

Lecture 14

Wireless Communication

CE346 – Microcontroller System Design
Branden Ghena – Fall 2025

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

Administrivia

- Heads up: office hours today are going to be *busy*
 - Quite a few groups still need Lab 6 checkoffs
- I'm still ordering more hardware if people need things
- How to get project help
 - Office hours (including Fridays)
 - Piazza post (I've added some posts on general stuff)
 - Find guides on the Internet

Today's Goals

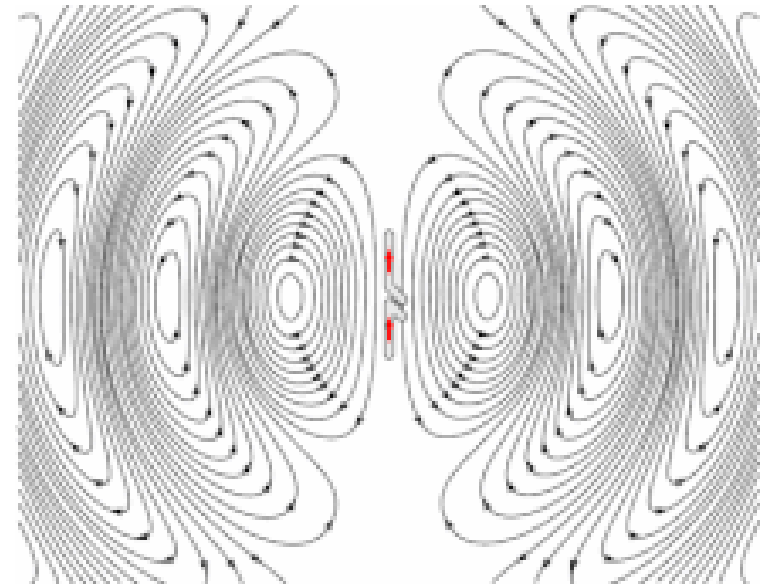
- Explore important issues in wireless communication
 - Physical and Data Link layers particularly
 - Describe several wireless networks that are very important to modern Internet of Things devices
 - Bluetooth Low Energy
 - Thread and Zigbee (802.15.4)
 - WiFi (802.11)
 - Low-Power Wide-Area Networks
- } nRF52833 supports BLE!
But our Microbit library doesn't 😞
- 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?

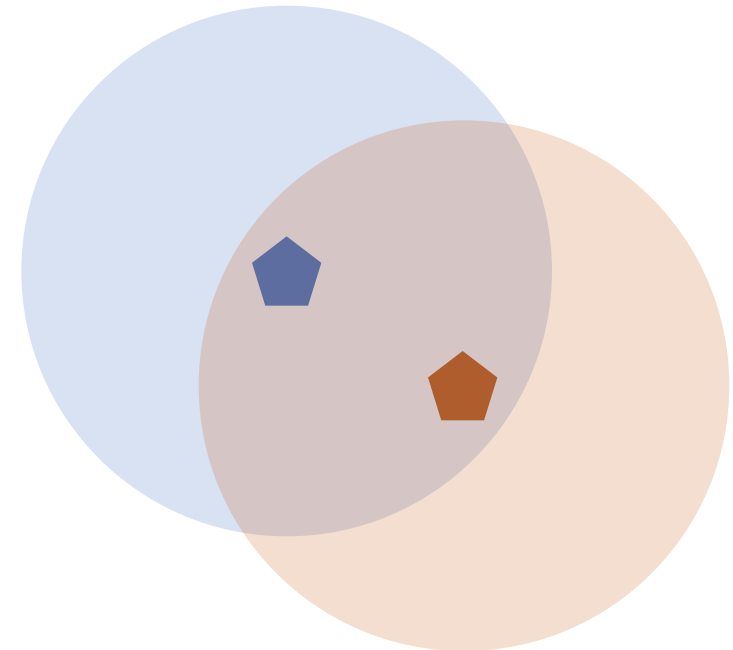
- There are no wires!
- No need to install and maintain wires
 - Reduces cost
 - Simplifies deployment – place devices wherever makes sense
- Supports mobile users
 - Move around office, campus, city
 - Move devices around home

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

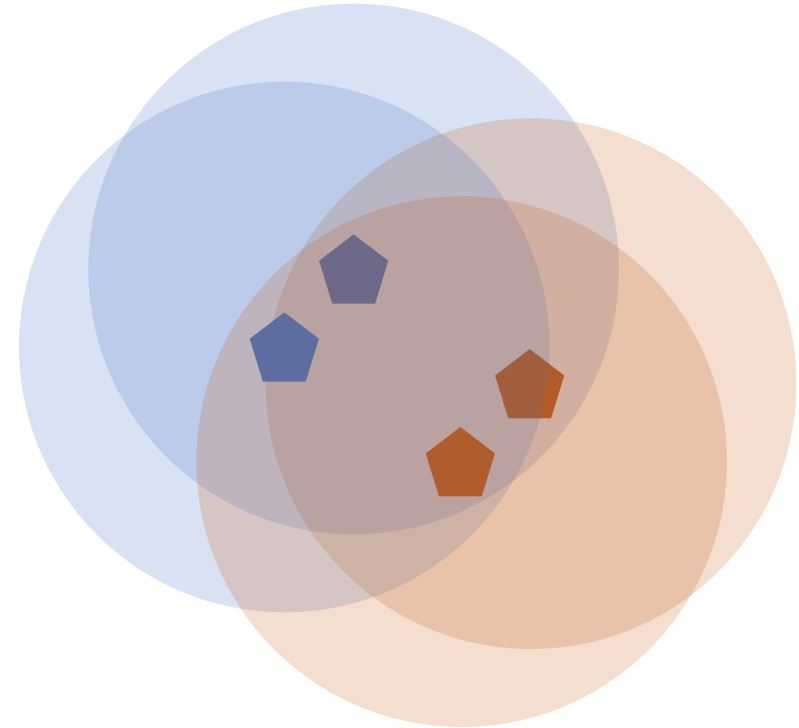
Wireless is a shared medium

- 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



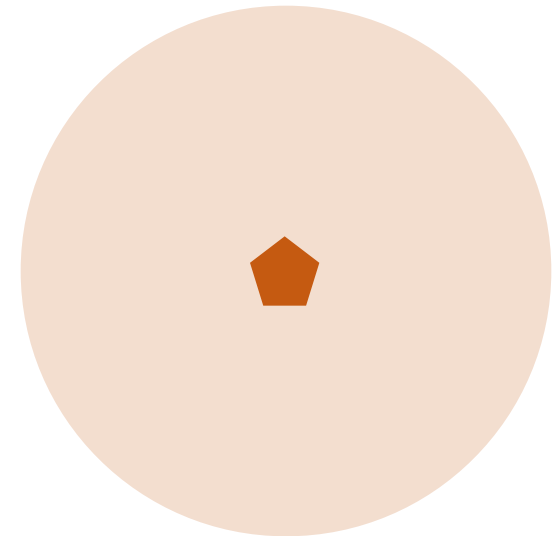
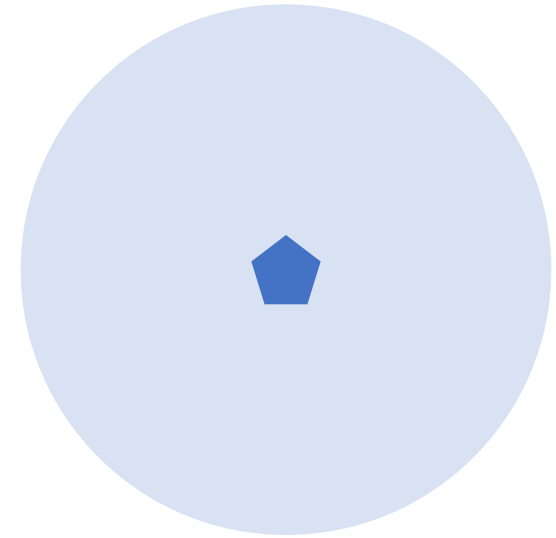
Increasing network capacity is challenging

