

Lecture 14

Wireless Communication

CE346 – Microprocessor System Design
Branden Ghena – Fall 2022

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

Administrivia

- Last postlab questions! Be sure to answer them
- I'm still ordering more hardware if people need things
 - Going to be ordering less often now
 - I'll email you to come pick stuff up from my office
- How to get project help
 - Office hours
 - Campuswire post
 - 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 these!

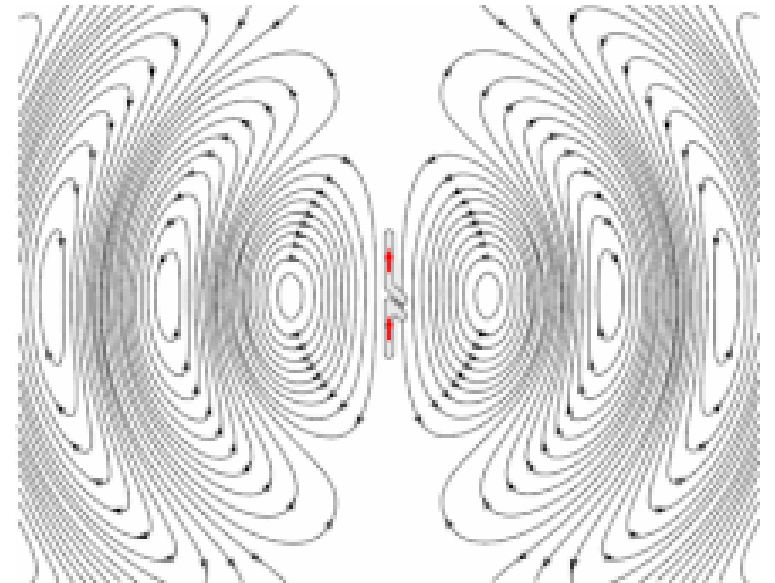
But our Microbit library doesn't 😞

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?

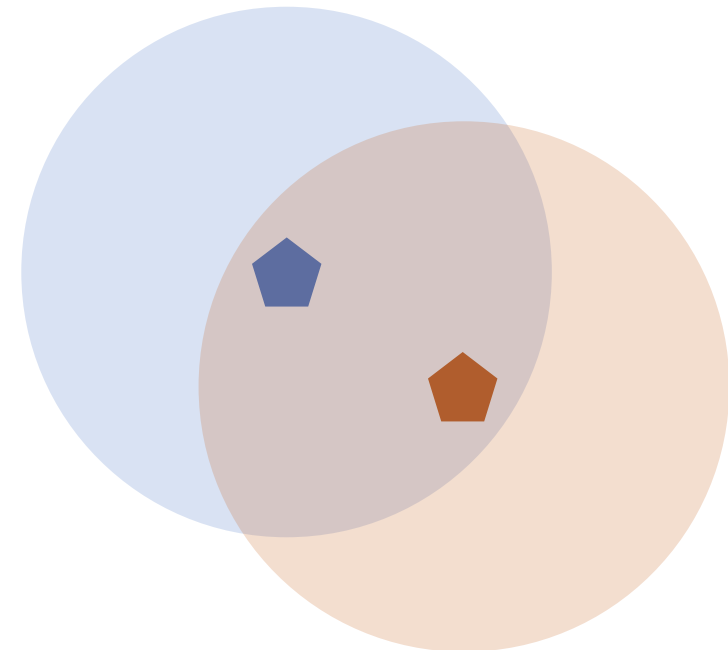
- There are no wires!
- No need to install and maintain wires
 - Reduces cost
 - Simplifies deployment – place devices wherever makes sense
- Supports mobile users
 - Move around office, campus, city
 - Move devices around home

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

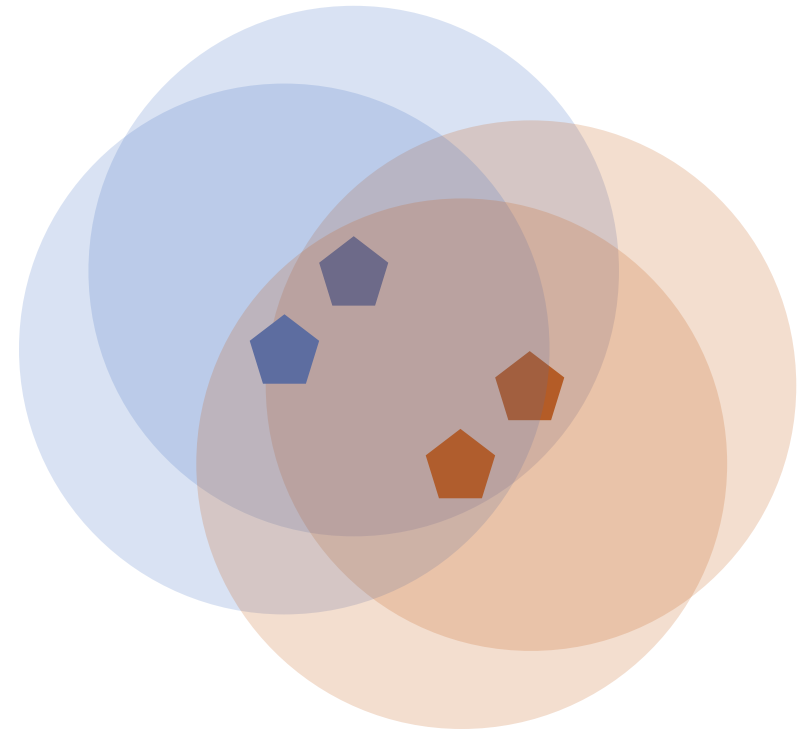
Wireless is a shared medium

- 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



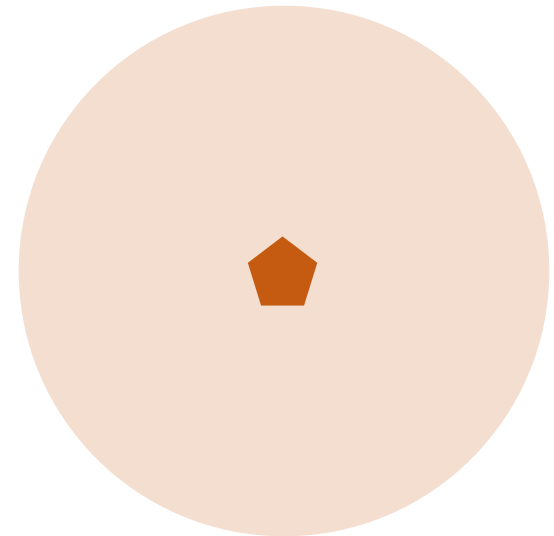
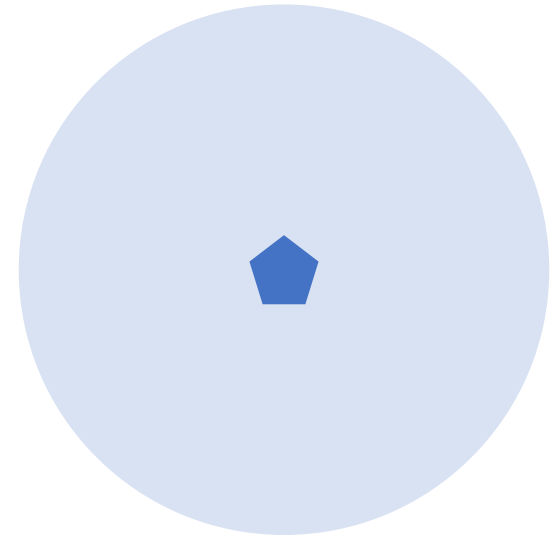
Increasing network capacity is challenging

- 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



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

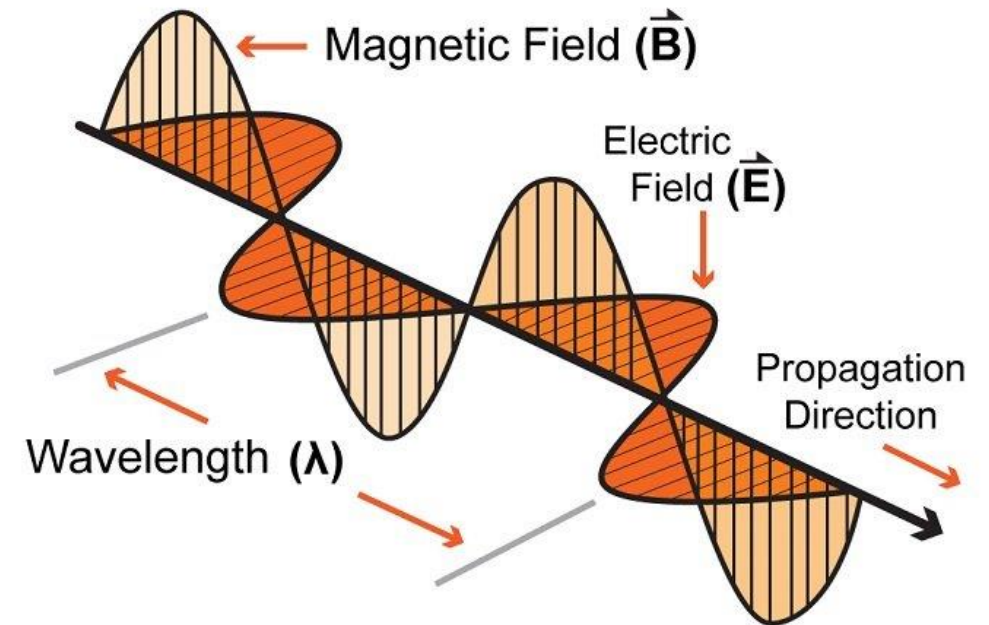
- The amount of energy transmitted/received

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

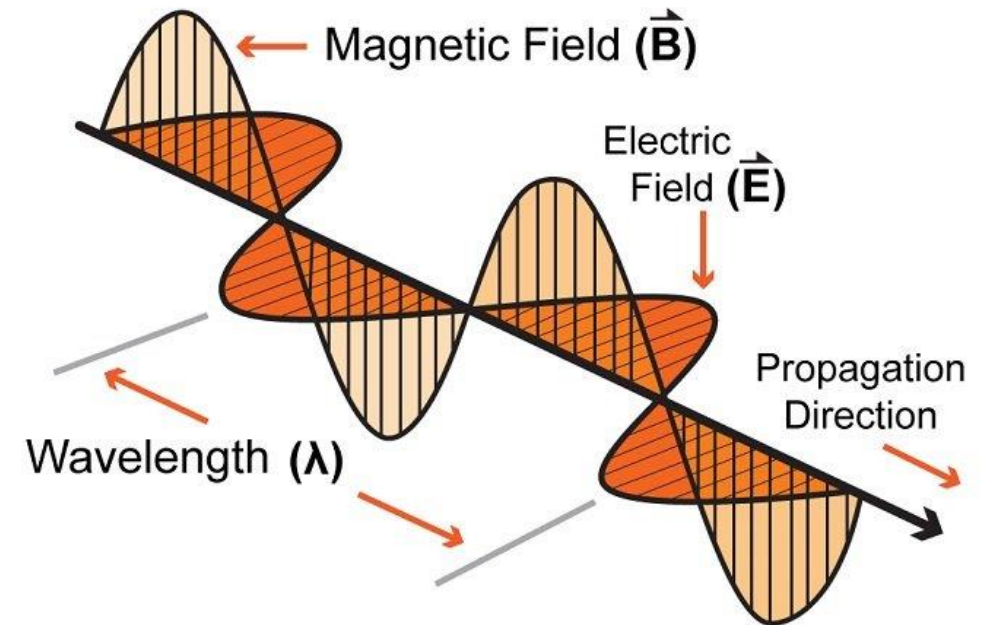
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Wireless signals are incredibly low power

