovery of sensors and actuators

802.15.4 topology

- Expects use cases as Star or Mesh networks



Matter standard



Lots of member companies

- Standard for interoperable smart home devices (October 2022)
  - Uses IPv6 over 802.15.4/Thread to send packets
  - Uses standardized device classes with descriptors for application logic

Protocols

- Bluetooth Low Energy
- 802.15.4 – Zigbee and Thread
- **WiFi**
- Low-Power Wide-Area Networks

WiFi (802.11)

- Ubiquitous wireless communication
  - High energy requirements for high throughput communication

- Now accessible through relatively low power radios
  - ESP32, Electric Imp, and company
  - Still significantly more effort than BLE or Thread

- IoT devices can use the same WiFi that's already available
  - No need for additional infrastructure!!

802.11 major amendments

	Protocol	Year	Frequency	PHY	Max Rate	Range
-	802.11	1997	2.4 GHz	DSSS/FHSS	2 Mbps	20 m
1	802.11b	1999	2.4 GHz	DSSS	11 Mbps	35 m
2	802.11a	1999	5 GHz	OFDM	54 Mbps	35 m
3	802.11g	2003	2.4 GHz	OFDM	54 Mbps	38 m
4	802.11n	2009	2.4/5 GHz	OFDM + MIMO (single user)	600 Mbps	70 m
5	802.11ac	2013	5 GHz	OFDM + MU-MIMO (downlink only)	3400 Mbps	35 m
6	802.11ax	2021	2.4/5/[6] GHz	OFDMA + MU-MIMO (up and down)	9600 Mbps	35 m
7	802.11be	2024	2.4/5/6 GHz	OFDMA + MU-MIMO (up and down)	23000 Mbps	35 m

- 802.11b was very popular but is now usually unsupported
- 802.11a never saw major deployment

