

Lecture 02

Network Fundamentals

CS397/497 – Wireless Protocols for IoT
Branden Gena – Spring 2024

Some slides borrowed from: Peter Steenkiste (CMU),
Christian Poellabauer (Notre Dame)

Materials in collaboration with
Pat Pannuto (UCSD) and Brad Campbell (UVA)

Administrivia

- Let me know if you don't have access to something
- Wireless lab comes out either late tonight or early tomorrow
 - Individual: using wireshark and sniffing packets
- Group survey is out (posted on Piazza)
 - Everyone will be working in groups of three
 - If you're missing a group member, I can pair you
 - If you have a full group, still fill it out so I know

Forgotten last lecture: late policy and slip days

- Late policy
 - You can submit assignments late
 - 20% reduction in maximum points per day late
- Slip days
 - Automatically extend deadlines without penalty (automatic, don't ask)
 - **Three total** to use throughout the quarter
 - Example
 - Submit an assignment three days late with no penalty
 - Submit an assignment four days late with a one-day penalty
 - Submit three assignments each one day late with no penalty
 - Warning: all group members are charged a slip day
 - So it's possible one person gets a penalty when the others don't

Today's Goals

- Introduce OSI layer model of communication
- Provide background on Internet layering
- Overview of concerns for the Physical layer
 - Speak the “lingo” of wireless communication
 - Present technology aspects that we will return to in specific protocols

Outline

- **OSI Layers**
- Internet Architecture (Upper Layers)
- Physical Layer
 - Overview
 - Signal Strength
 - Signal Frequency and Bandwidth
 - Signal Modulation

Communication layers

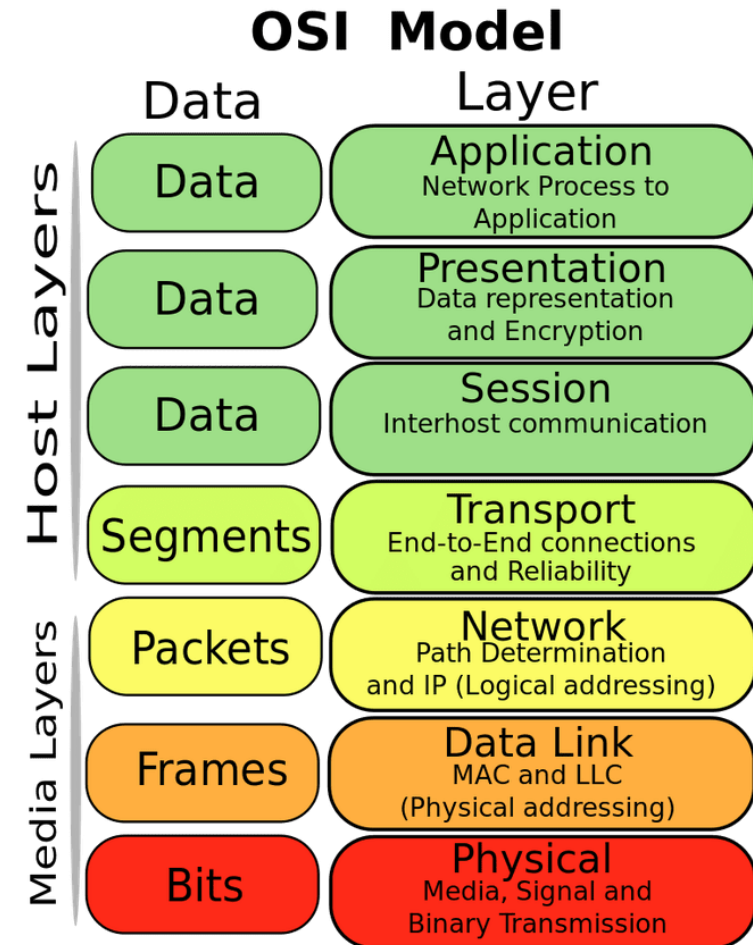
- Application
- Presentation
- Session
- Transport
- Network
- Data Link
- Physical

What goes on at each of these?