- 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

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

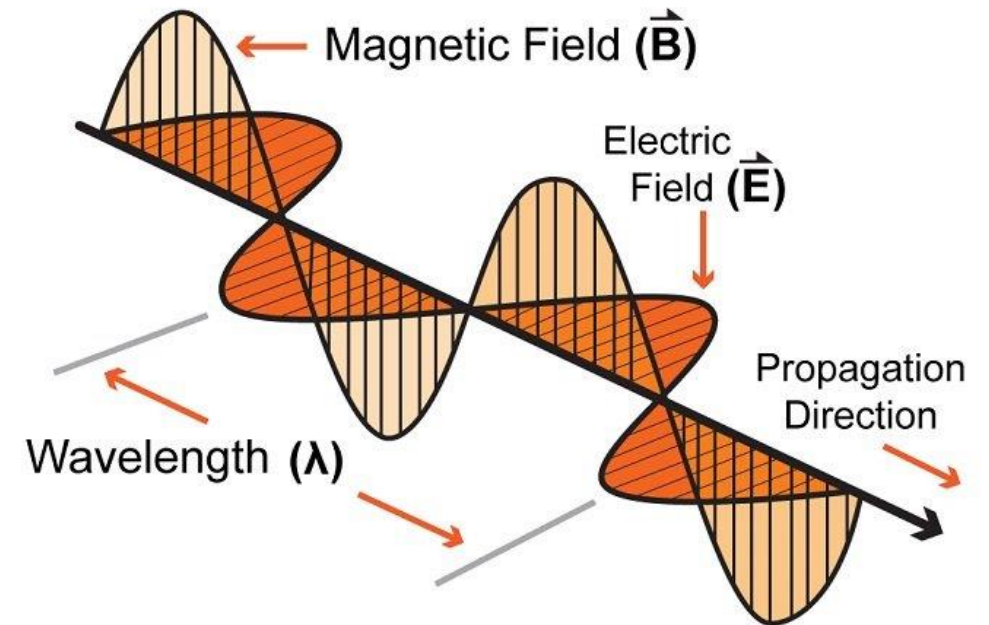
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2. Signal frequency and bandwidth

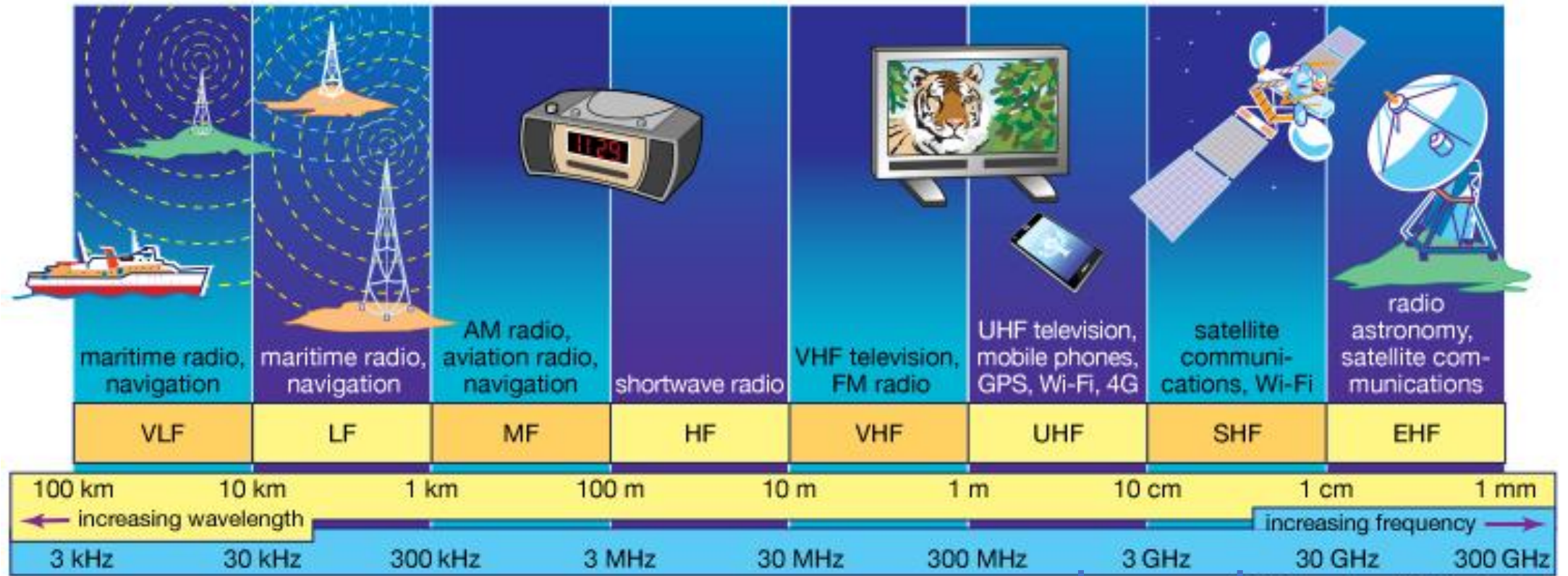
- Which "channel" the signal is sent on

3. Signal modulation

- How data is encoded in the signal



RF communication



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IoT focus

Wireless spectrum is allocated to specific uses

UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

AIRBORNE MOBILE	AIRTEL SATELLITE	RADIO AMATEUR
AIRBORNE MOBILE SATELLITE	LAND MOBILE	AIRBORNE OBSTACLE SATELLITE
AIRBORNE MOBILE (NON-INTERFERING)	LAND MOBILE SATELLITE	RADIOLOCATION
JONATHAN	MARITIME MOBILE	RADIOLOCATION SATELLITE
AIRBORNE SATELLITE	MARITIME MOBILE SATELLITE	RADIOLOCATION
BROADCASTING	MARITIME BROADCASTING	RADIOLOCATION SATELLITE
BROADCASTING SATELLITE	METEOROLOGICAL	SPACE RESEARCH
SPACE EXPLORATION SATELLITE	METEOROLOGICAL SATELLITE	SPACE RESEARCH
FIXED	MOBILE	STANDARD FREQUENCY AND TIME SIGNAL
FIXED SATELLITE	MOBILE SATELLITE	STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

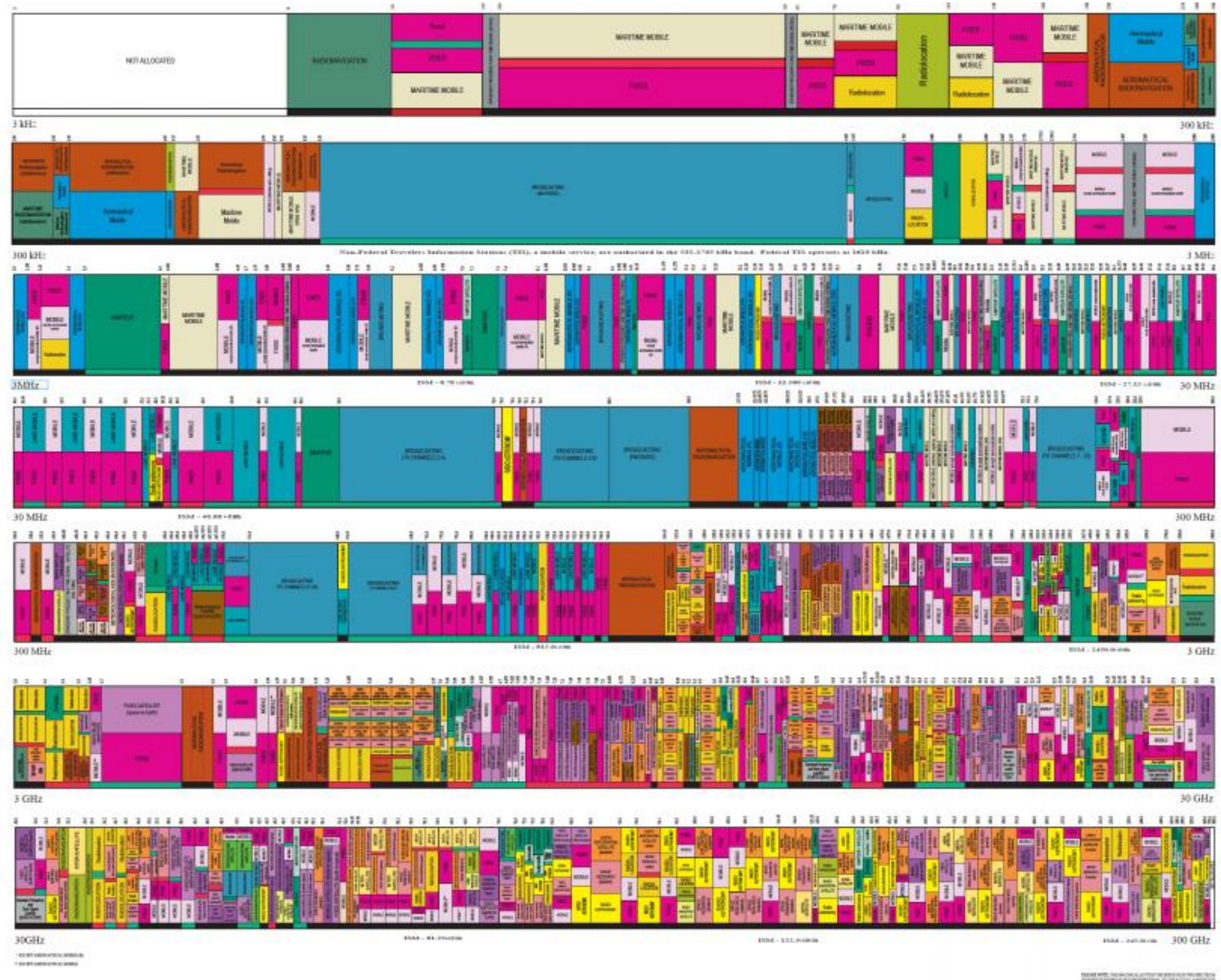
GOVERNMENT ESTABLISHMENT	GOVERNMENT-ASSISTED SERVICE
NON-GOVERNMENT ESTABLISHMENT	