- WiFi Alliance rebranded 802.11ac as “WiFi 5” and backported scheme

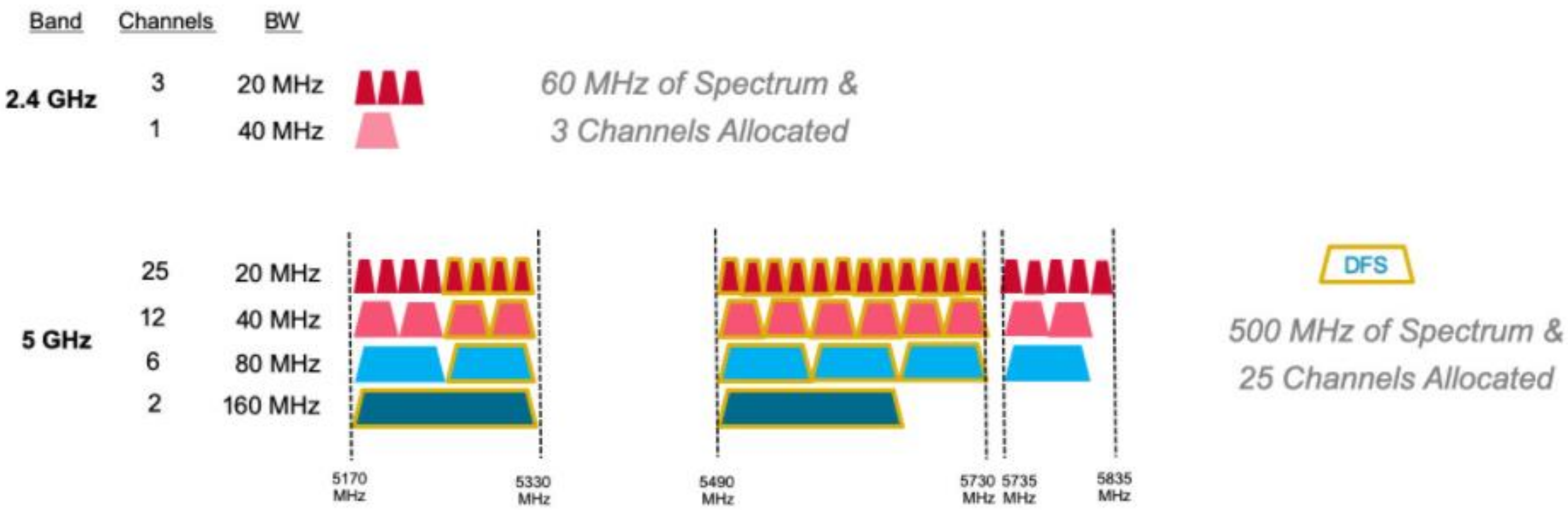
WiFi bandwidth

Band	Channels	BW
2.4 GHz	3	20 MHz
	1	40 MHz

60 MHz of Spectrum &
3 Channels Allocated

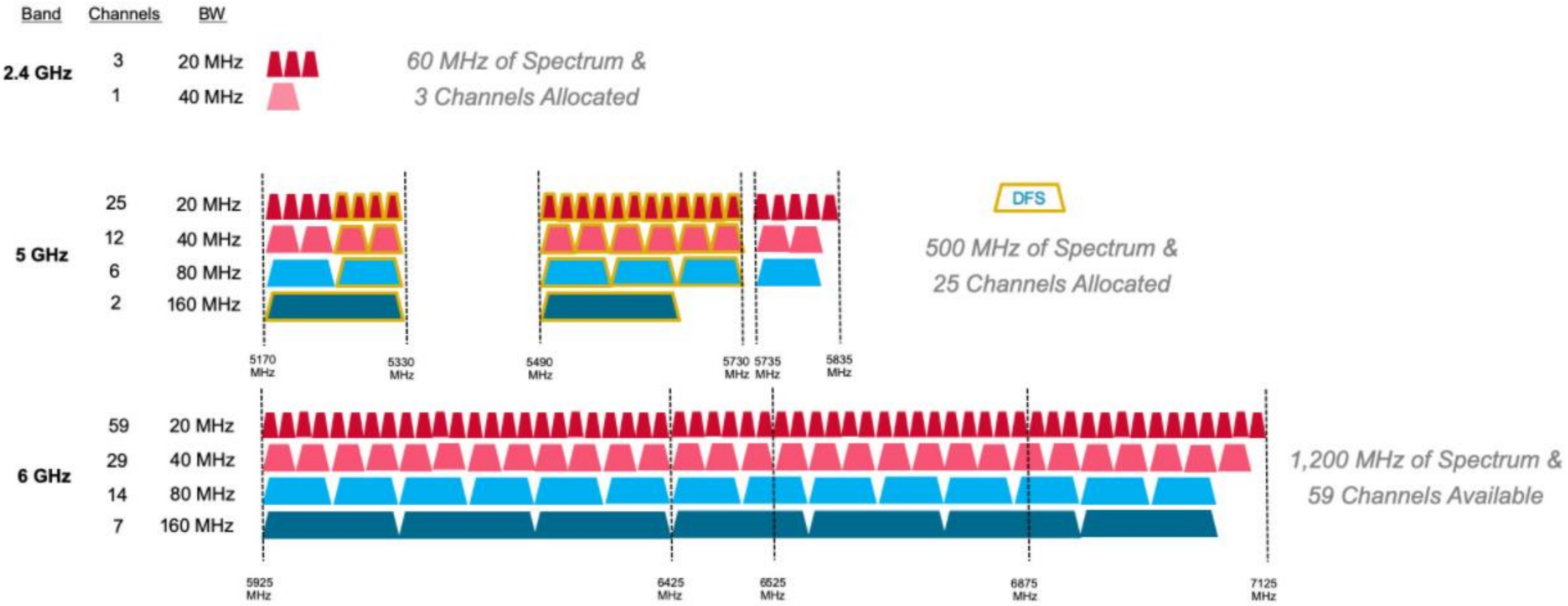
- More bandwidth means higher data rate (with same error rate)

WiFi bandwidth



- More bandwidth means higher data rate (with same error rate)
- 5 GHz band allows larger bandwidth allocations for more data rate

WiFi 6E: WAY more bandwidth means even better data rates



Protocols

- Bluetooth Low Energy
- 802.15.4 – Zigbee and Thread
- WiFi
- **Low-Power Wide-Area Networks**

LPWANs (Low-Power Wide-Area Networks)

- How do we collect data from city-scale deployments?
  - There's an unmet need for long-range, but low-throughput networks
  - Existing cellular technologies focus on human requirements