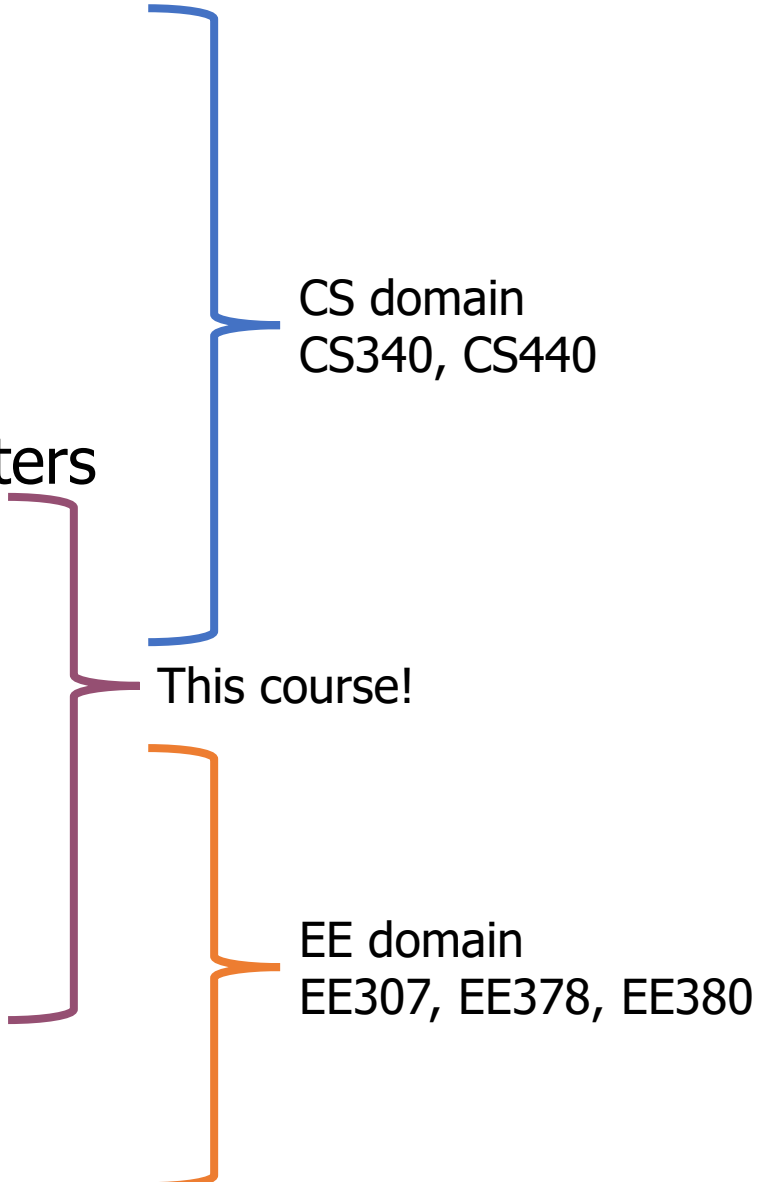
OSI model of communication layers

- Transport
 - Sending data between applications
 - TCP and UDP
- Network
 - Sending data between networked computers
 - IP
- Data Link
 - Sending collections of bits
 - Ethernet, WiFi
- Physical
 - Sending individual bits
 - Ethernet, WiFi

Open Systems Interconnection (OSI)

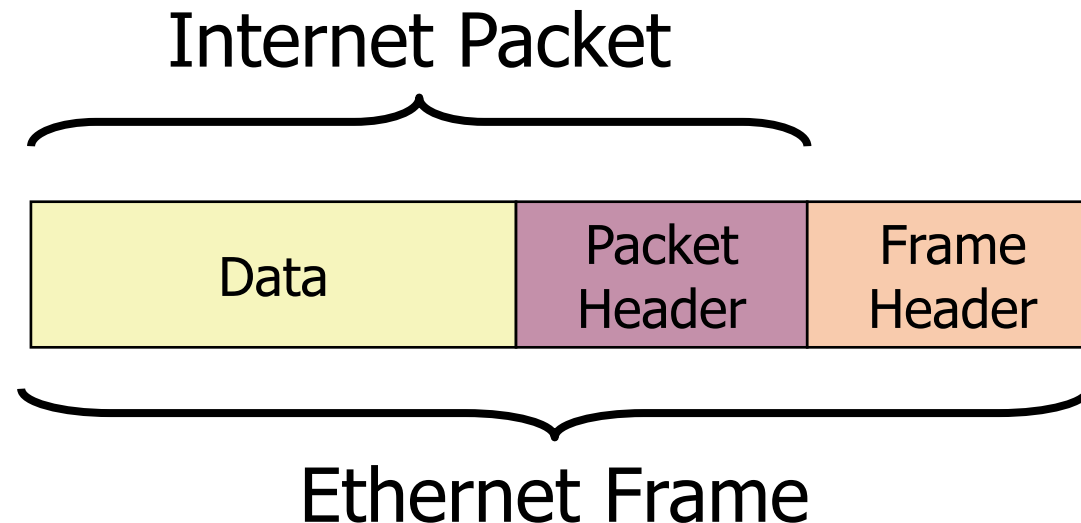


Where does this class focus?

- Transport
 - Sending data between applications
 - TCP and UDP
 - Network
 - Sending data between networked computers
 - IP
 - Data Link
 - Sending collections of bits
 - Ethernet, WiFi
 - Physical
 - Sending individual bits
 - Ethernet, WiFi
- 
- CS domain
CS340, CS440
- This course!
- EE domain
EE307, EE378, EE380

Protocols are “layered”

- Headers for each layer of communication wrap data
 - Data is wrapped with header for the network to make a packet
 - i.e., bytes are added to the start/end of it
 - Packet is wrapped with header for the link to make a frame