ALLOCATION USAGE DESIGNATION

OFFICE	EXAMPLE	DESCRIPTION
Primary	ST25	Land Lines
Secondary	SM25	Land Lines (Same use as Office)

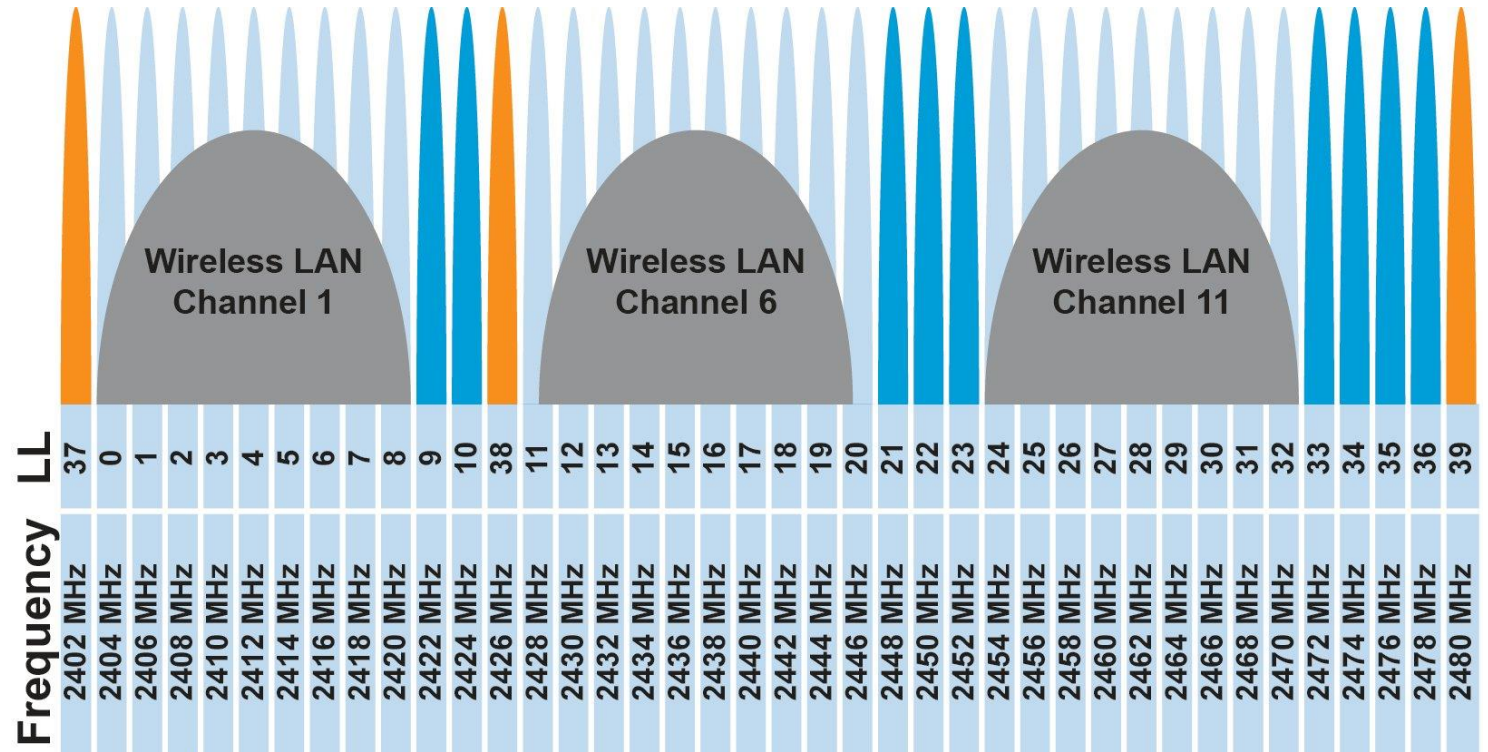
The radio spectrum information presented in this chart is derived from the Federal Communications Commission's (FCC) and the National Telecommunications and Information Administration's (NTIA) databases. It is not intended to be a substitute for the Commission's rules and regulations. For more information, please visit the FCC's website at www.fcc.gov.

U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management
 August 2011



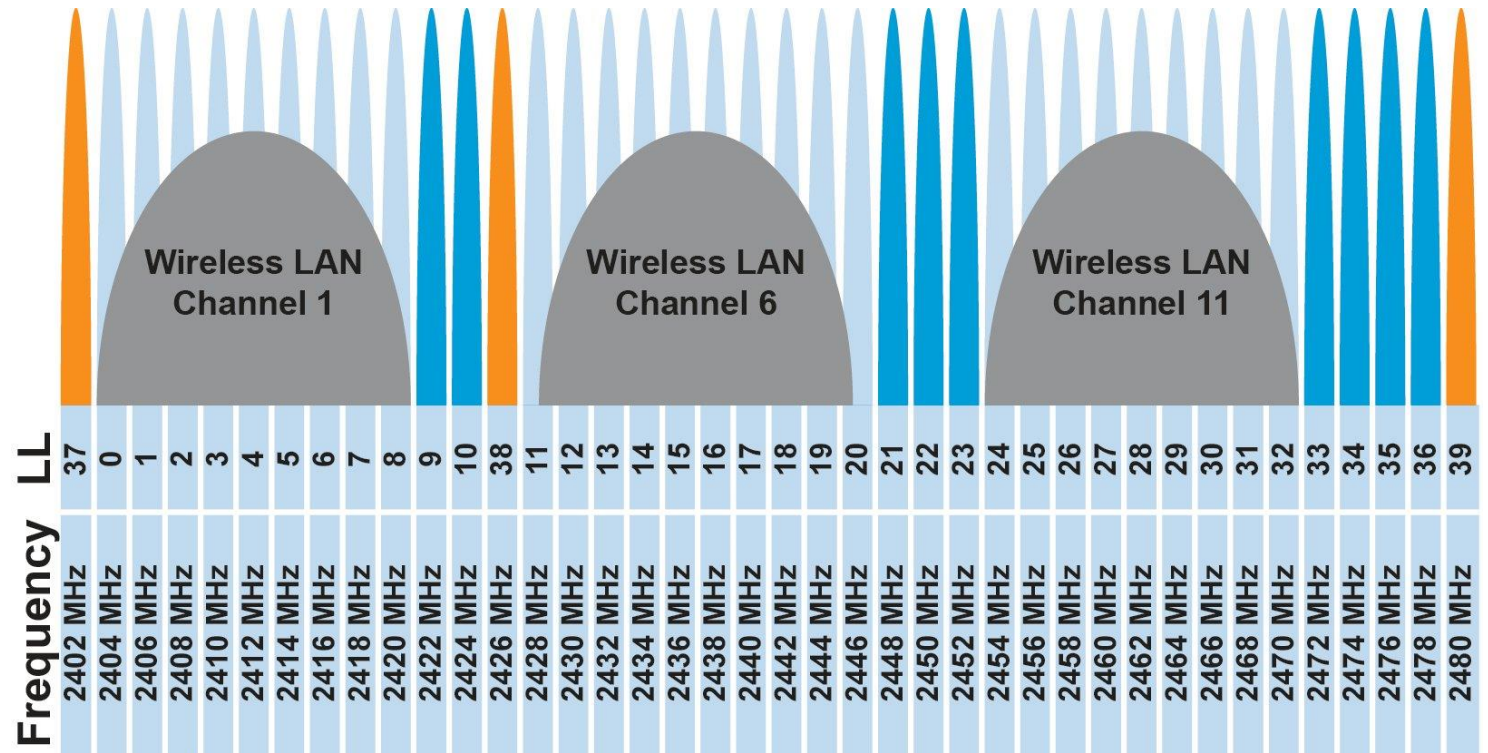
Unlicensed bands are where IoT thrives

- 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?**



Unlicensed bands are where IoT thrives

- 902 MHz – 928 MHz
 - LPWANs
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 - Faster WiFi
- Cellular uses licensed bands at great cost
 - **Why? No interference from other users**