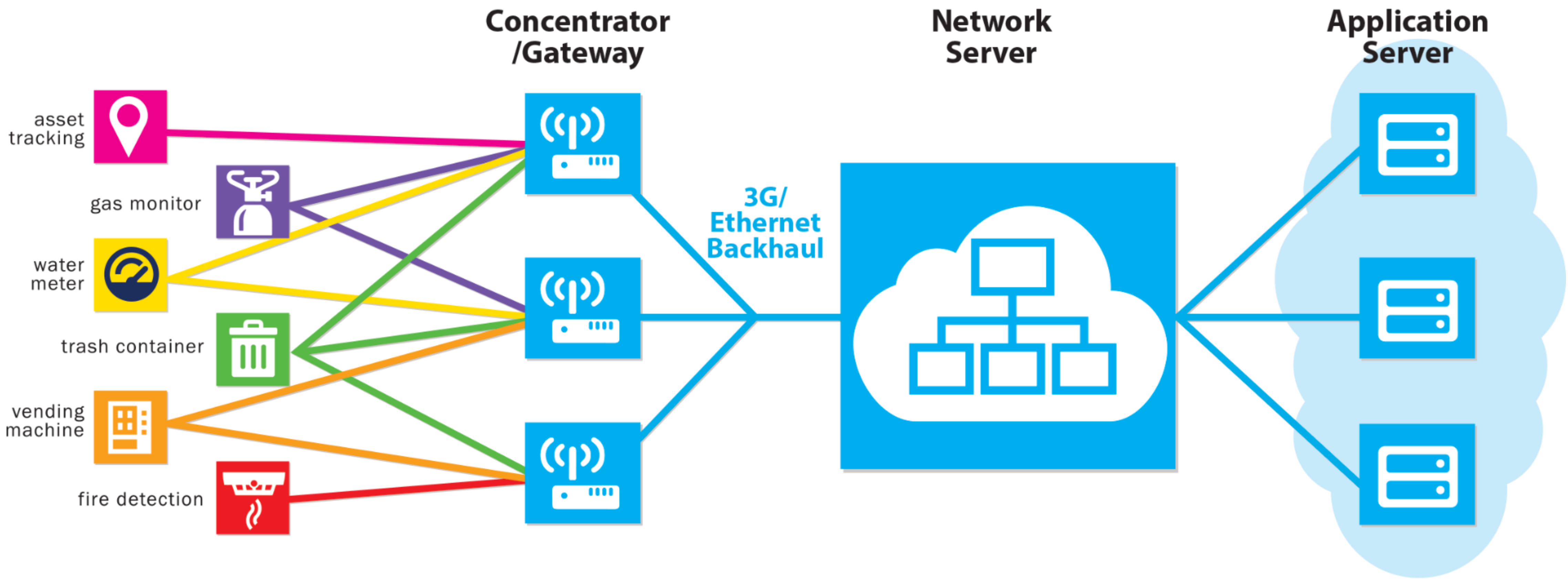
- Still a relatively new space
  - Unlicensed-band technologies since 2015: Sigfox and LoRaWAN
  - Cellular technologies since 2019: LTE-M and NB-IoT

- Focus on long-range, low-energy, low-throughput
  - One gateway can cover an entire city!!

LoRaWAN

- Open communication standard built with proprietary LoRa PHY
- Low rate (1-20 kbps) and long range (~5 km)
  - Shorter range than Sigfox but much higher bit rate
- Most popular LPWAN protocol
  - Target of academic research
  - Industry involvement in hardware and deployments

LoRaWAN network details



If you find this interesting…

- I also teach a special topics course!
  - CS433 Wireless Protocols for the Internet of Things
    - Spring quarter 2027
  - Lab course, similar to this one but more on-your-own
    - Design project on paper instead of a final project

- Spend some time learning and playing around with wireless protocols. Especially
  - Bluetooth Low Energy
  - 802.15.4 (Thread and Zigbee)
  - WiFi (802.11)
  - LPWANs (LoRaWAN and others)

Outline

- Wireless Communication Overview
- Wireless Protocols
  - Overview
  - Bluetooth Low Energy
  - 802.15.4
  - WiFi
  - Low-Power Wide-Area Networks