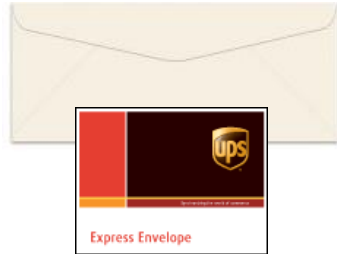


Analogy: Sending a letter

Application: Purpose/type of letter



Transport: Carrier service



Named recipient



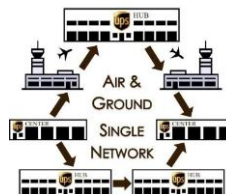
Network: Street Address



Courier



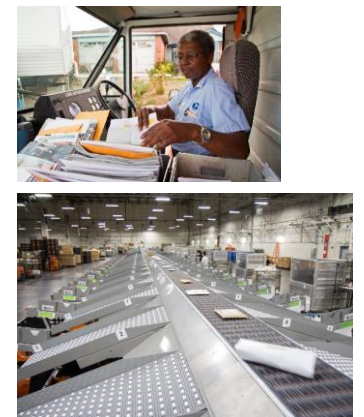
Mailing/shipping infrastructure



Link: Transfer to post office

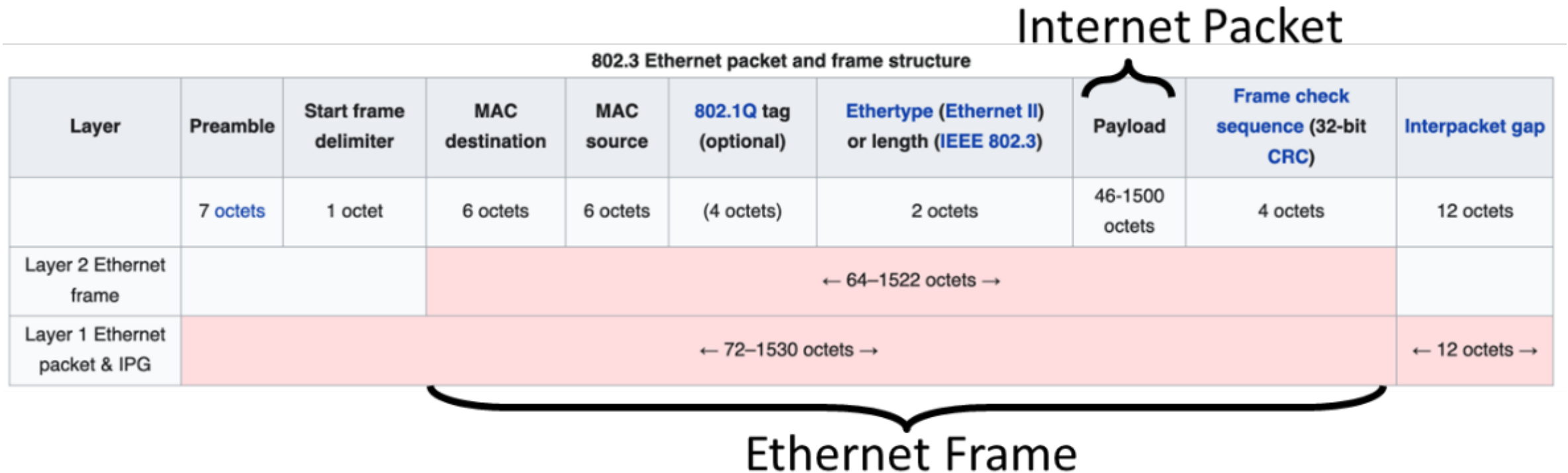


Physical: Moving tangible object



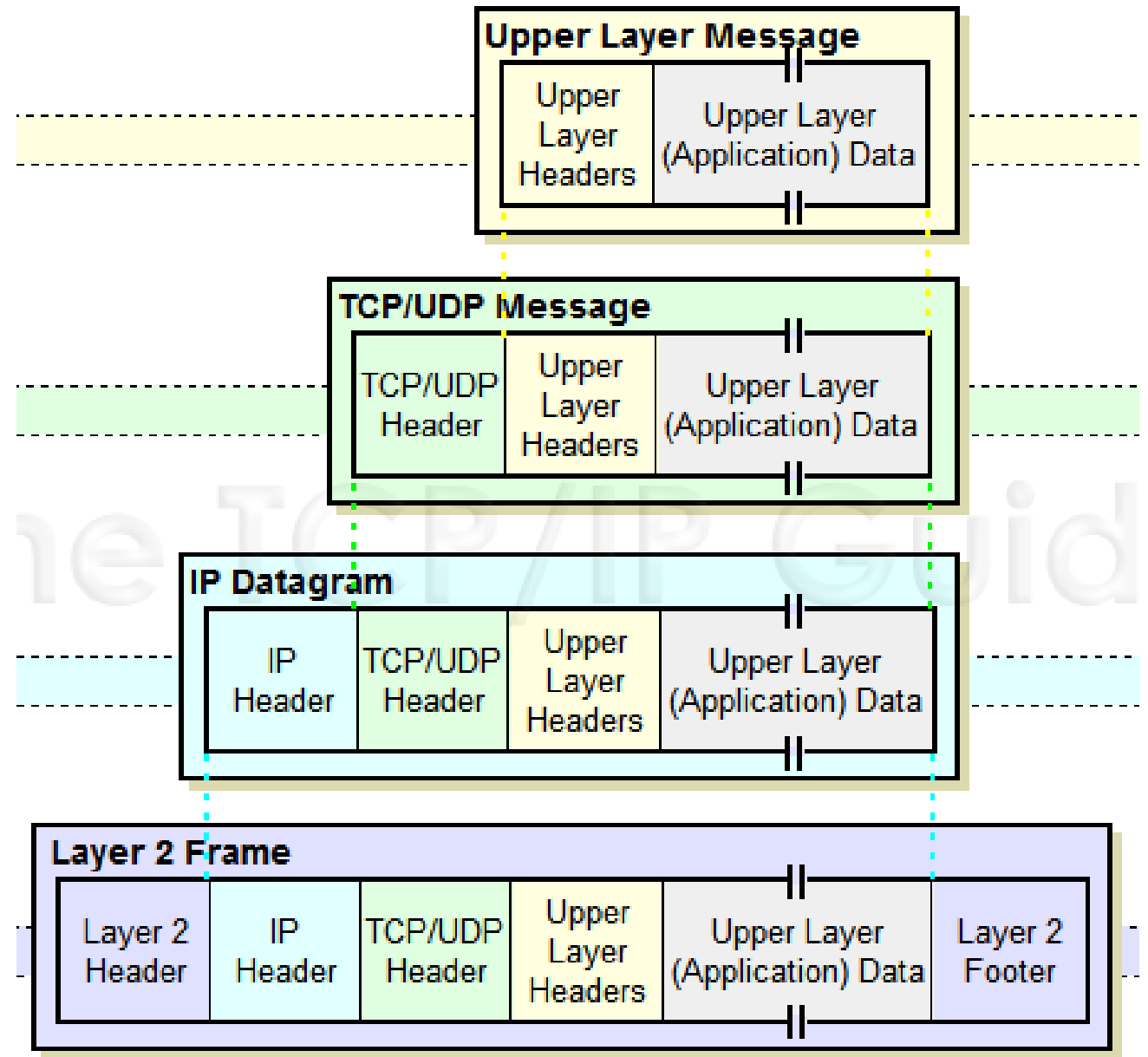
Example of layering for Ethernet and IP

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 - Data is wrapped with header for network to make a packet
 - Packet is wrapped with a header for the link to make a frame