Signal qualities

1. Signal strength

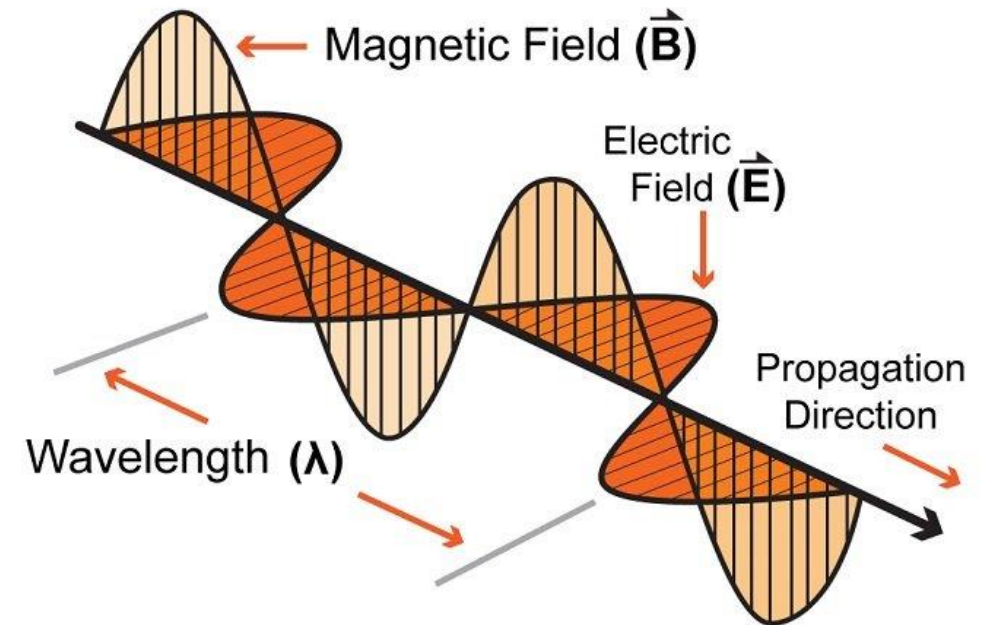
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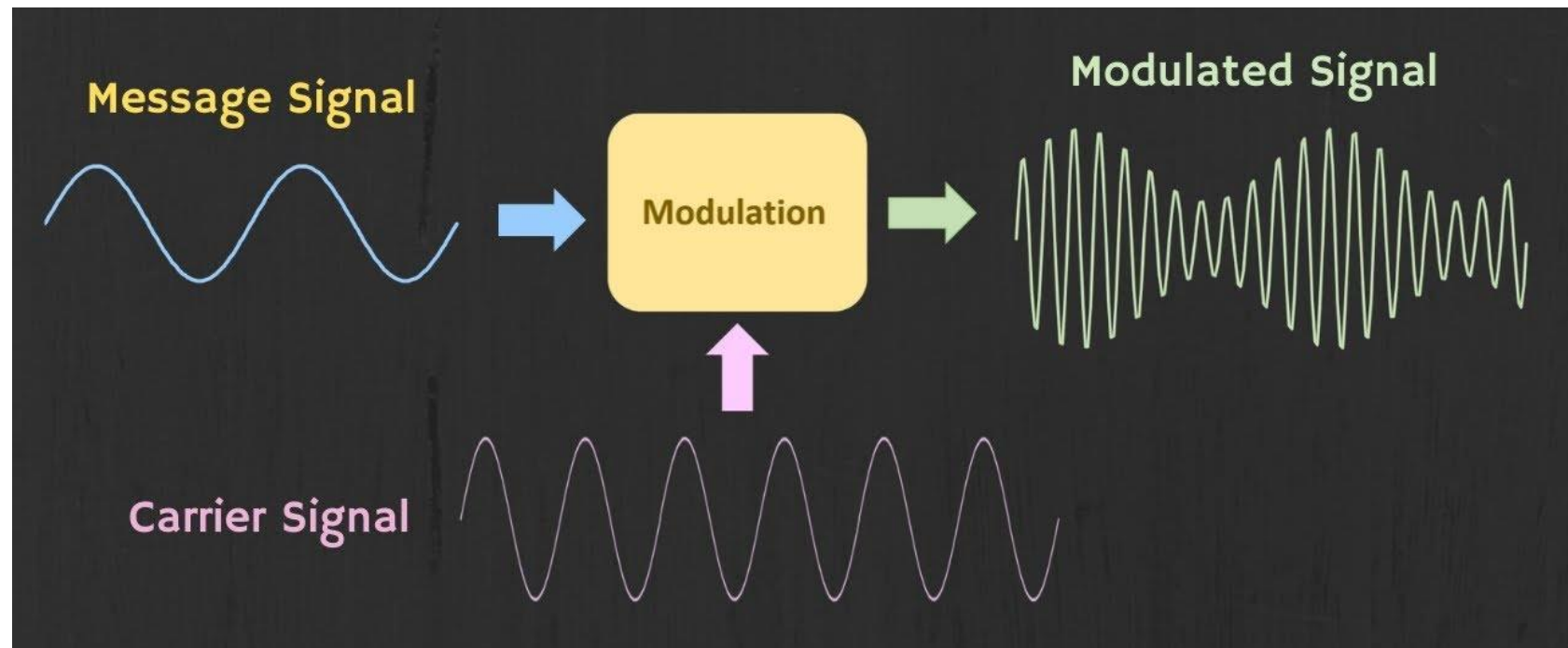
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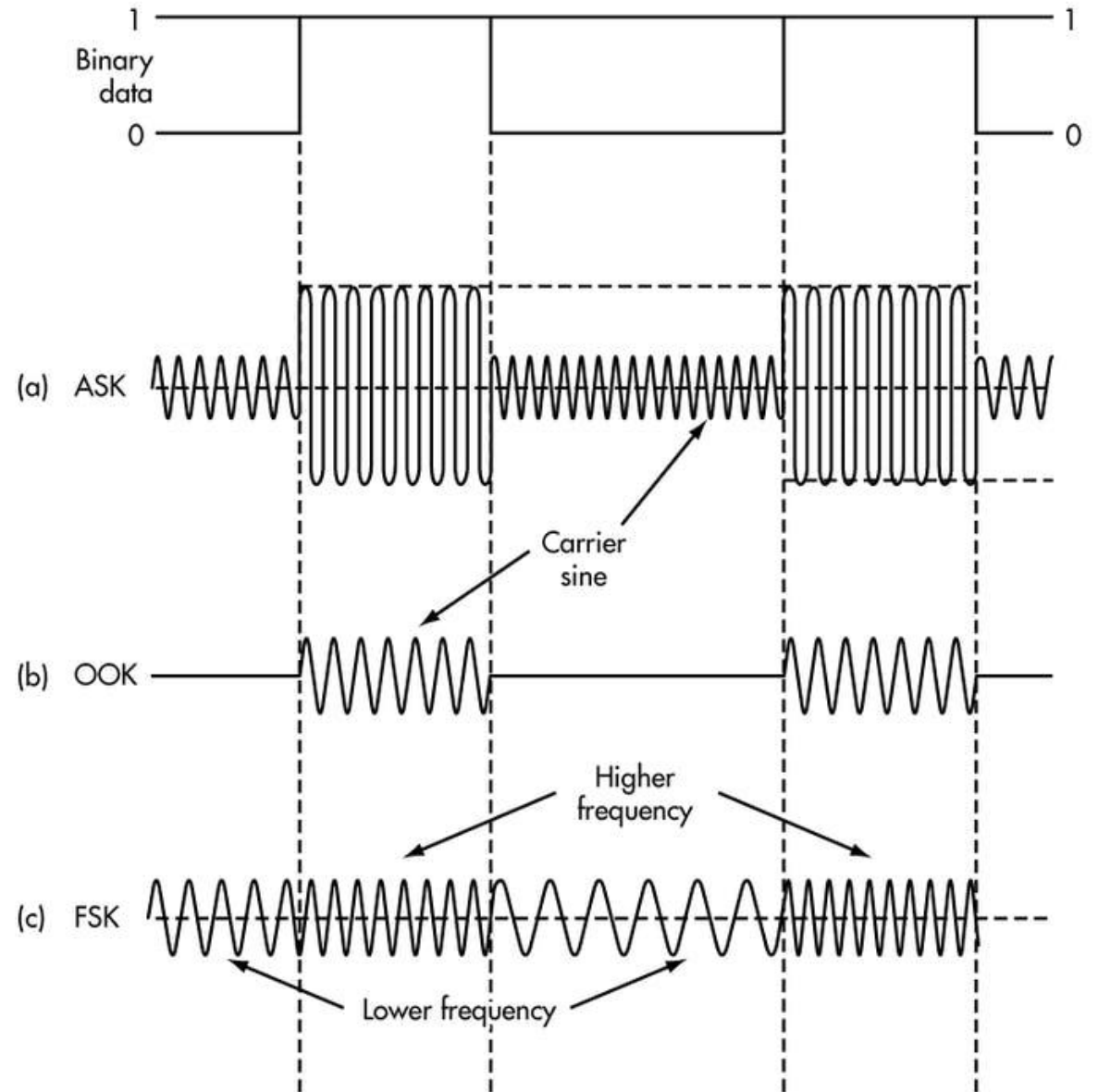
Modulation

- 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

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
 - Explicit multi-hop routing
 - 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

- **How do we determine who gets to speak?**
 - Two simultaneous speakers also lose both “transmissions”

Analogy: wireless medium as acoustic

- **How do we determine who gets to speak?**
 - Two simultaneous speakers also lose both "transmissions"
- 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

Break + Question

- Access controls to shared busses in wired systems as well!
- Which of these MAC protocols is I2C using?
- Which of these MAC protocols is USB using?

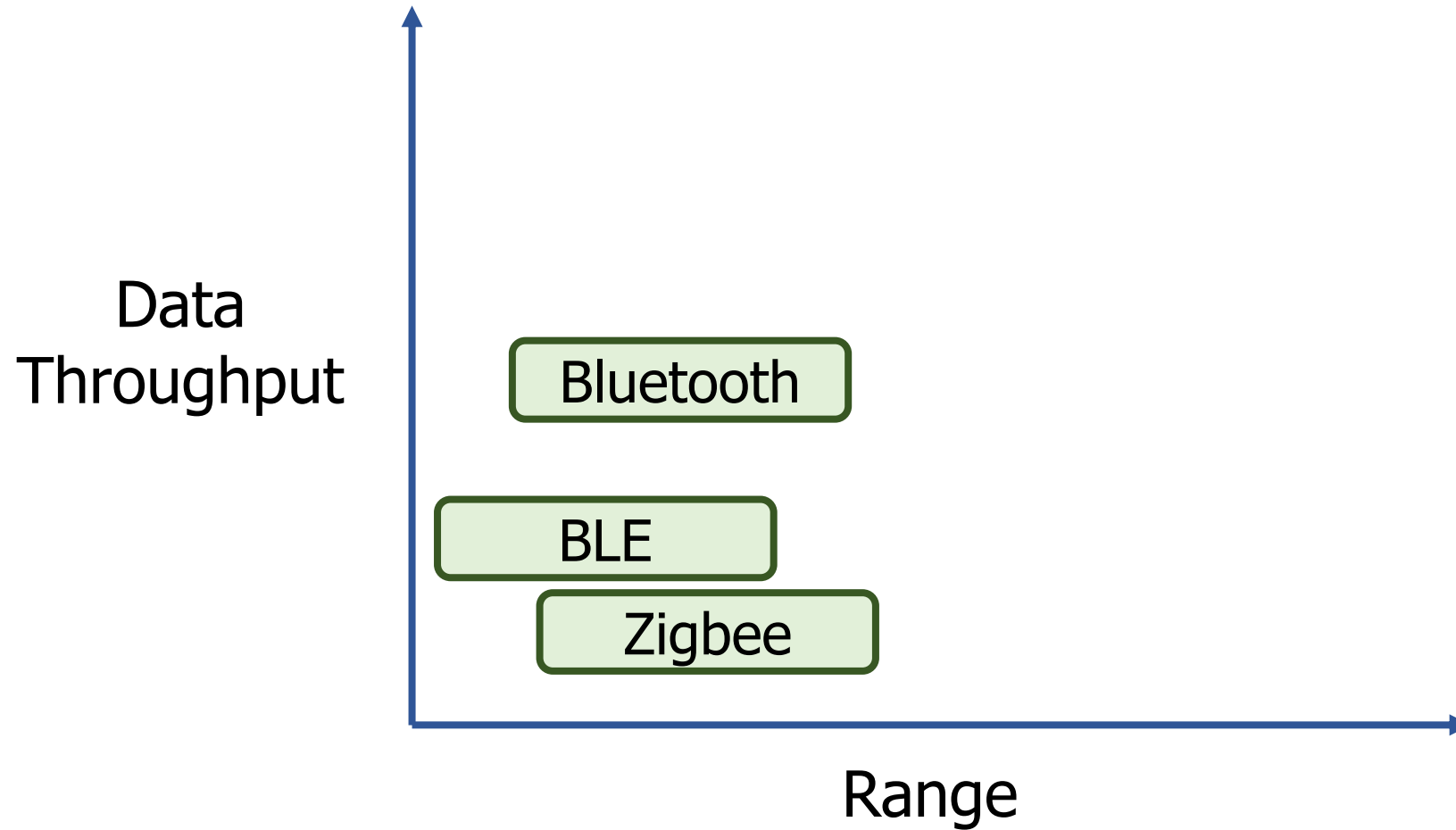
Break + Question

- Access controls to shared busses in wired systems as well!
- Which of these MAC protocols is I2C using?
 - CSMA/CA – senses the carrier to detect collisions
- Which of these MAC protocols is USB using?
 - TDMA – Host decides when each device can talk