- 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*



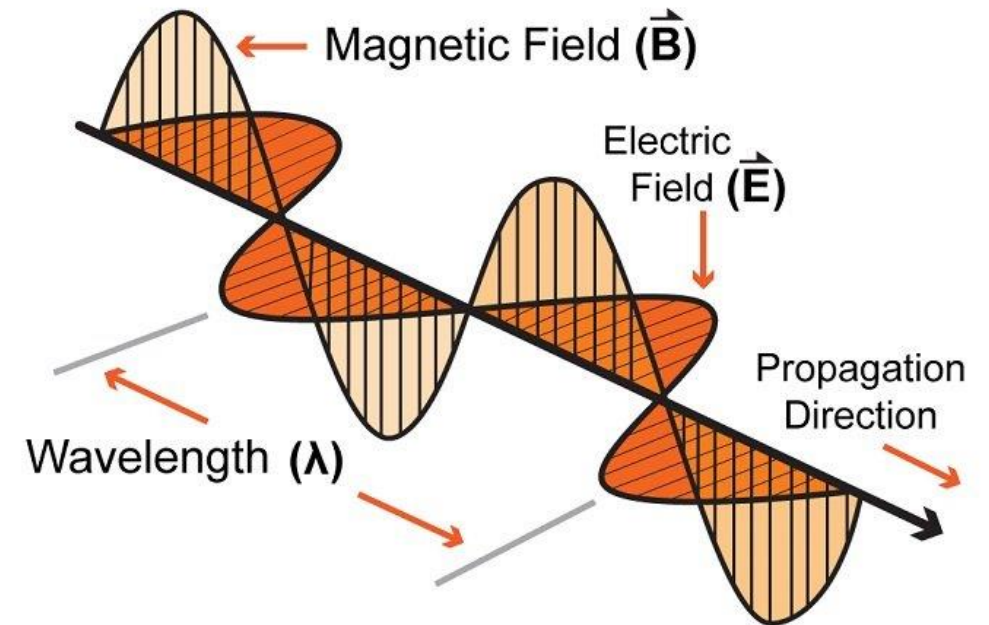
Model of RF communication

- 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



Signal qualities

1. Signal strength

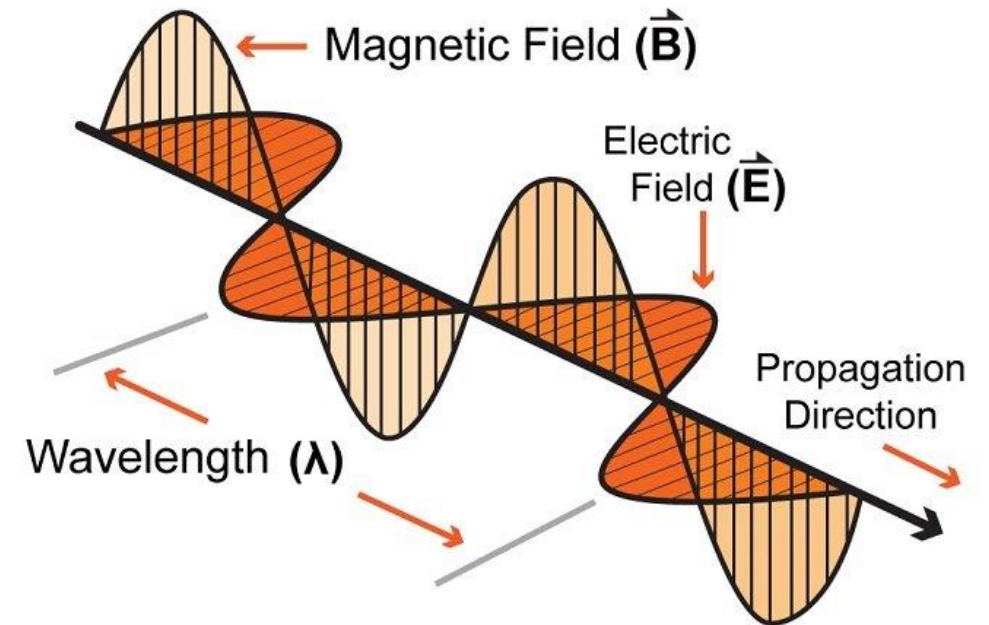
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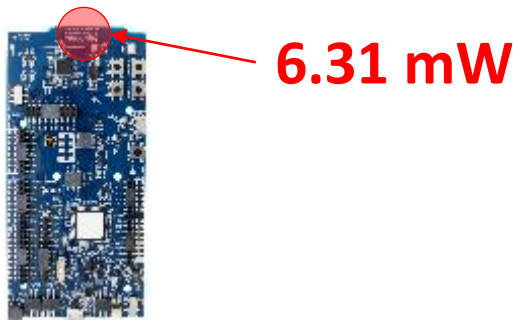


Wireless signals are incredibly low power

- 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

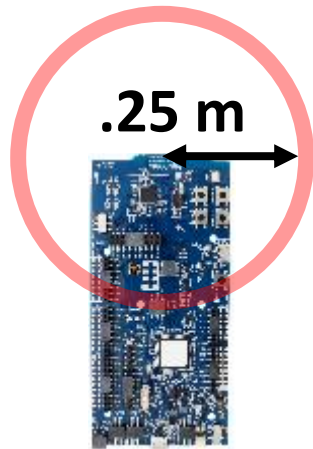
Some Intuitions for Signal Propagation, Power, Gain, etc.

- 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)



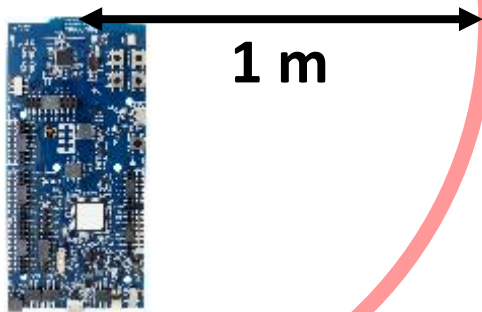
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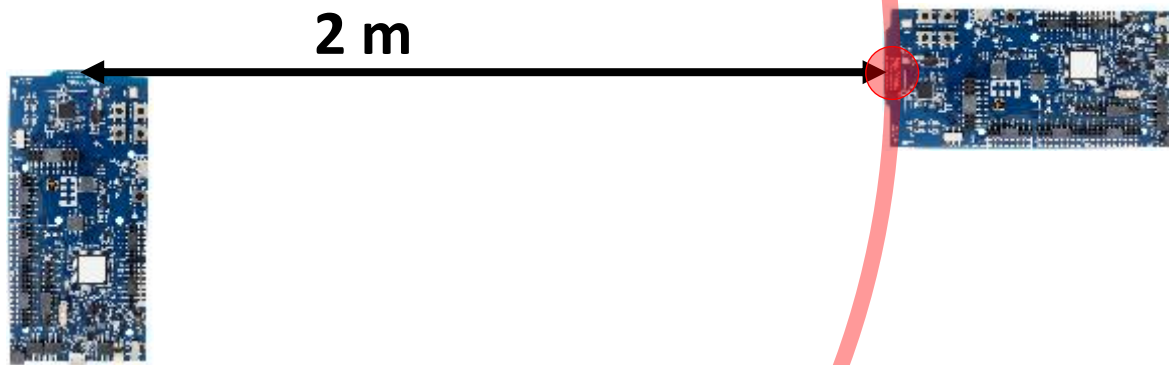
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Signal strength varies significantly across technologies

- 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

1. Signal strength

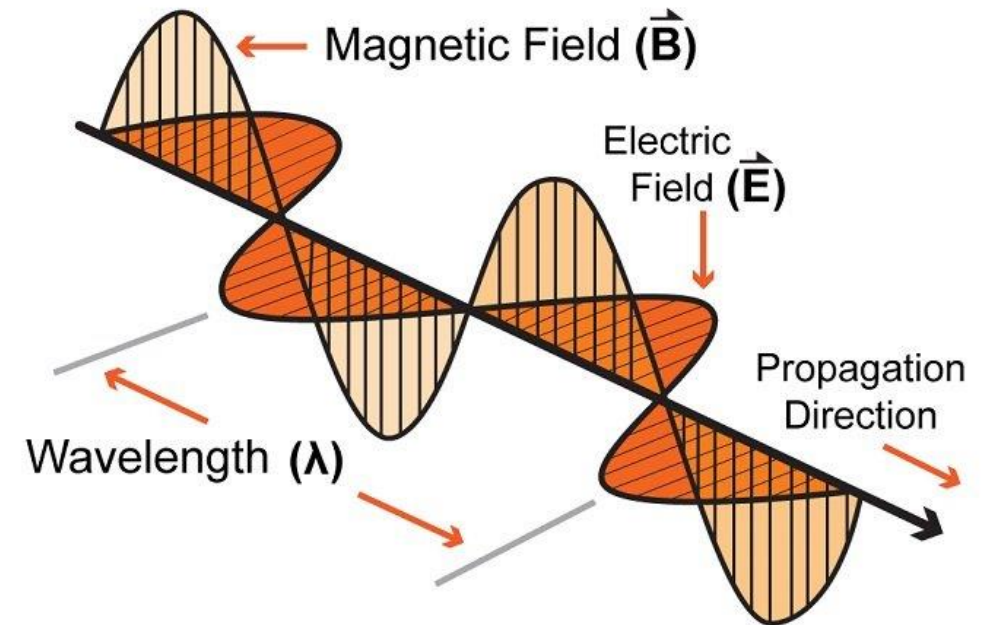
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2. Signal frequency and bandwidth