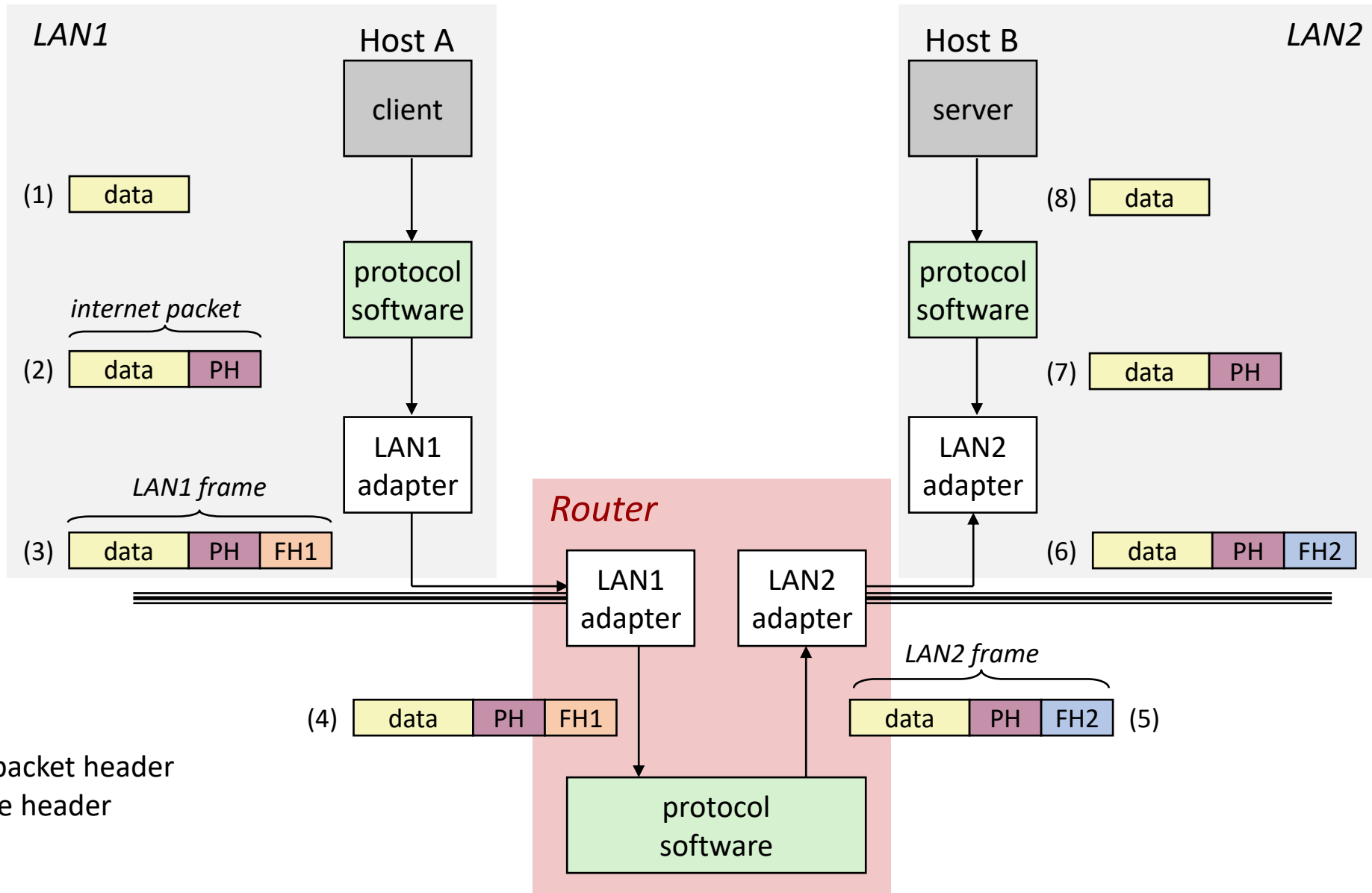


Packet encapsulation

- Upper-layer packet is the payload for the lower-layer packet

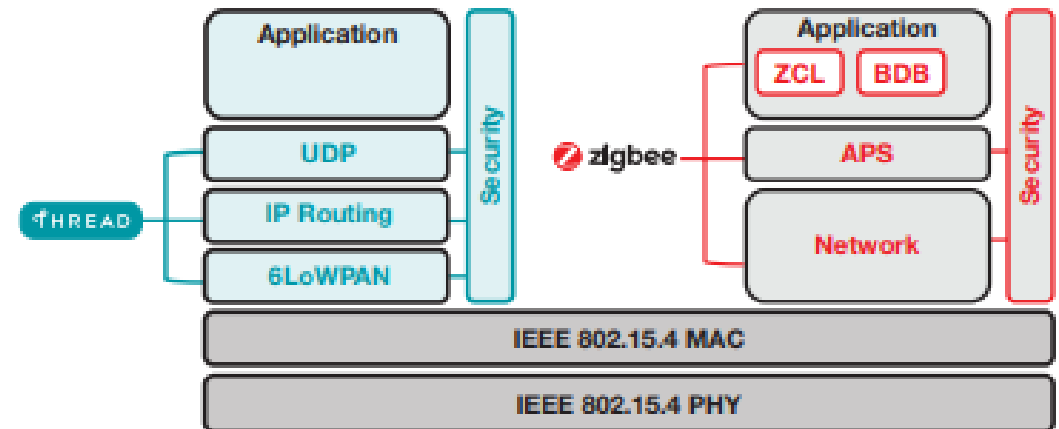
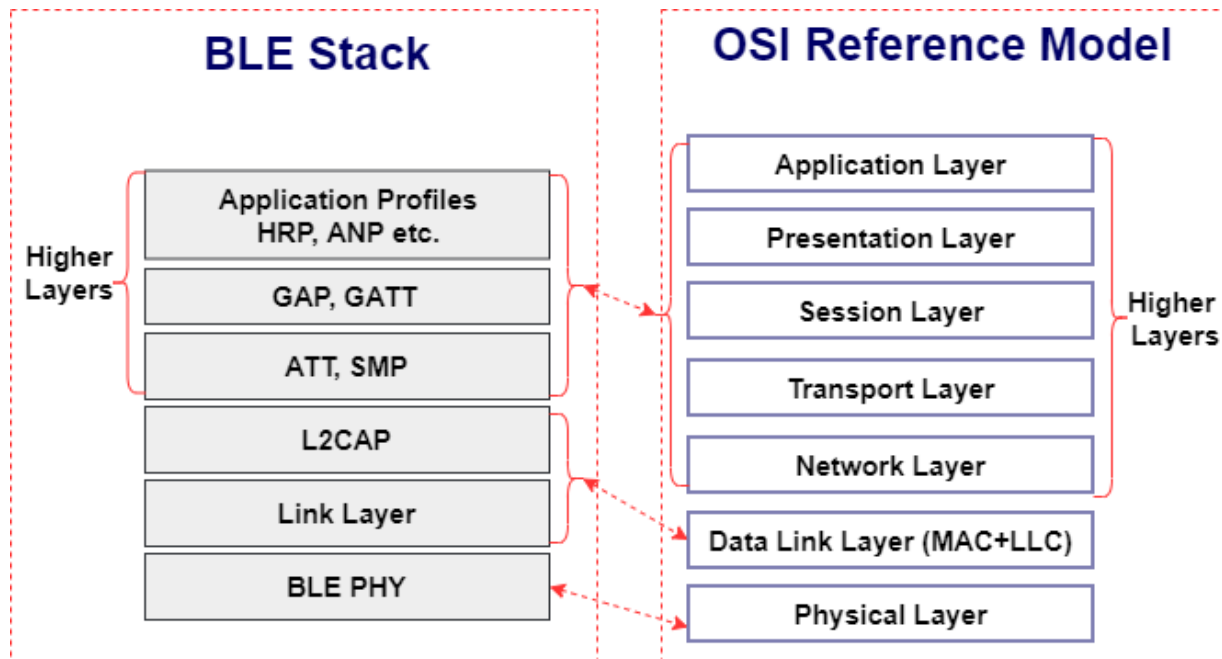