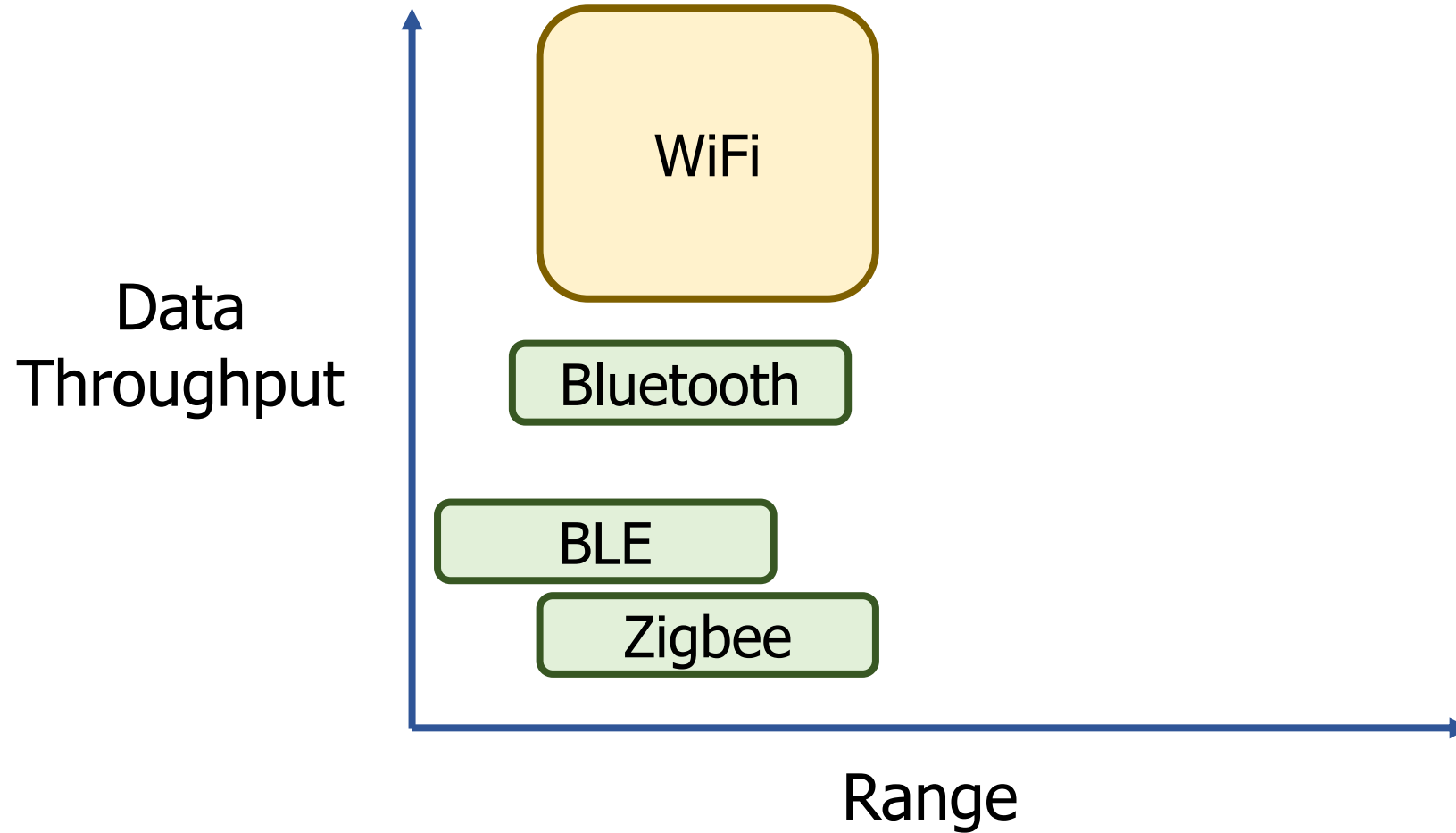
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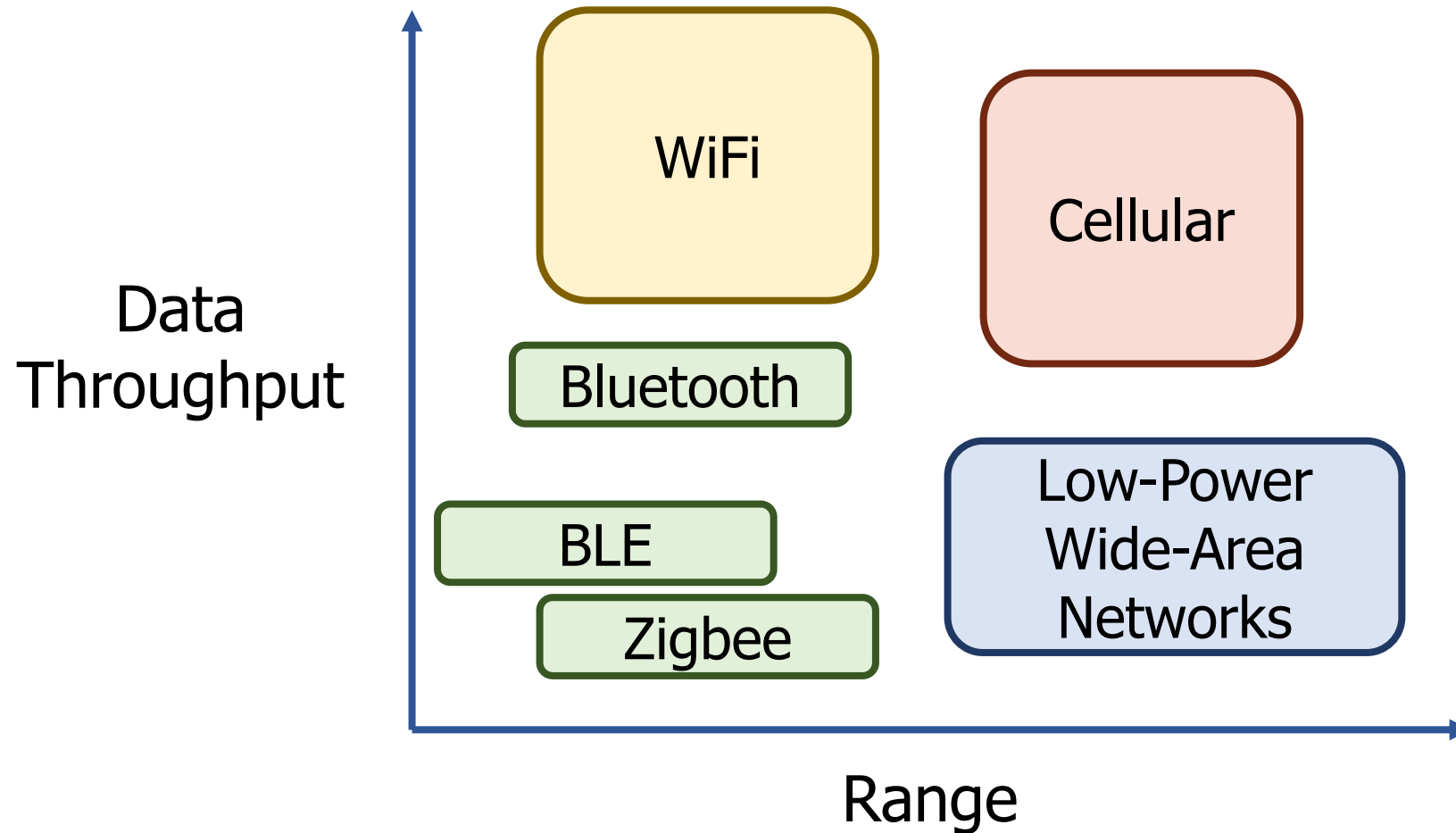
Comparison of wireless protocols