- Which “channel” the signal is sent on

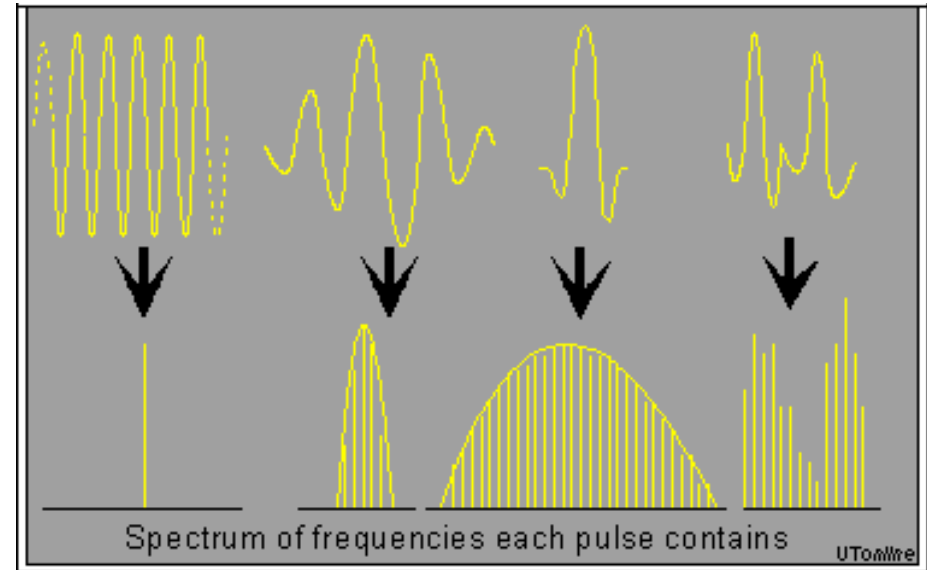
3. Signal modulation

- How data is encoded in the signal



Complex waveforms have a center frequency and a width

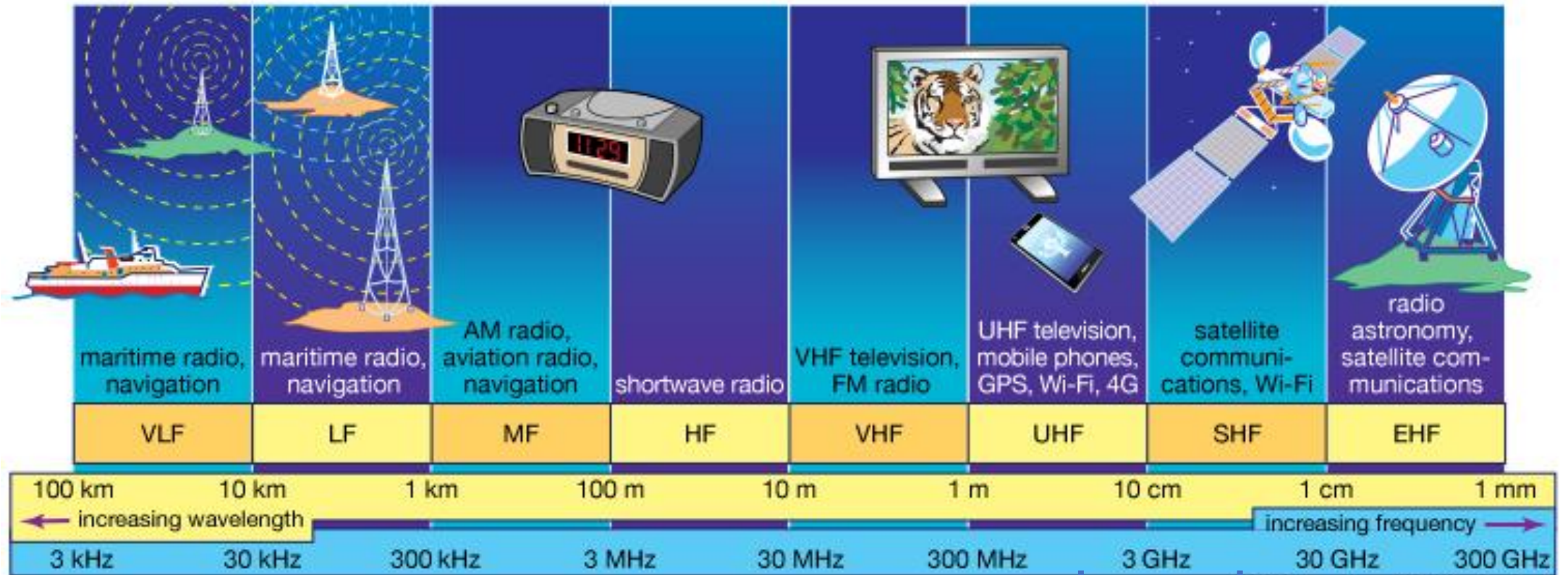
- A pure sinusoid is energy at exactly one frequency
- A messy sinusoid with data layered on top of it has nearby energy
 - There's a center of the signal energy
 - Plus some amount of width, which depends on how complicated the data layered on top is



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

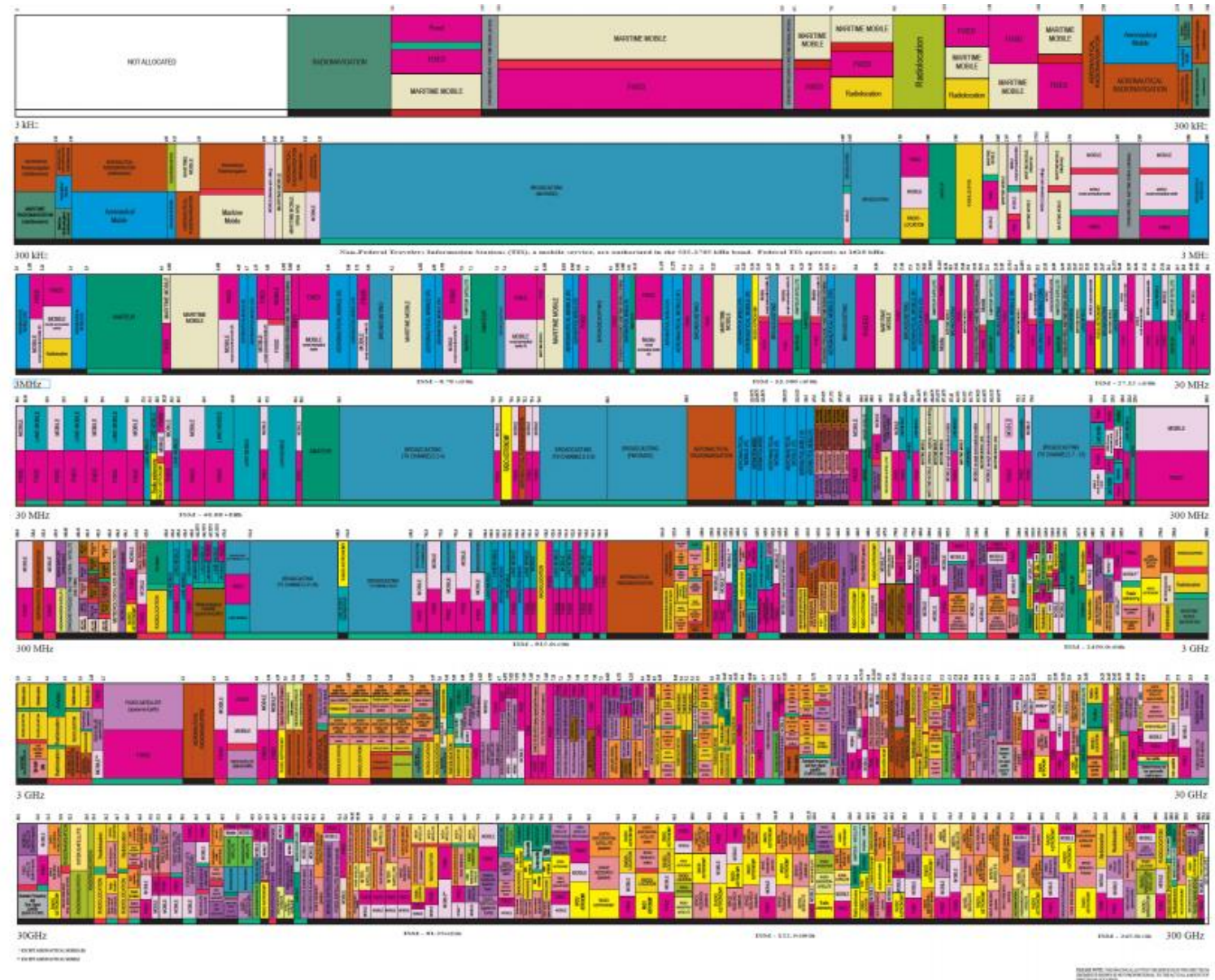


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IoT focus

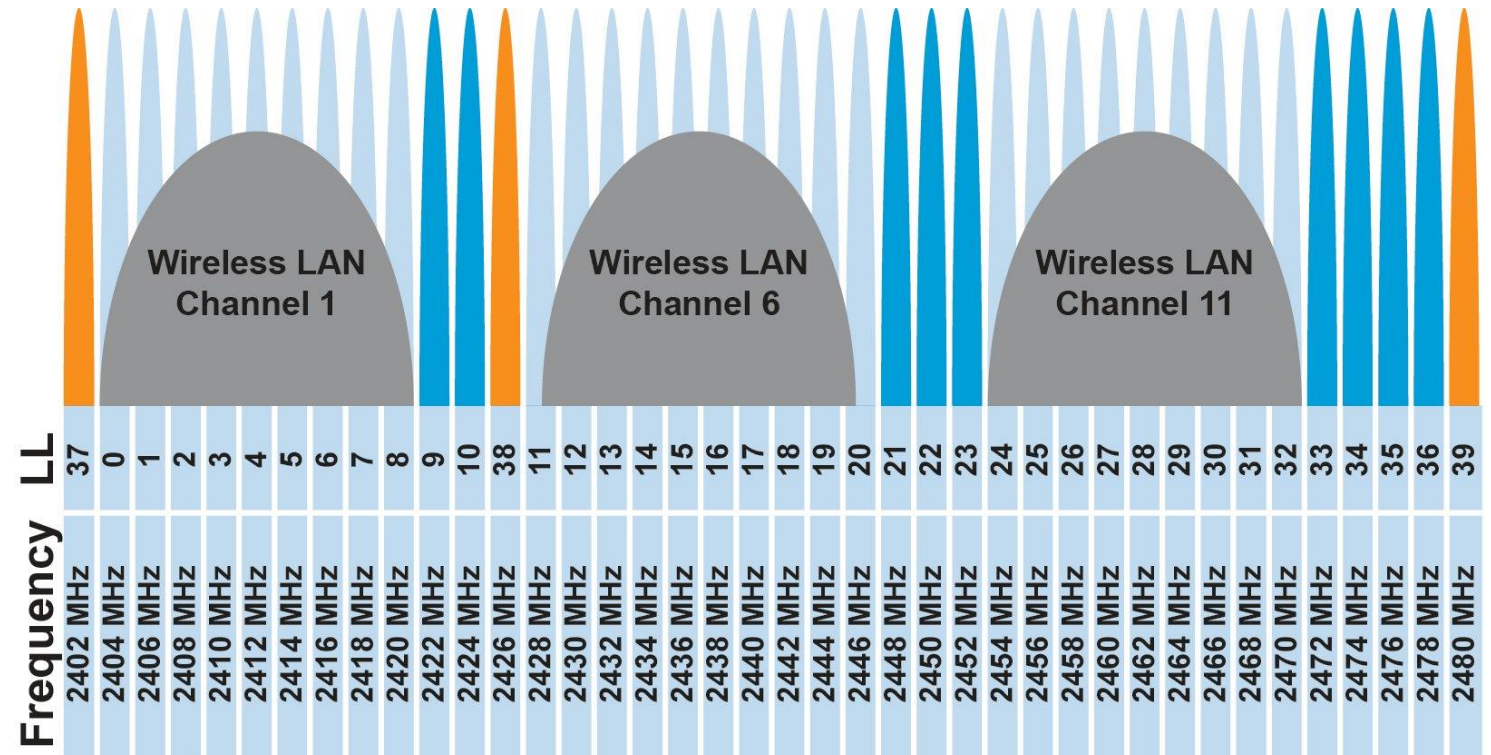
Wireless spectrum is allocated to specific uses