Transmitting data between networks

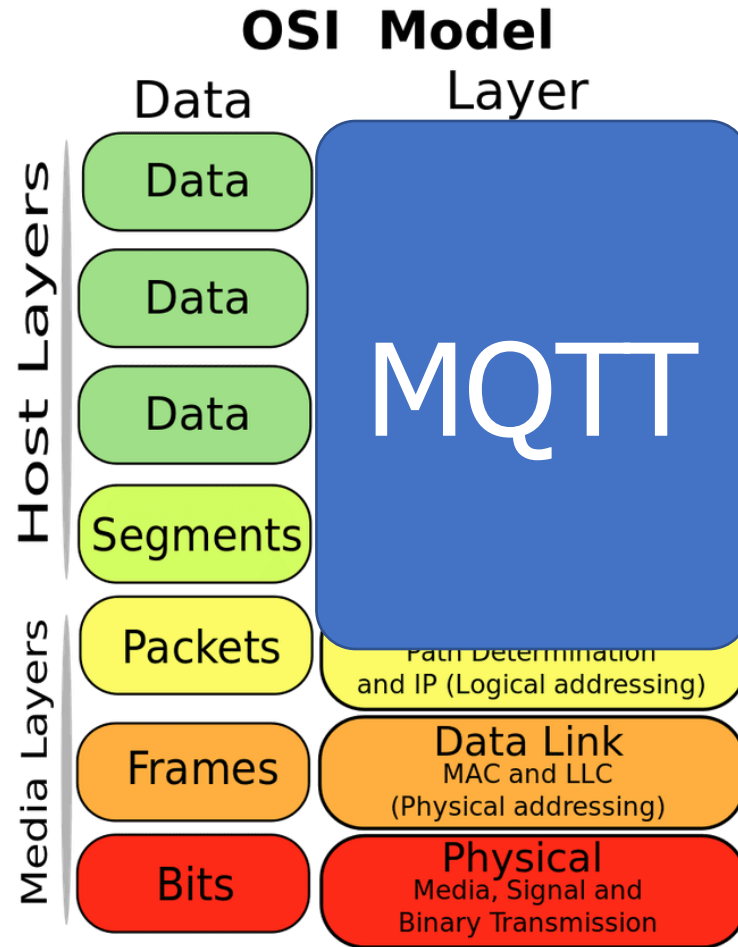


Model does not equal reality

- Wireless protocols don't always split between layers cleanly
 - Usually explain parts of physical, data link, and possibly upper layers
- Model still helps conceptualize stack-up though
 - Layering of some type still occurs



Layering for IoT (joke) (kind of)