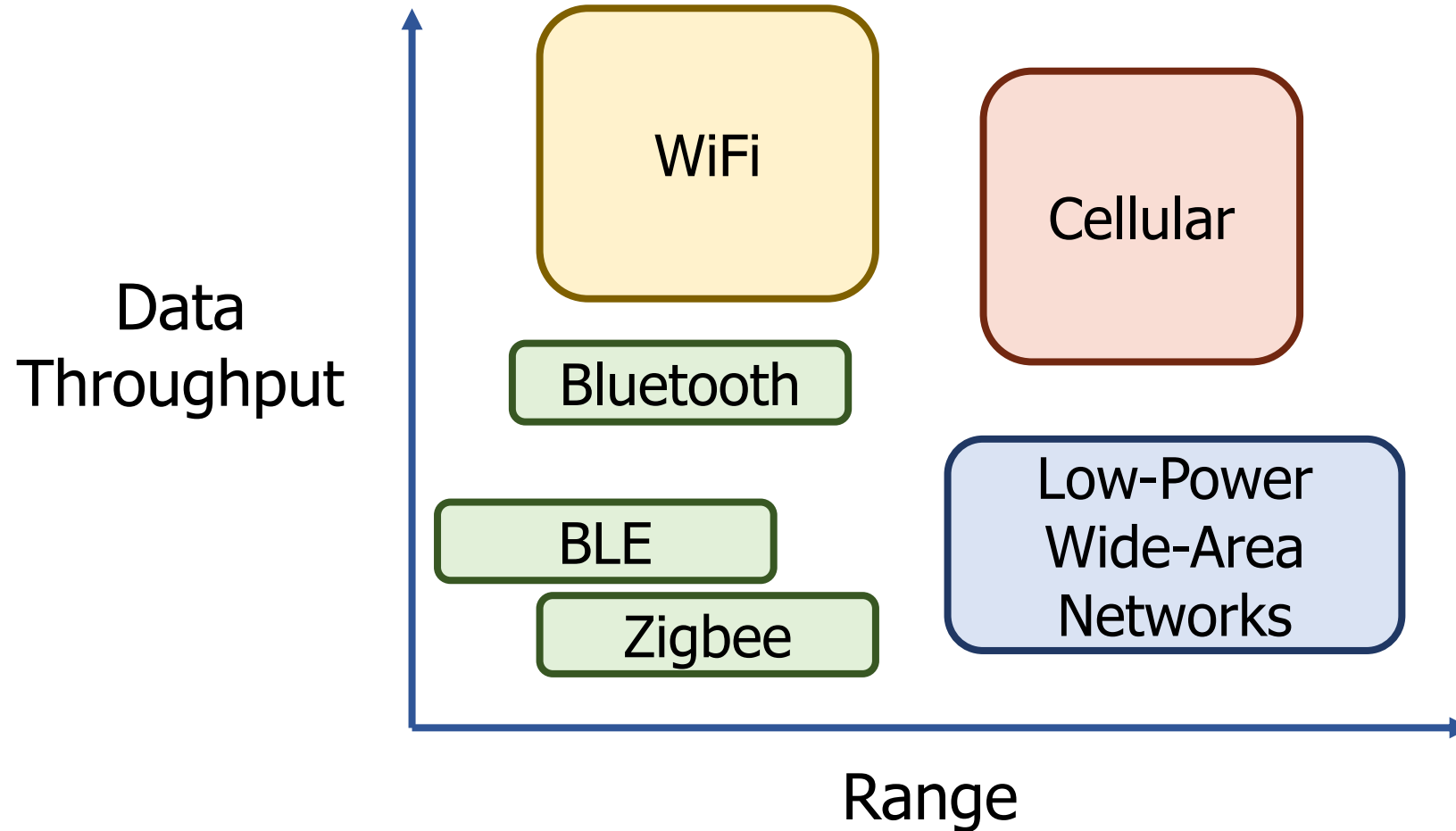
Comparison of wireless protocols



Comparison of wireless protocols

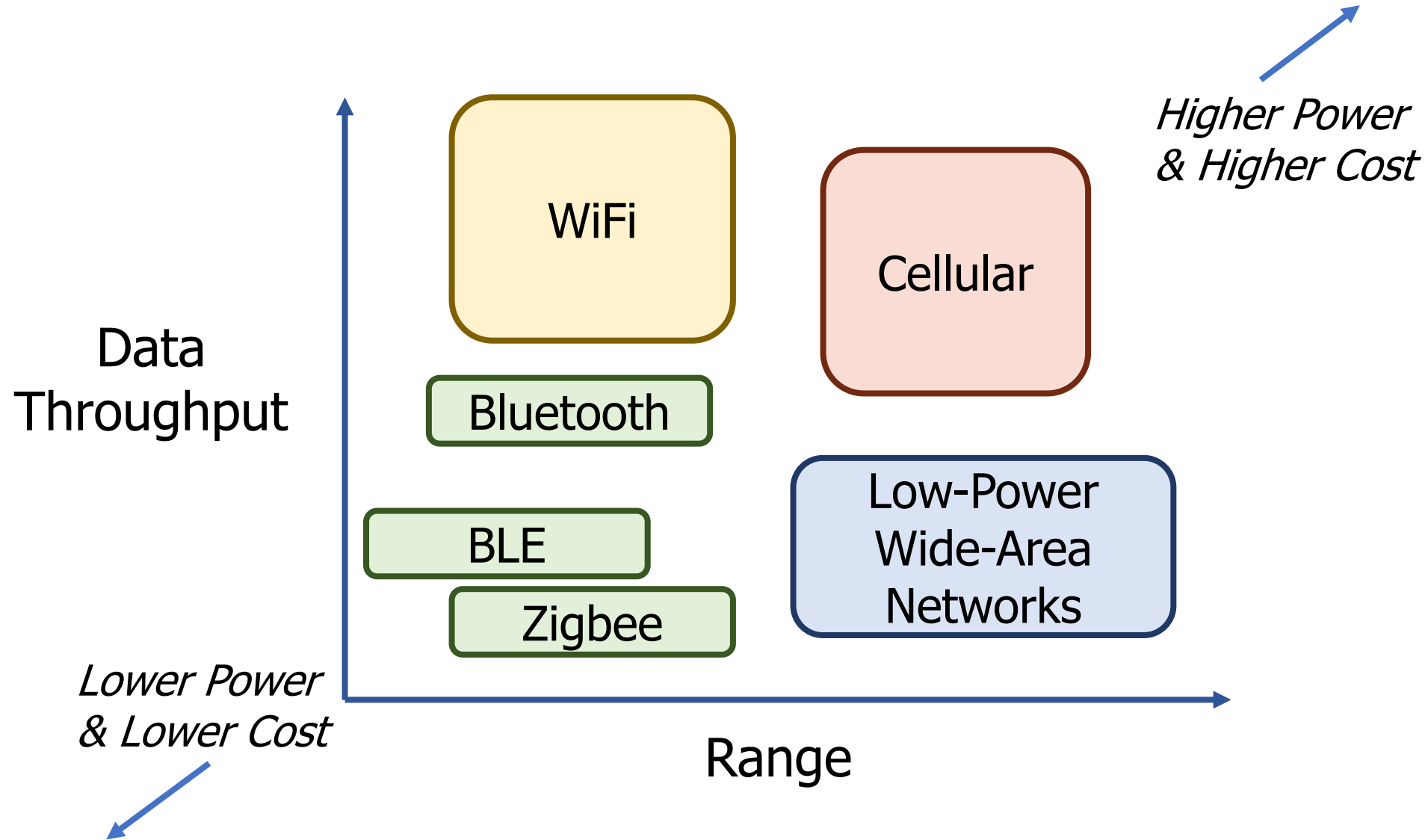


Comparison of wireless protocols



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

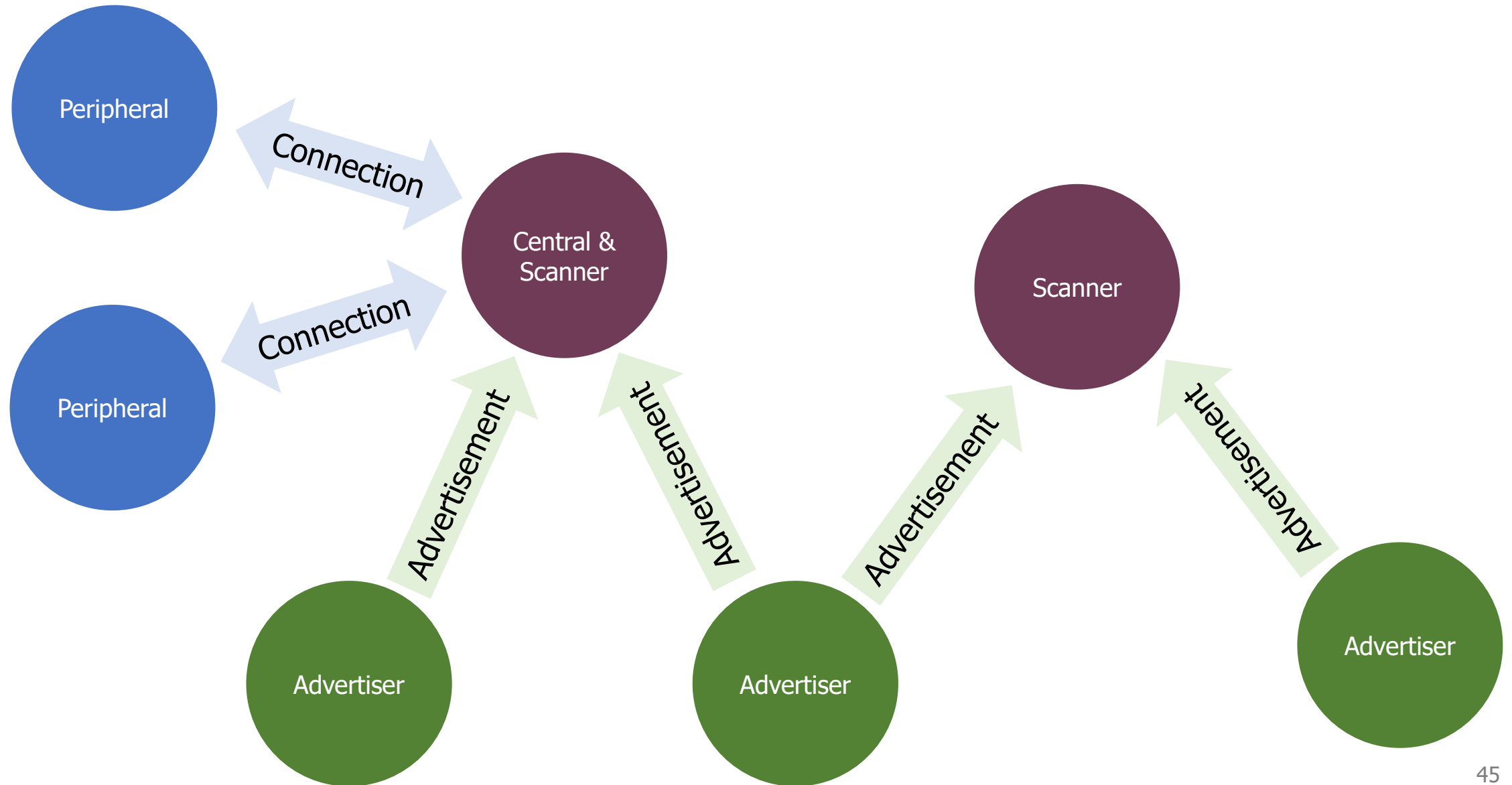
Bluetooth Low Energy

- 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

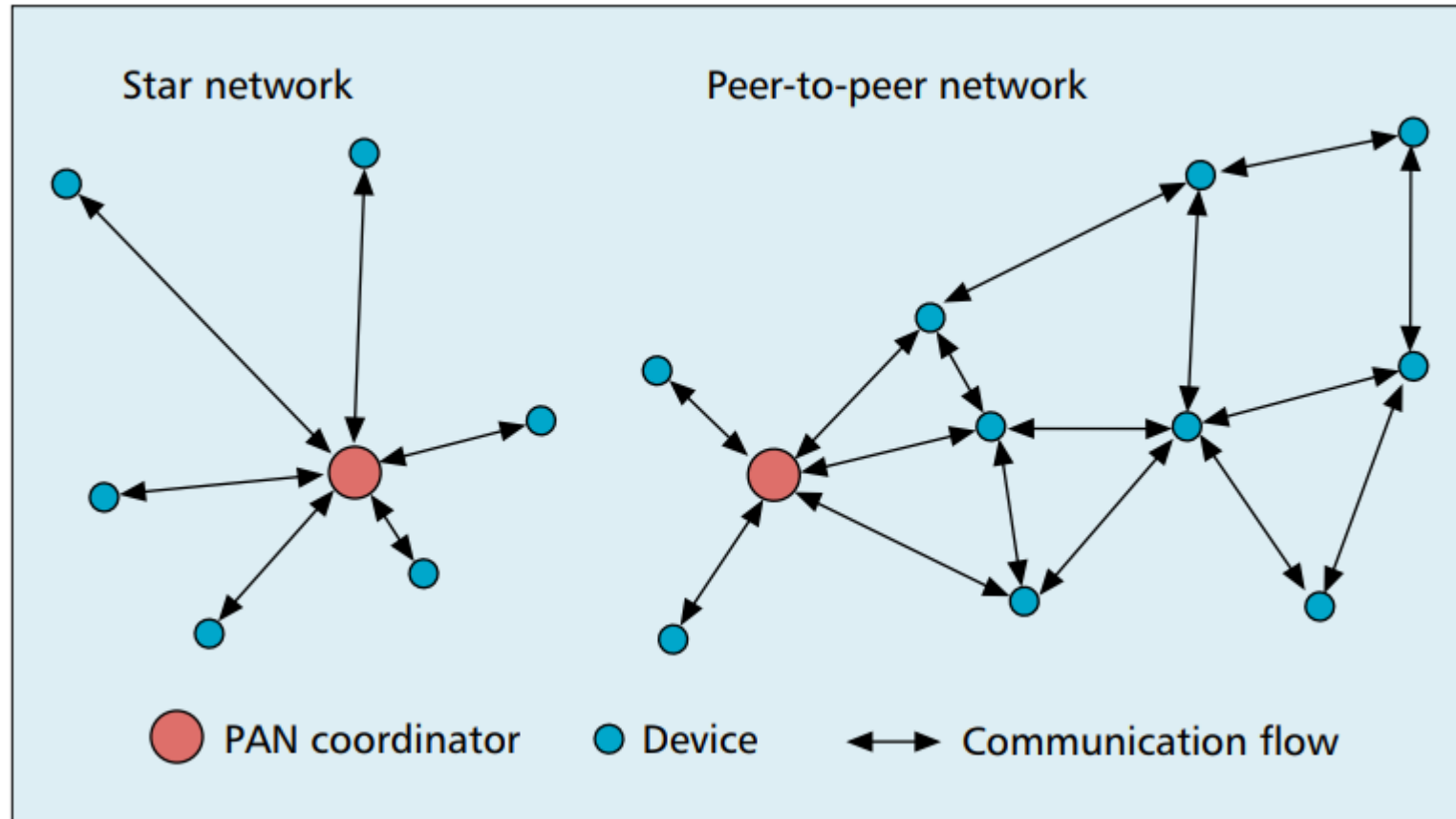
- Bluetooth Low Energy
- **802.15.4 – Zigbee and Thread**
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802.15.4 & Thread & Zigbee