UNITED STATES FREQUENCY ALLOCATIONS THE RADIO SPECTRUM



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?**



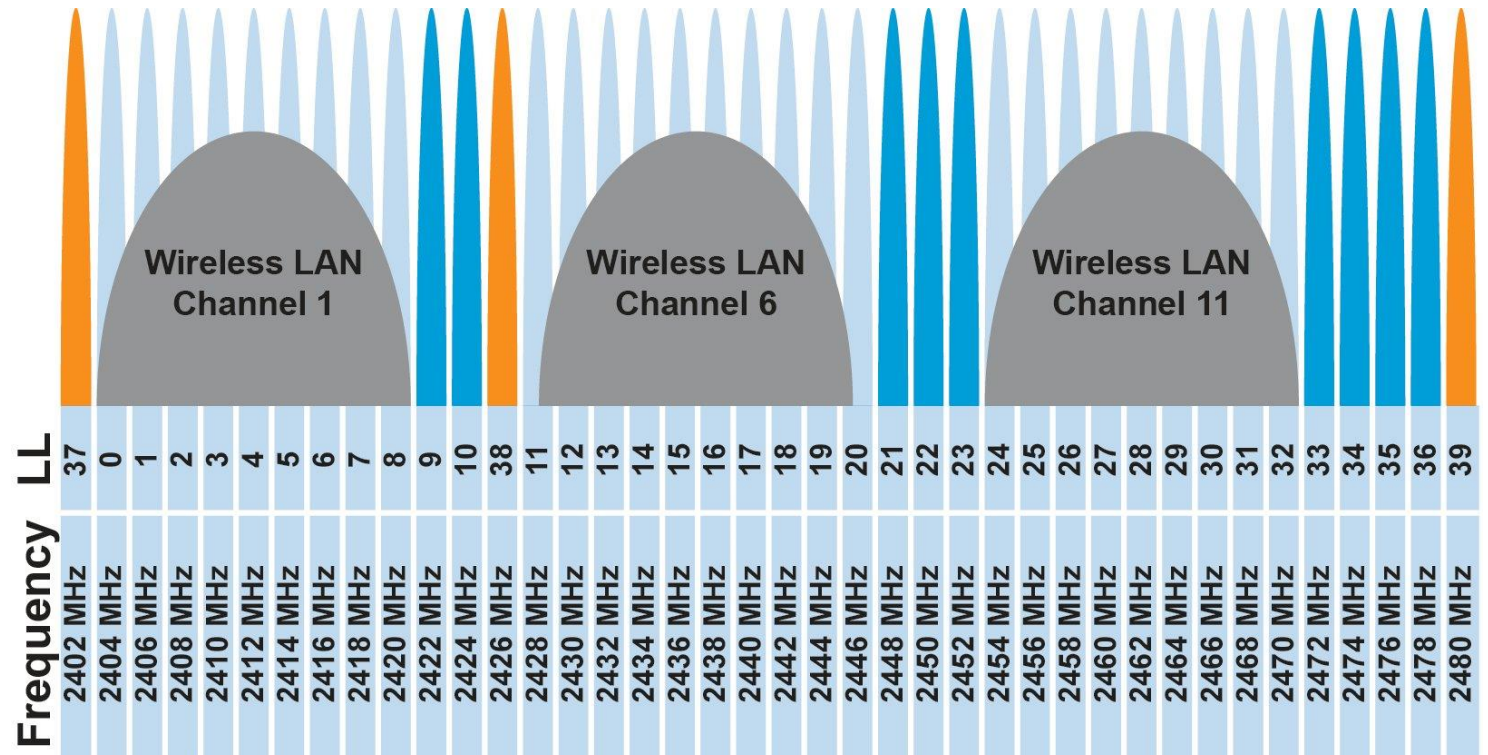
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- 902 MHz – 928 MHz
 - LPWANs

- 2.4 GHz to 2.5 GHz
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- 5 GHz
 - Faster WiFi

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



Signal qualities

1. Signal strength

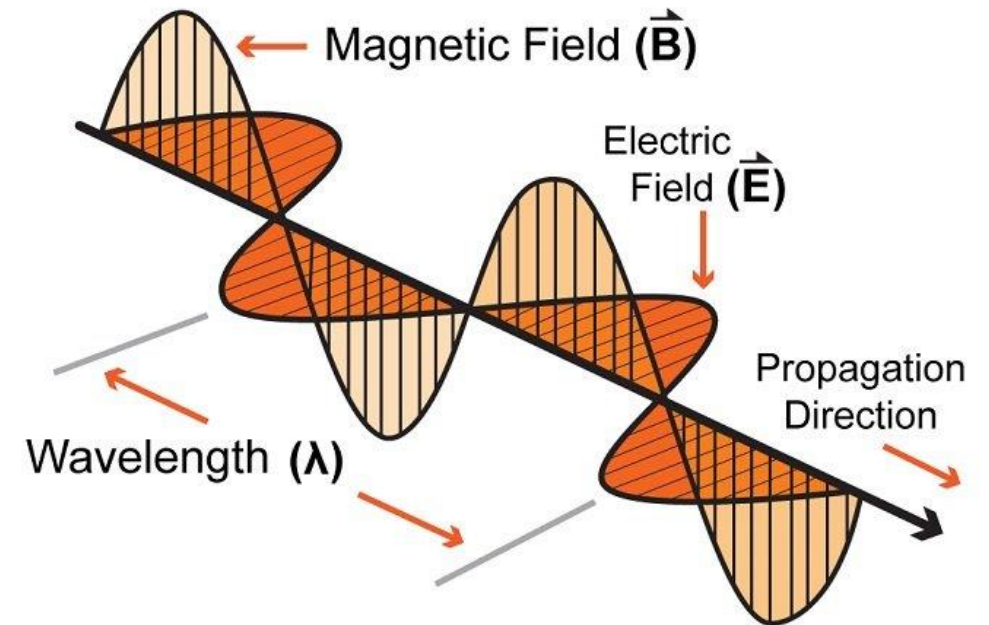
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2. Signal frequency and bandwidth