MQTT is a
publish/subscribe
message broker

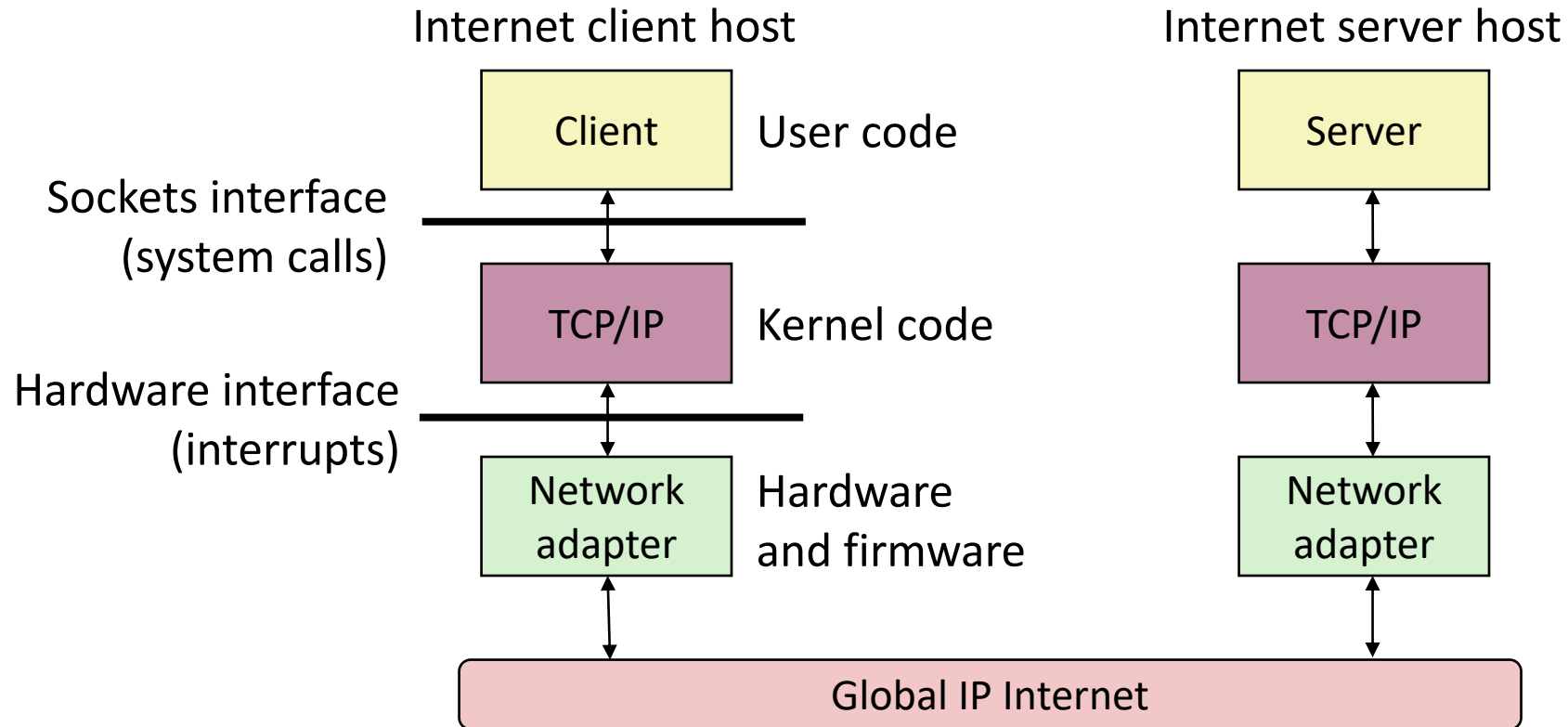
Outline

- OSI Layers
- **Internet Architecture (Upper Layers)**
- Physical Layer
 - Overview
 - Signal Strength
 - Signal Frequency and Bandwidth
 - Signal Modulation

The global Internet

- Most famous example of an internet (uppercase to distinguish)
- Based on the TCP/IP protocol family
 - **IP** (Internet Protocol)
 - Provides a *naming scheme* and unreliable *delivery of packets* from **host-to-host**
 - **UDP** (Unreliable Datagram Protocol)
 - Uses IP to provide *unreliable data delivery* from **process-to-process**
 - **TCP** (Transmission Control Protocol)
 - Uses IP to provide *reliable data delivery* from **process-to-process**
- Accessed via a mix of Unix file I/O and the **sockets** interface