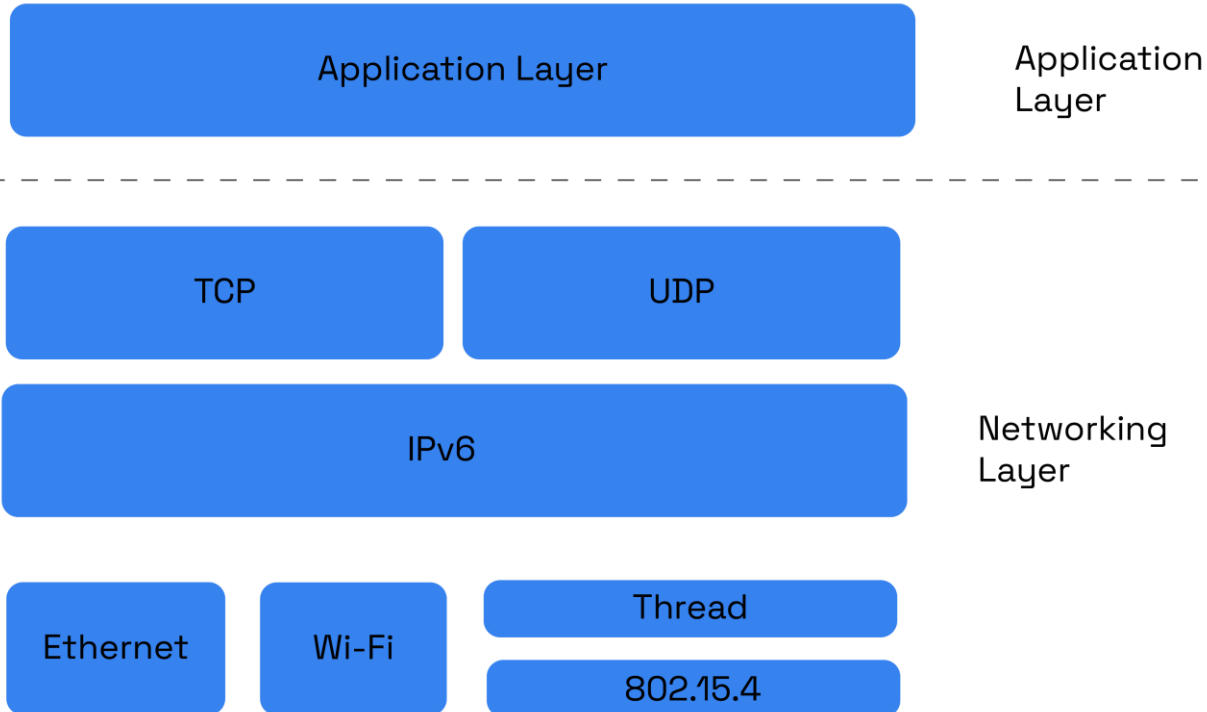
- 802.15.4 is a low-energy physical layer
 - Radio chips have been widely available for 15-20 years
- *Significant* amounts of sensor network research have focused on building layers on top of 802.15.4
 - Access control layers (CSMA)
 - Network layers
- Thread is a selection of these possibilities to 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	600 Mbps	70 m
5	802.11ac	2013	5 GHz	OFDM + MIMO	3.4 Gbps	35 m

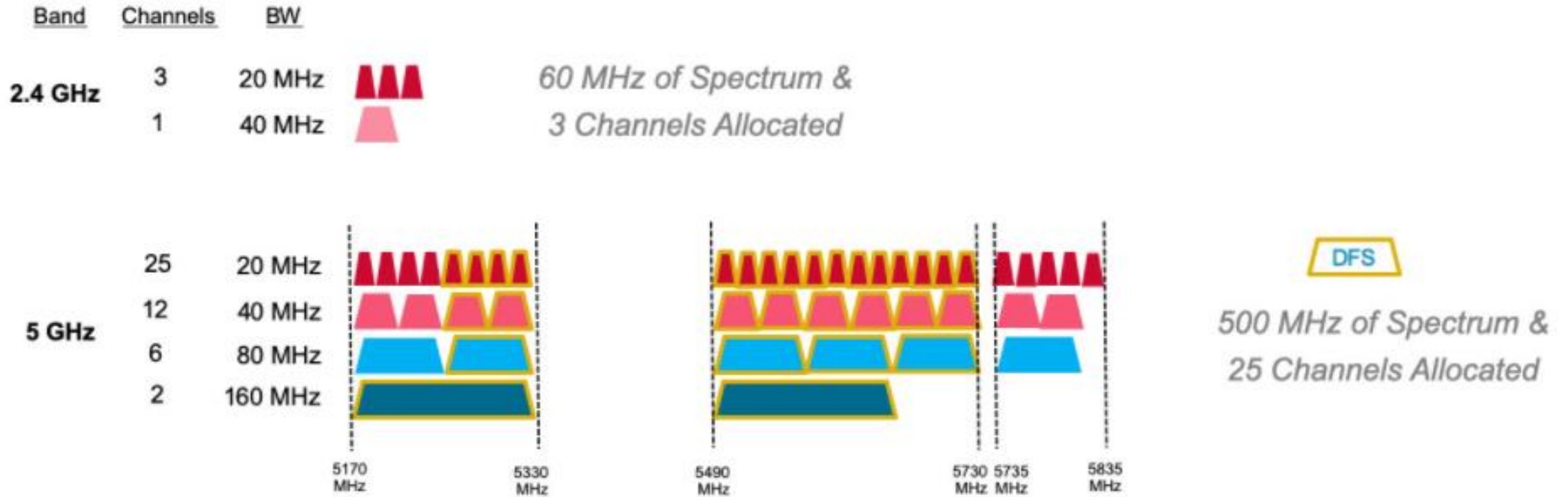
- 802.11b was very popular but is now usually unsupported
- 802.11a never saw major deployment
- WiFi Alliance rebranded 802.11ac as “WiFi 5” and backported scheme

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		

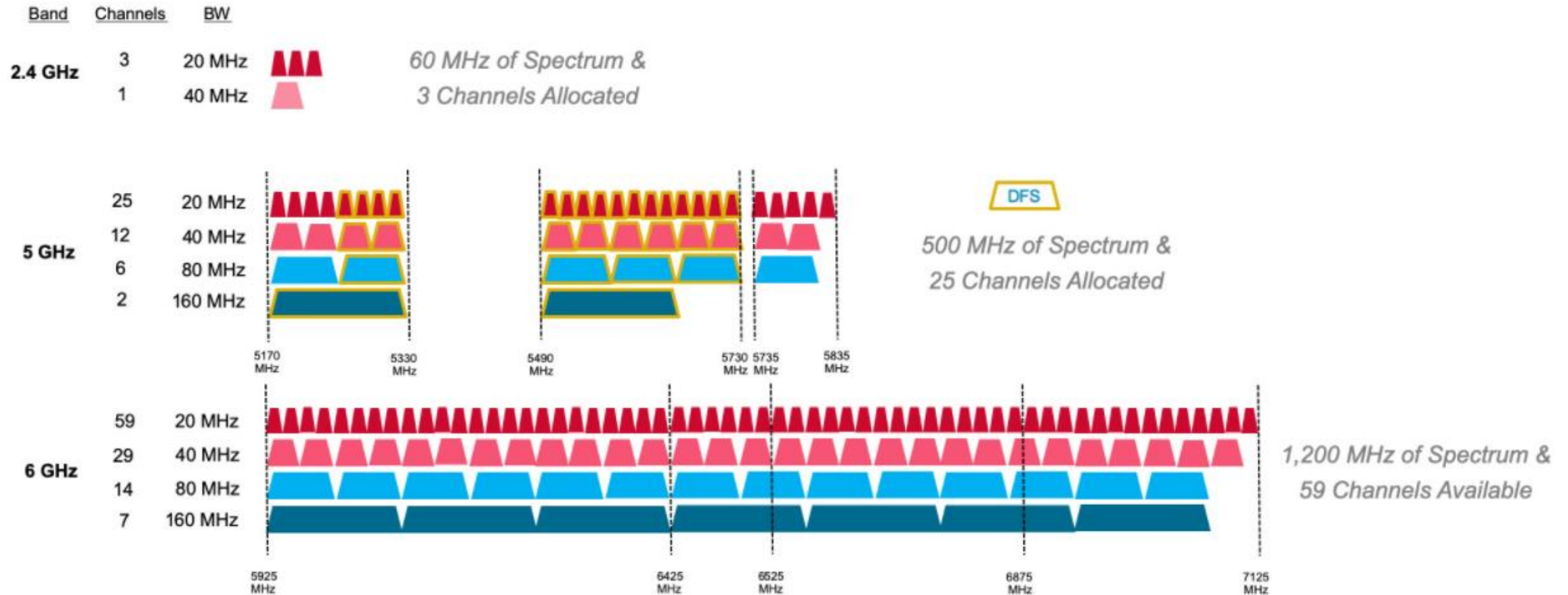
- More bandwidth means higher data rate (with same error rate)