- Which “channel” the signal is sent on

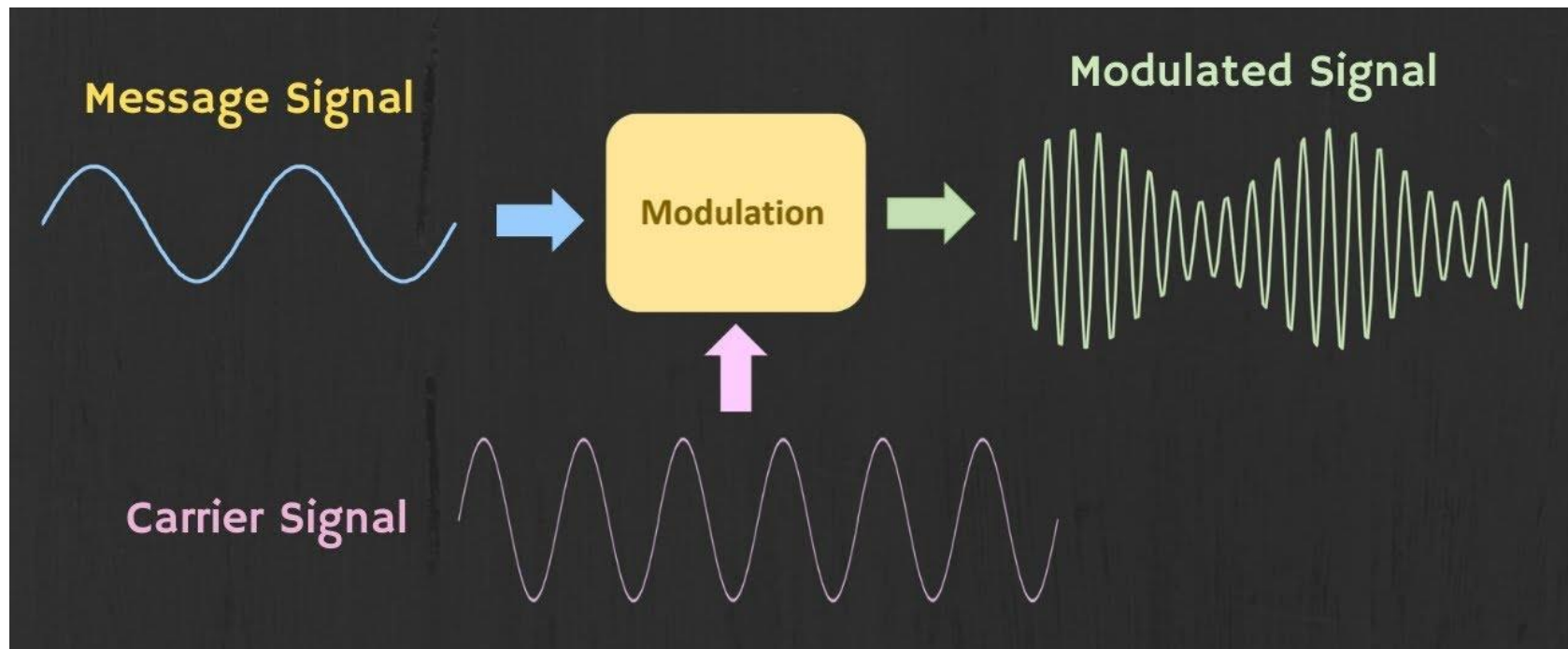
3. Signal modulation

- How data is encoded in the signal



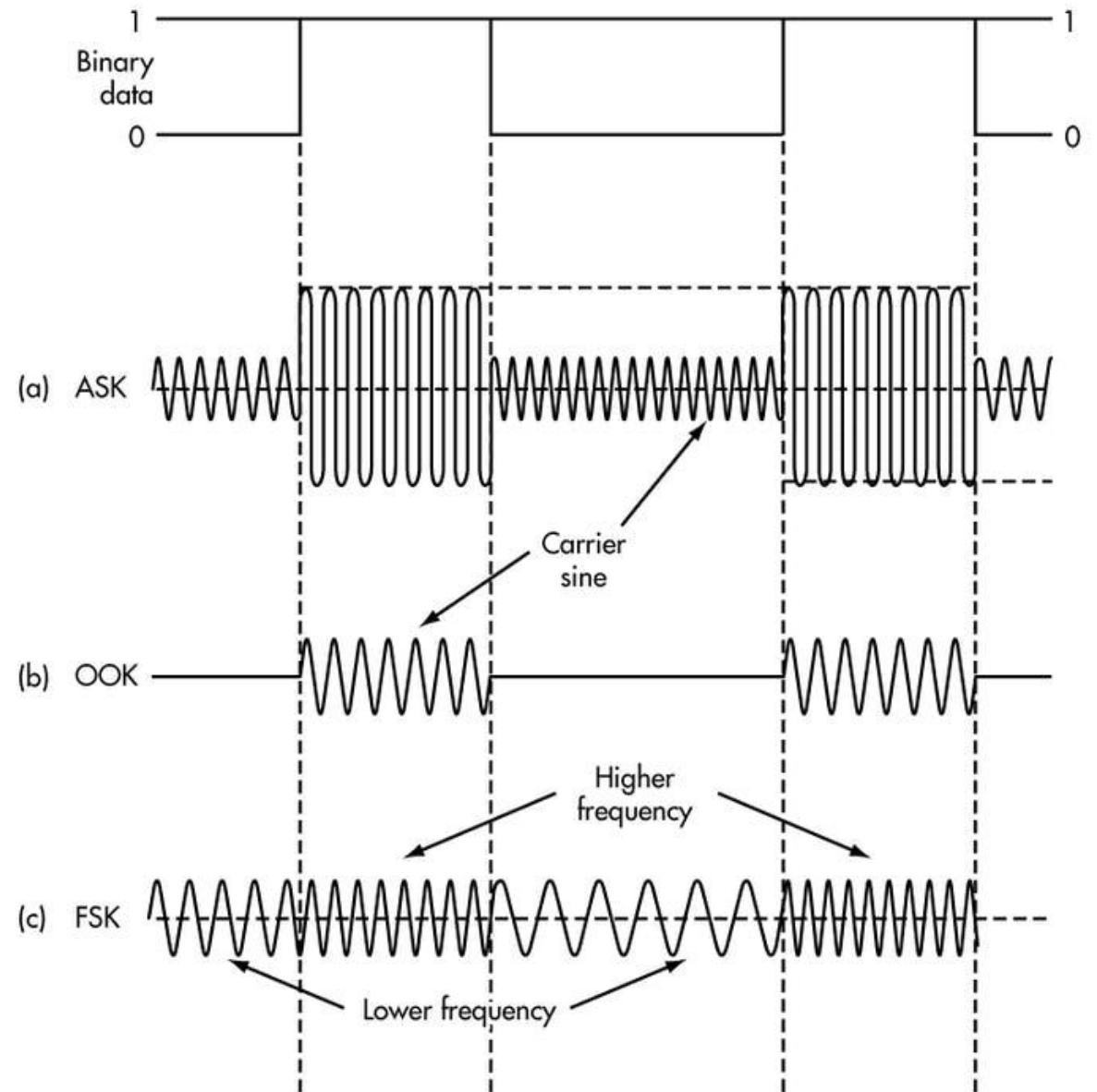
Modulation

- 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



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



- 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

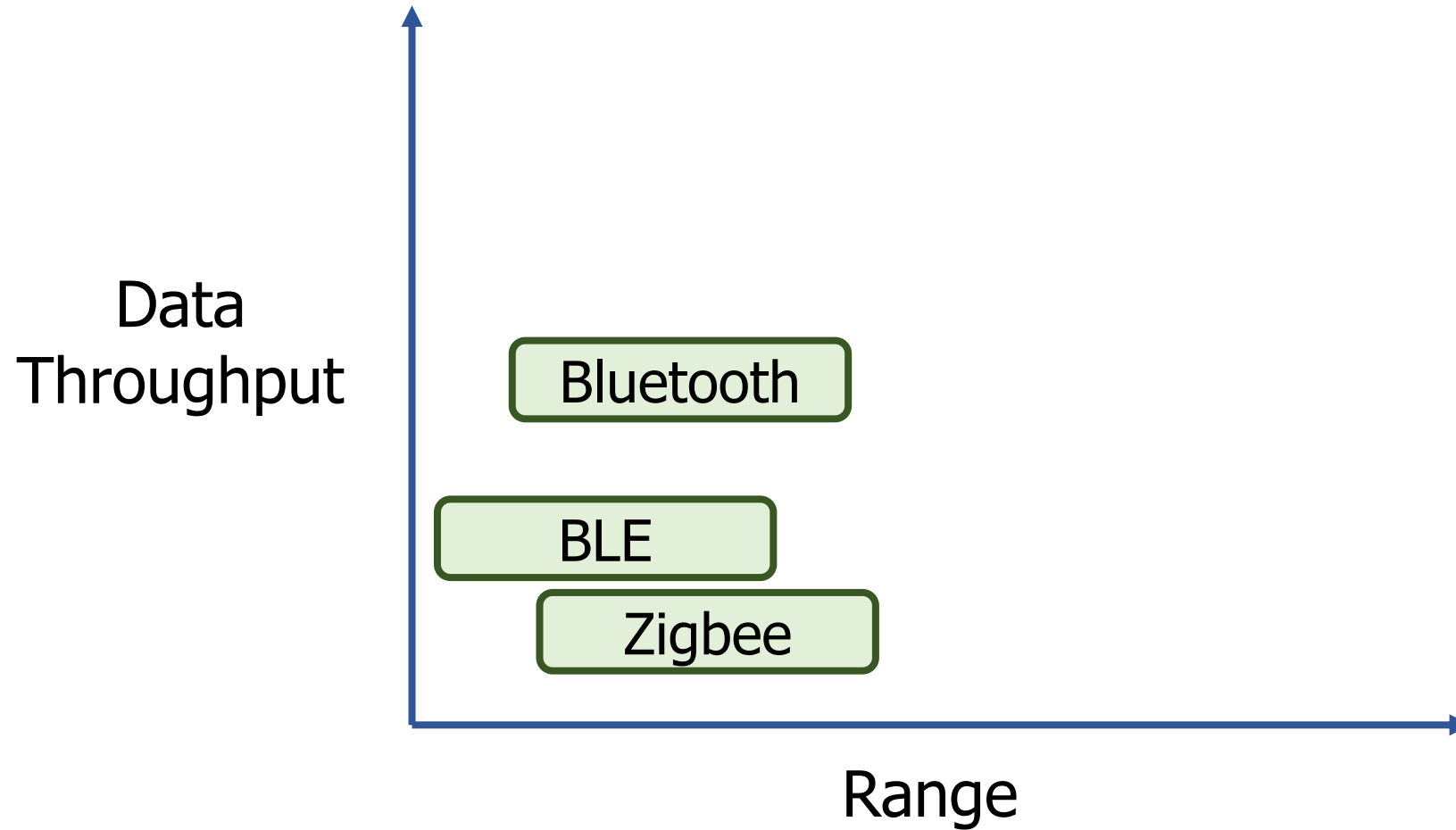