Hardware and software organization of an Internet application



A programmer's view of the internet

1. Hosts are mapped to a set of 32-bit **IP addresses**

- 129.105.7.30

2. The set of IP addresses is mapped to a set of identifiers called Internet **domain names**

- 129.105.7.30 is mapped to moore.wot.eecs.northwestern.edu

3. A process on one Internet host can communicate with a process on another Internet host over a **connection**

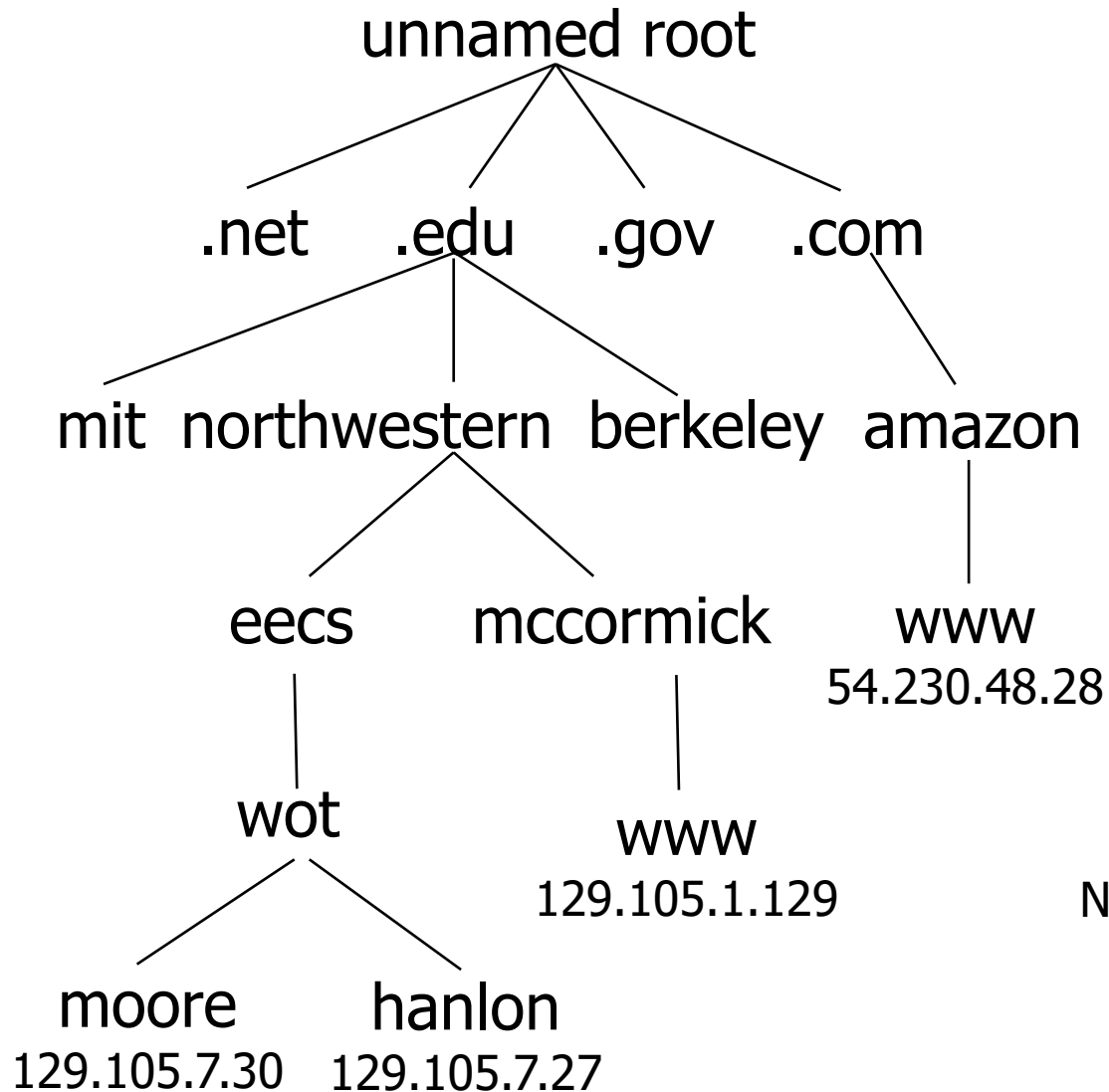
1. IP addresses

- 32-bit IP addresses are stored in an **IP address struct**
 - IP addresses are always stored in memory in *network byte order* (big-endian)
 - Remember: most computers use little-endian 😞