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 better data rates



Protocols

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

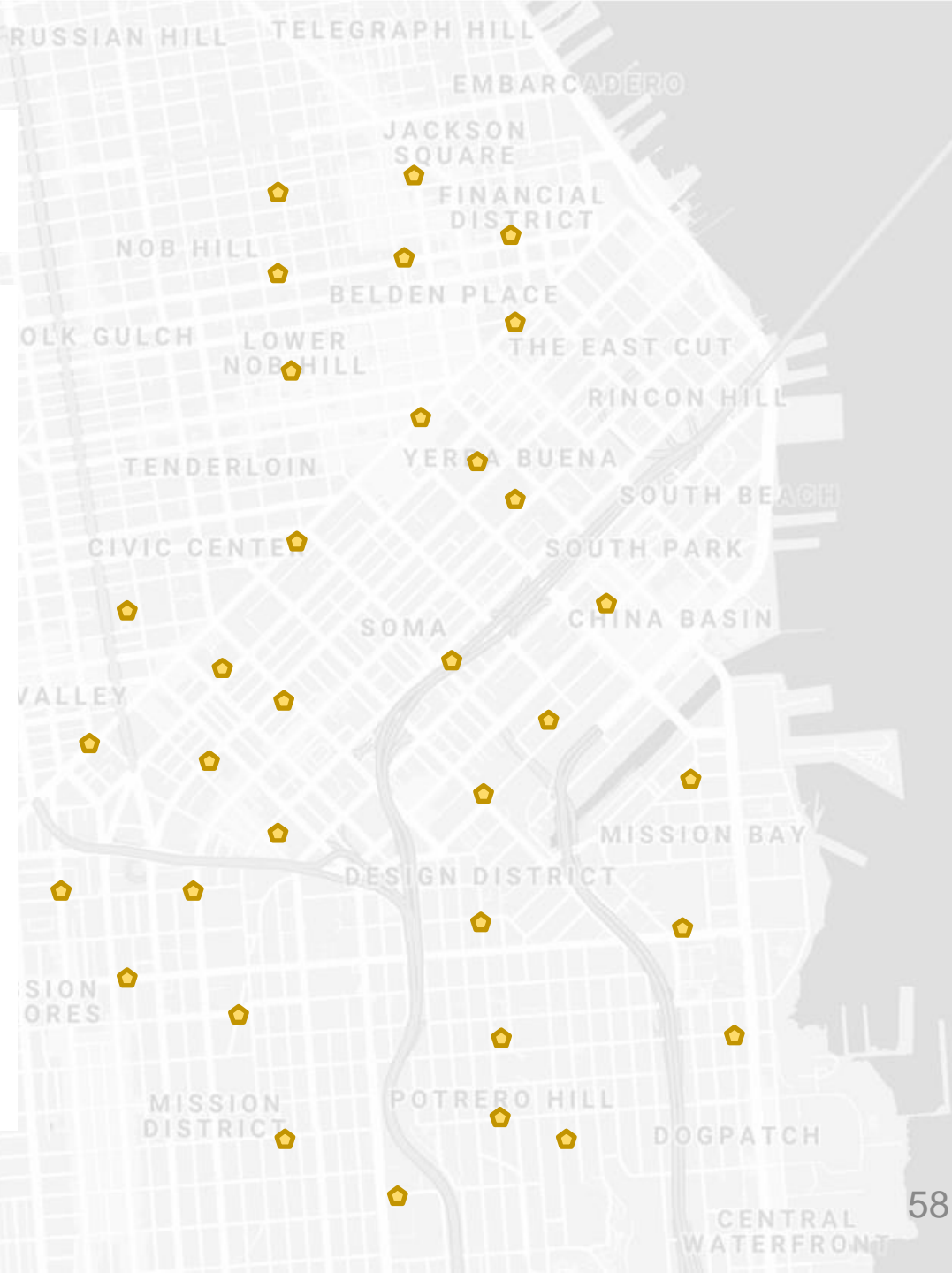


LPWANS: How do we collect data from a sensor?

- Manually collect measurements
- Connect it to WiFi (or Ethernet)
- Pay for cellular access

LPWANS: How do we collect data from MANY sensors?

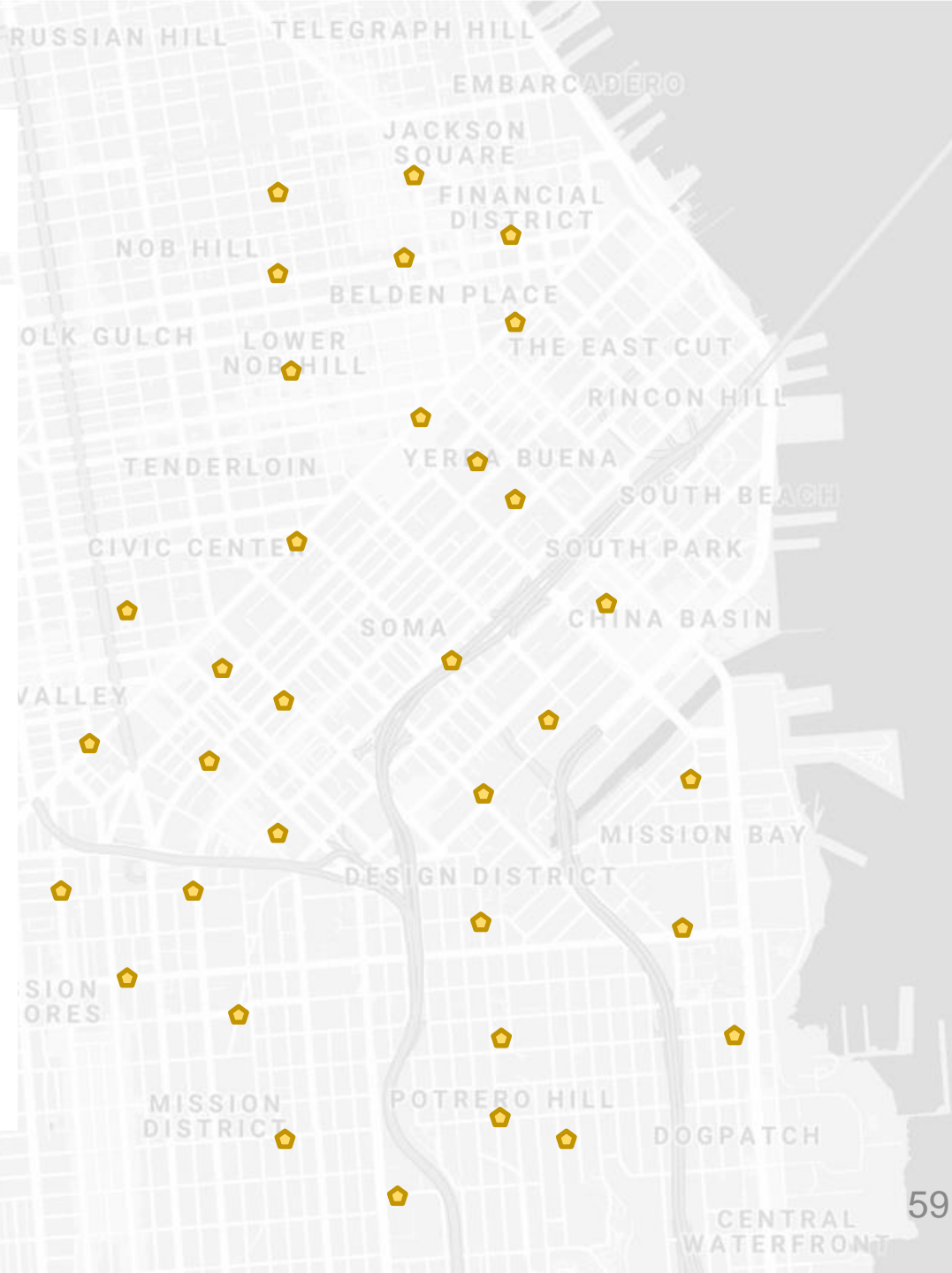
- Manually collect measurements
- Connect it to WiFi (or Ethernet)
- Pay for cellular access



We need another network option

Requirements:

- Wide area of coverage
 - Deploy fewer gateways
- Low power
 - So we can deploy on batteries
- Doesn't need high throughput
 - Sensor data is relatively small



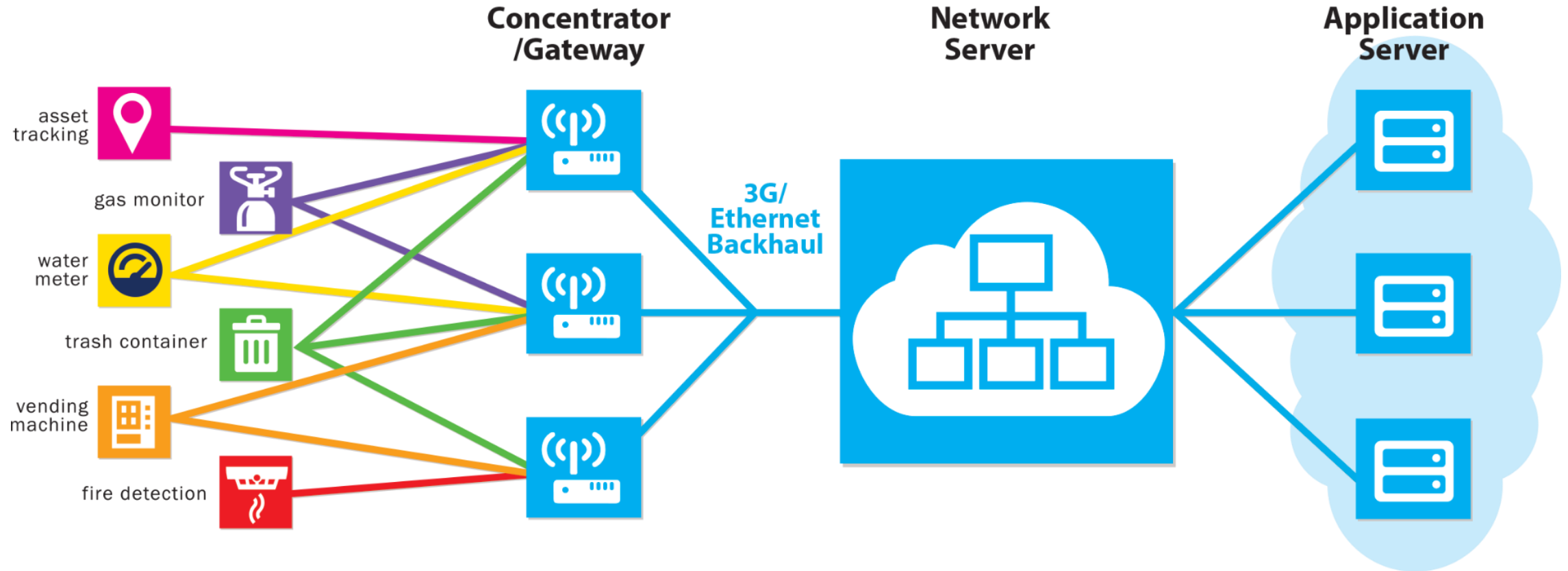
LPWANs (Low-Power Wide-Area Networks)

- 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 brand new space (relatively)
 - 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!
 - CS397/497 Wireless Protocols for the Internet of Things
 - Winter quarter 2023 (should be every winter quarter)
 - Project and Lab course, similar to this one but more on-your-own
- 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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