TDMA – Time Division Multiple Access

- 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

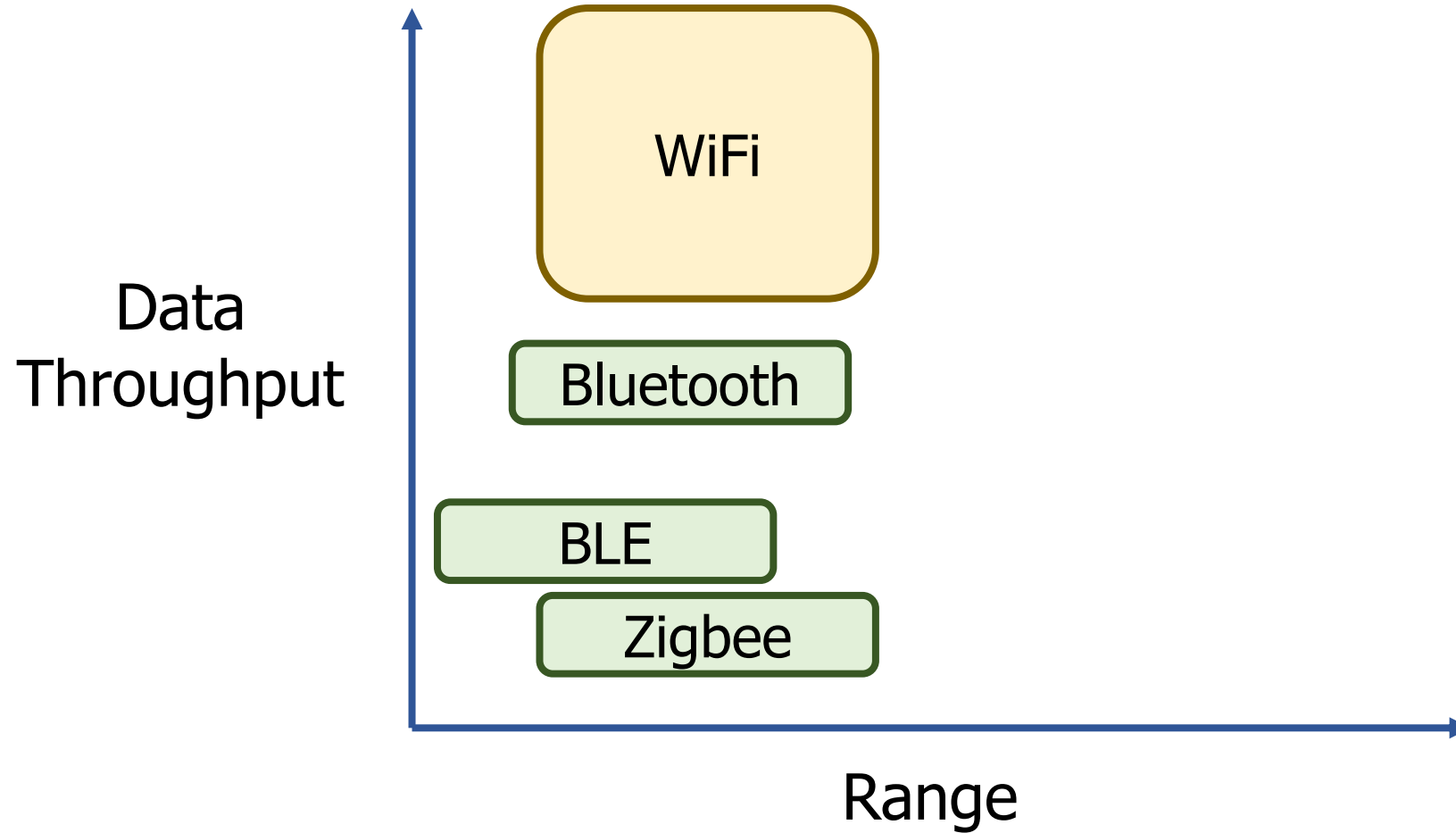
Outline

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

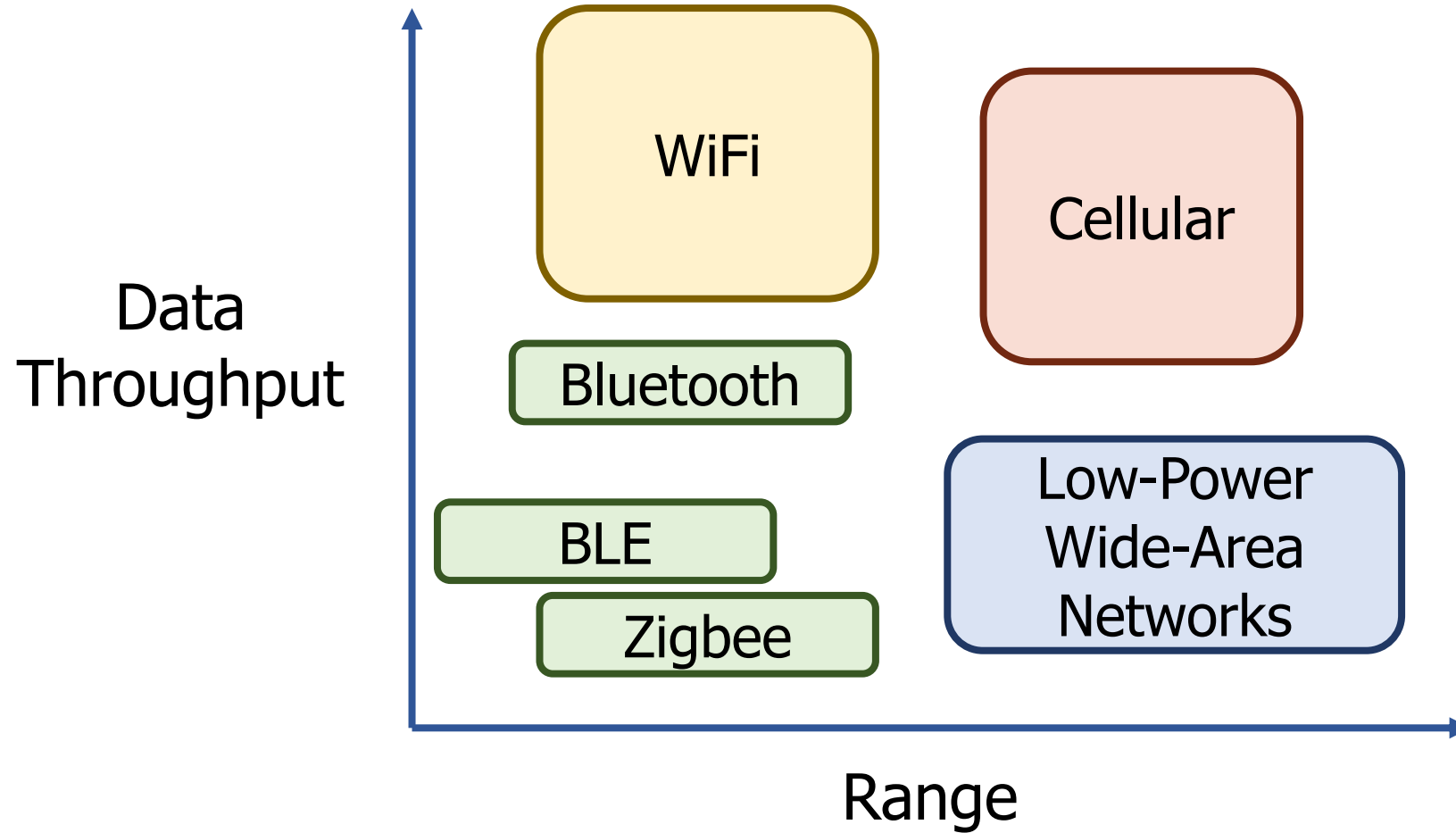
Comparison of wireless protocols



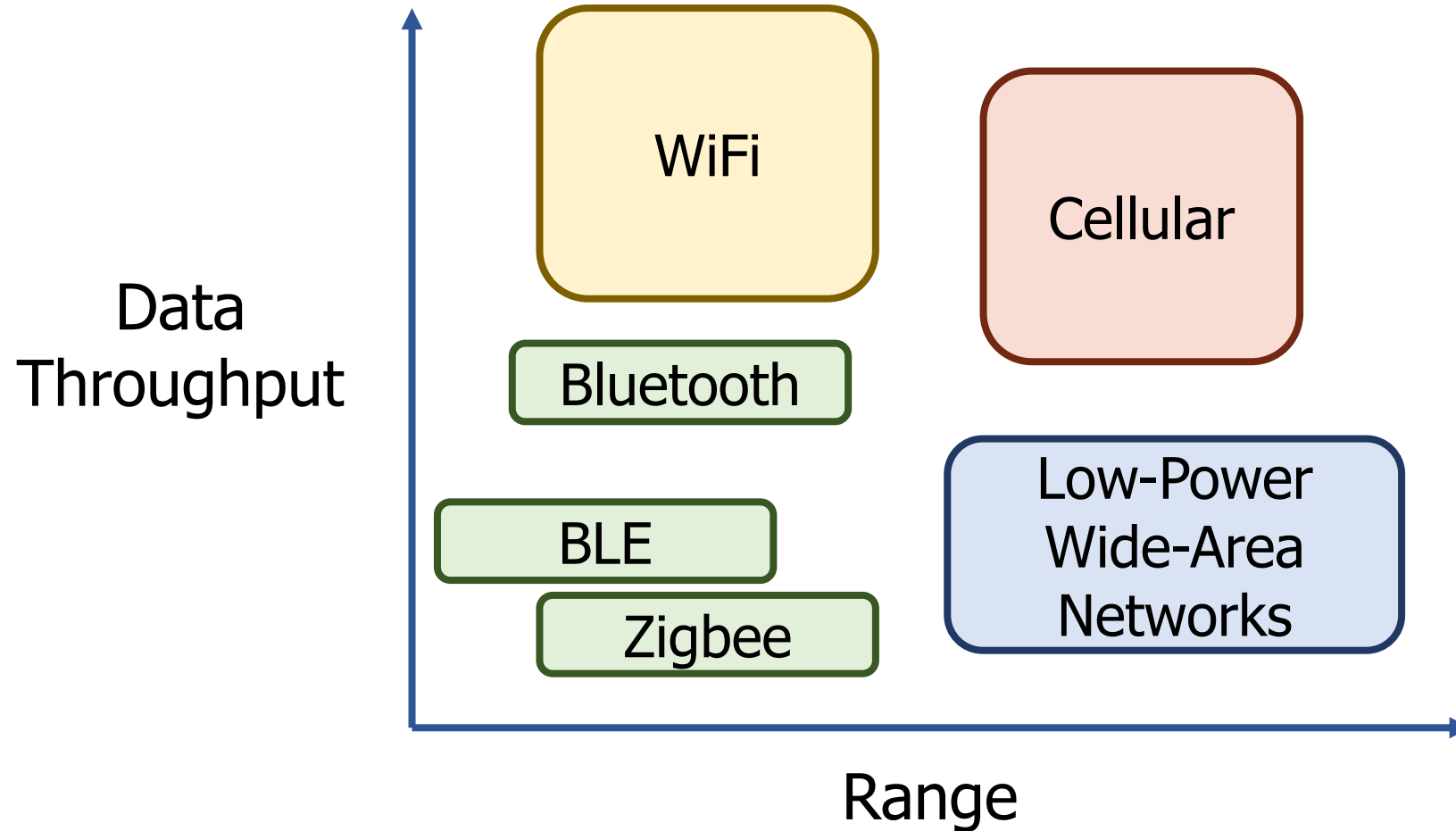
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Comparison of wireless protocols

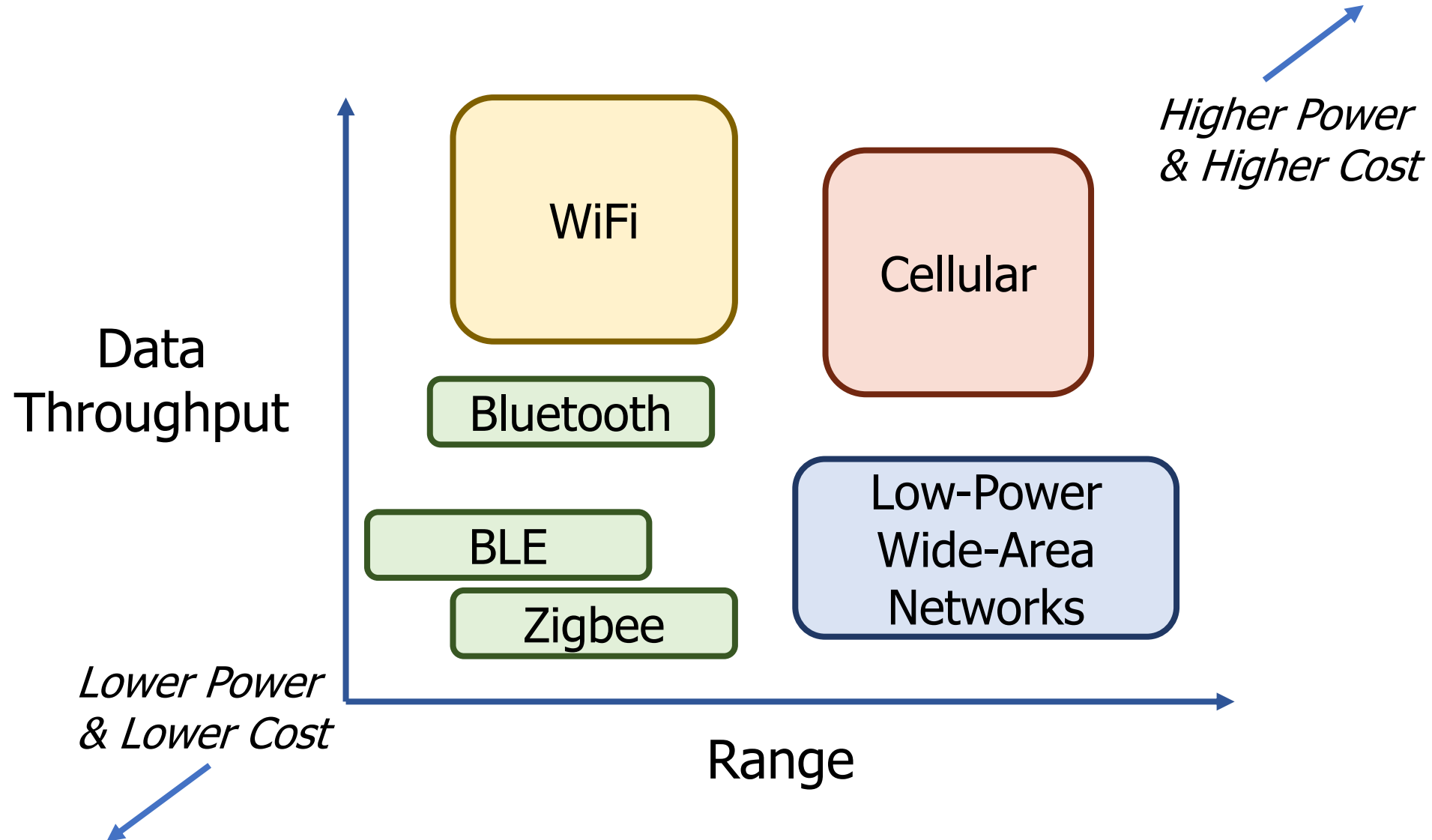


Comparison of wireless protocols



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

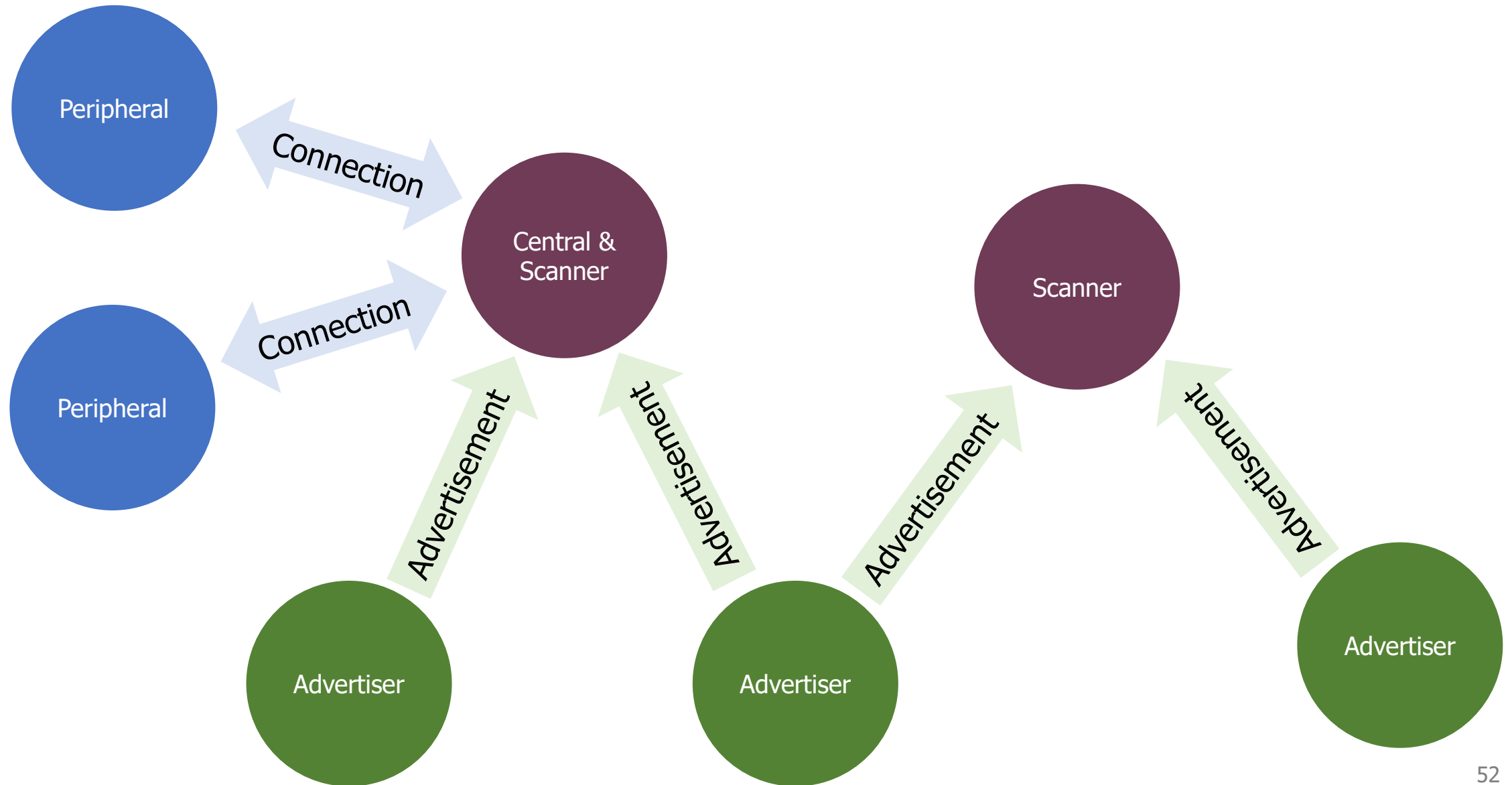
Bluetooth Low Energy

- 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 than 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

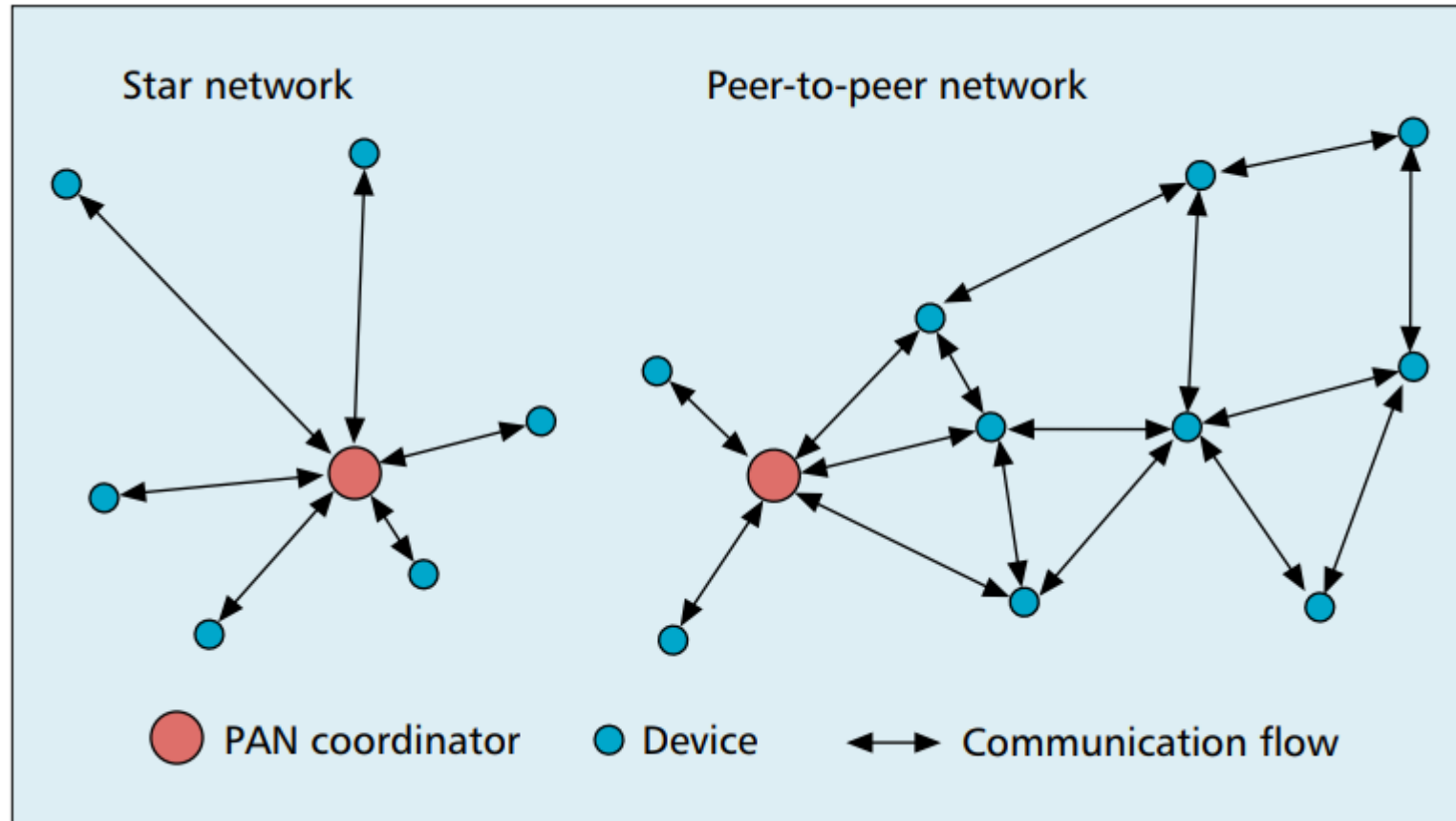
- Bluetooth Low Energy
- **802.15.4 – Zigbee and Thread**
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802.15.4 & Thread & Zigbee

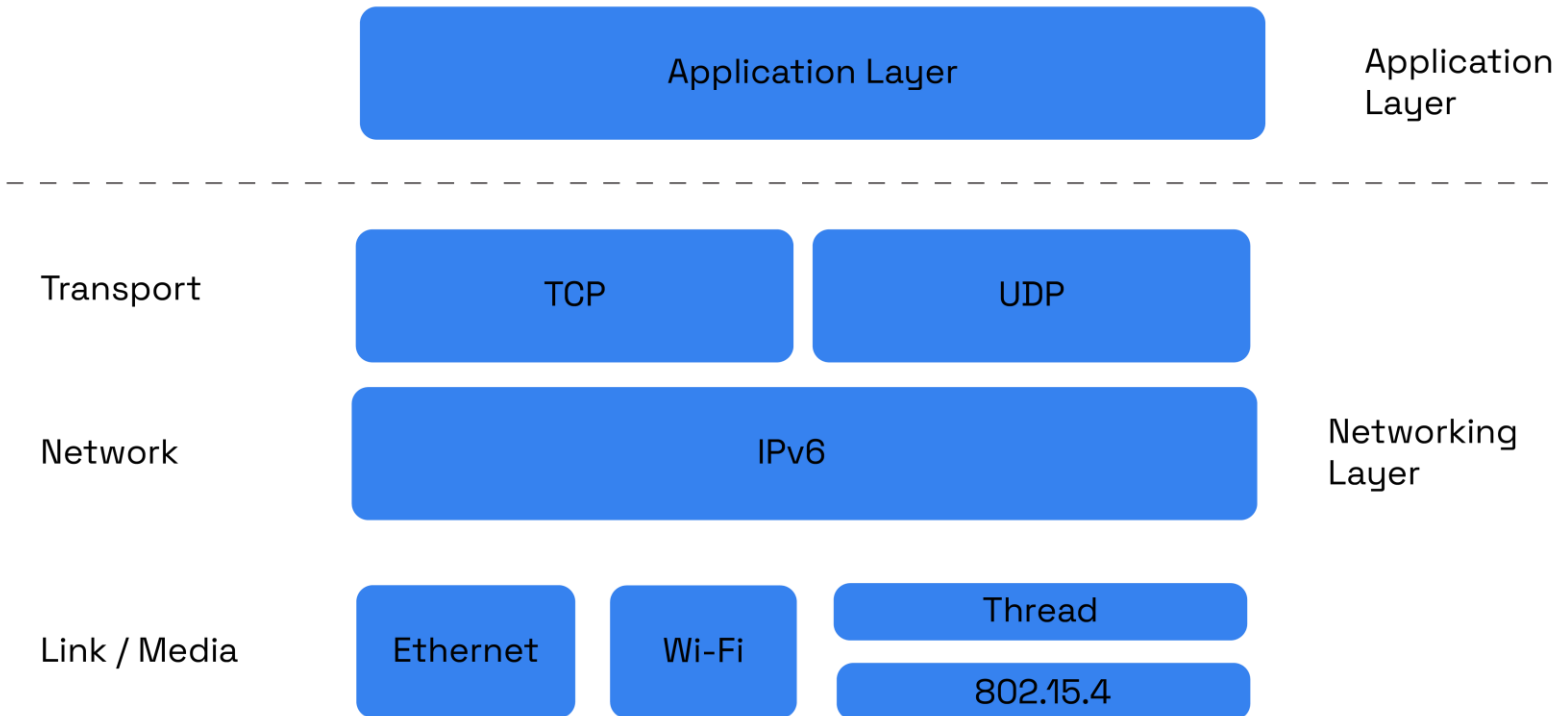
- 802.15.4 is a low-energy method for transmitting bits (physical layer)
 - Radio chips have been widely available for 15-20 years
- *Significant* amounts of sensor network research have focused on building layers on top of 802.15.4
 - Access control layers (CSMA)
 - Network layers
- Thread is a selection 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 updates

	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	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	9600 Mbps	35 m
7	802.11be	2024	2.4/5/6 GHz	OFDMA + MU-MIMO	23000 Mbps	35 m

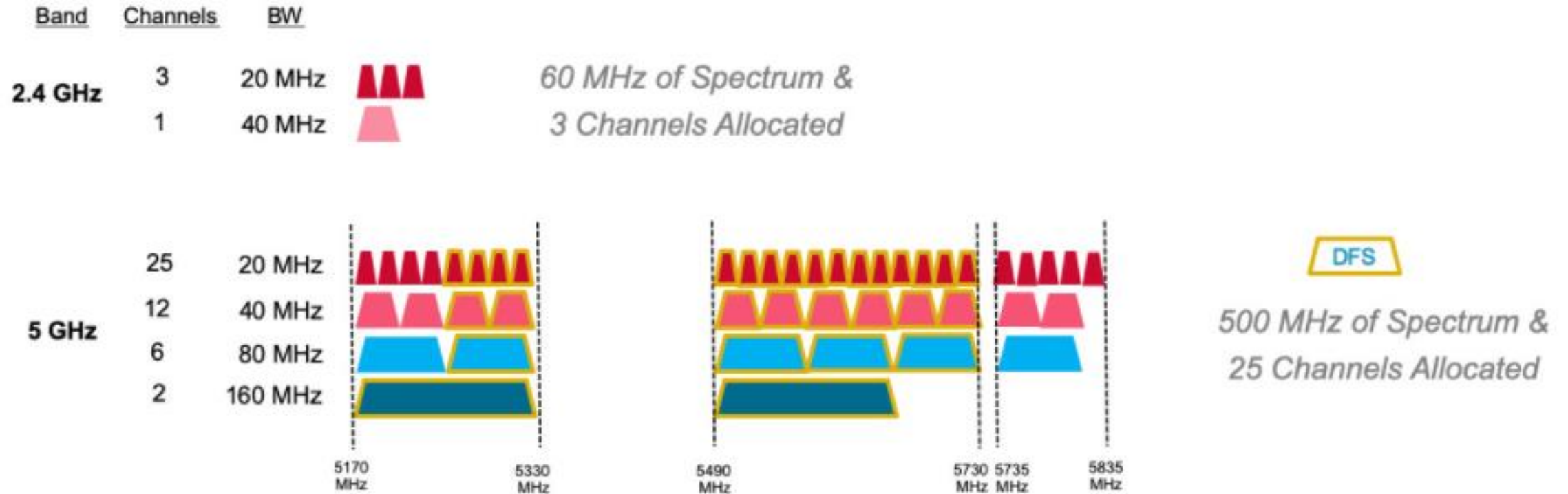
- 802.11b was very popular but is now usually unsupported
- 802.11a never saw major deployment
- WiFi Alliance rebranded 802.11ac as “WiFi 5” and backported scheme

WiFi bandwidth

<u>Band</u>	<u>Channels</u>	<u>BW</u>		
2.4 GHz	3	20 MHz		<i>60 MHz of Spectrum & 3 Channels Allocated</i>
	1	40 MHz		

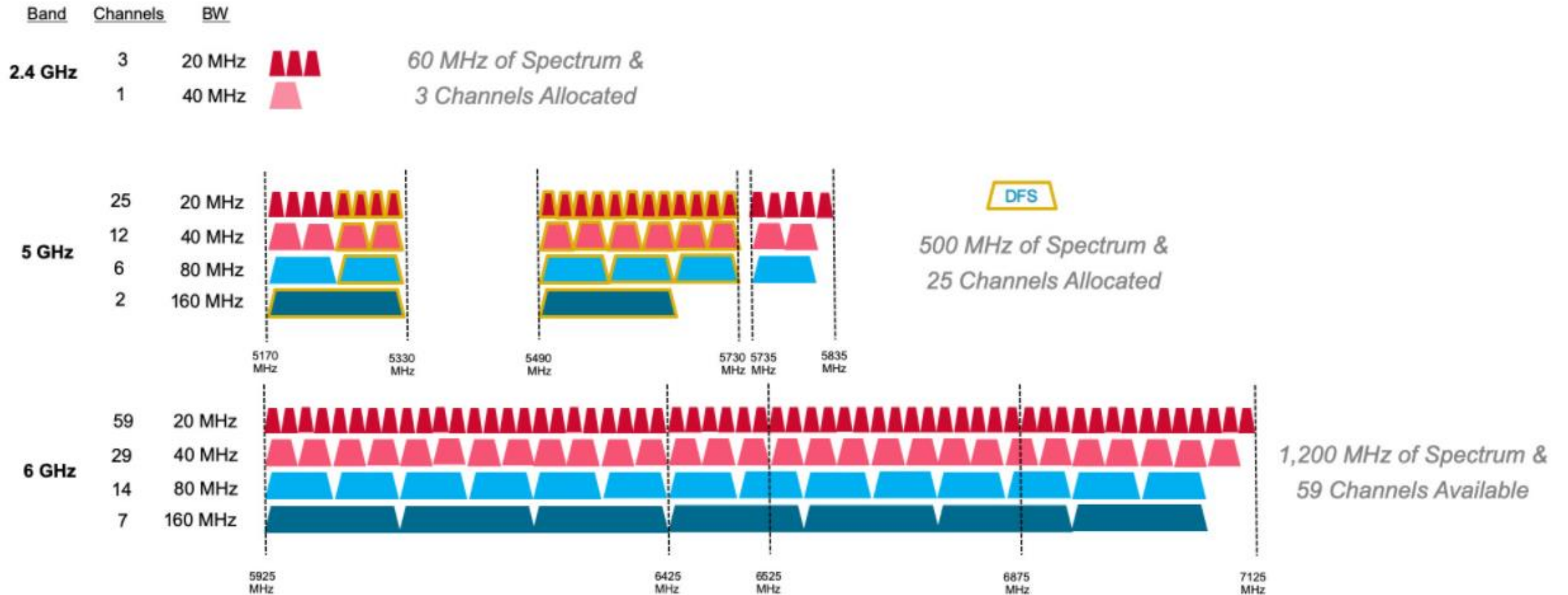
- More bandwidth means higher data rate (with same error rate)

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

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- **Low-Power Wide-Area Networks**

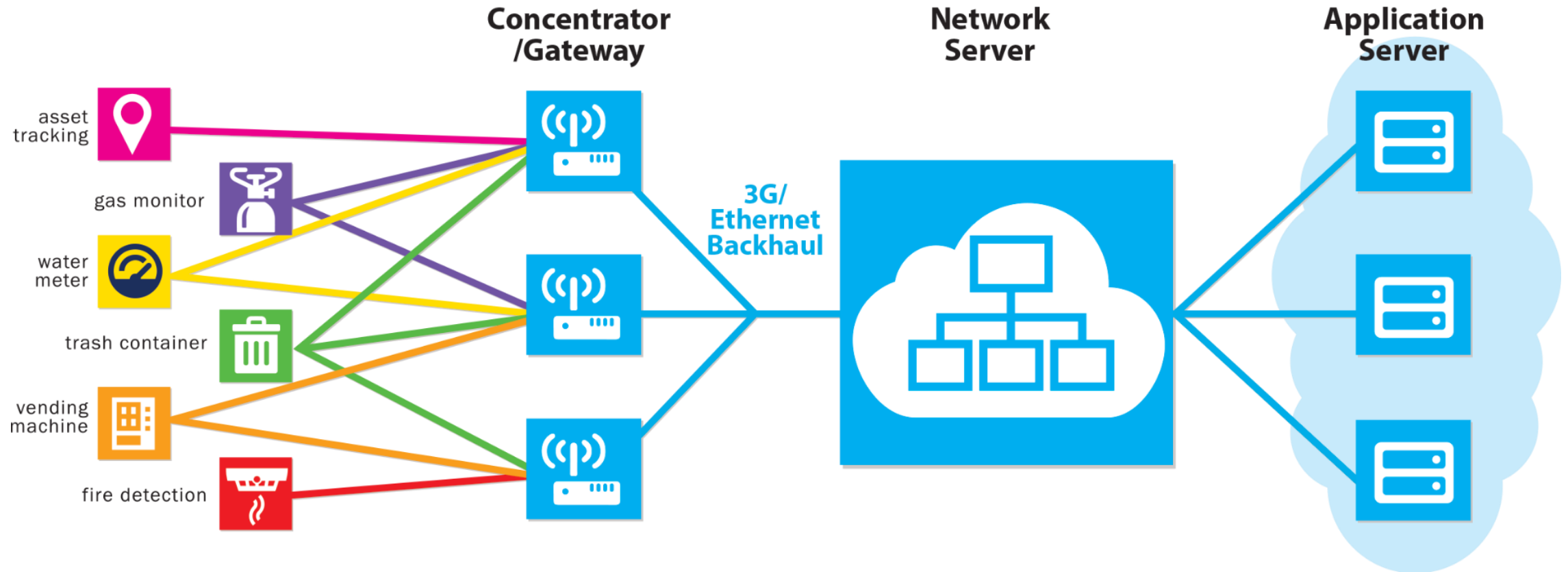
LPWANs (Low-Power Wide-Area Networks)

- 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 2026
 - 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)

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