 - True in general for any integer transferred in a packet header from one machine to another
 - E.g., the port number used to identify an Internet connection

```
/* Internet address structure */
struct in_addr {
    uint32_t    s_addr; /* network byte order (big-endian) */
};
```

- By convention, each byte in a 32-bit IP address is represented by its decimal value and separated by a period
 - IP address: $0x8169071E = 129.105.7.30$

2. Internet domain names



Top-level domain names

Second-level domain names

Third-level domain names
and onwards...

Note: Northwestern owns 129.105.x.x

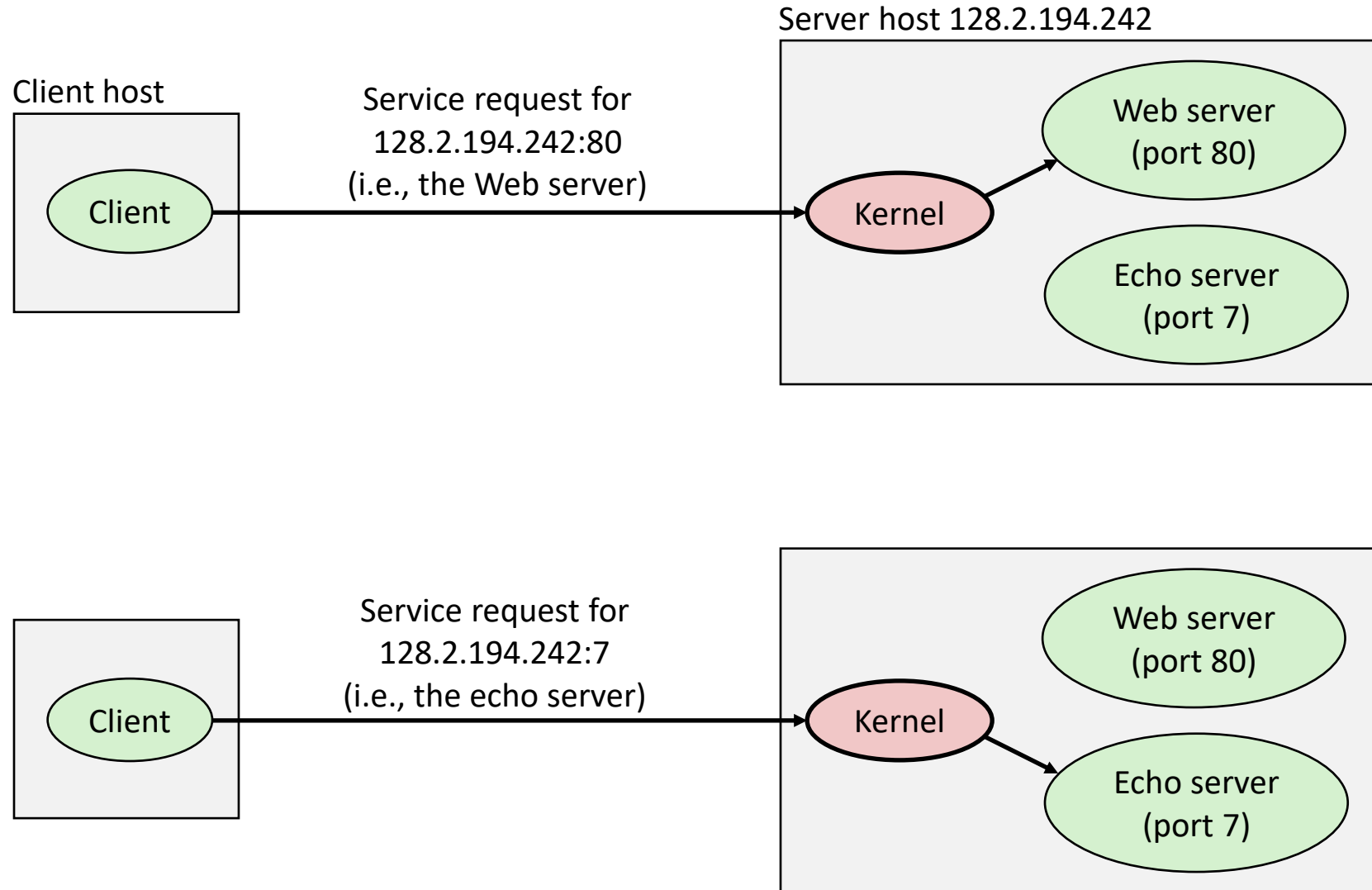
Domain Naming System (DNS)

- The Internet maintains a mapping between IP addresses and domain names in a huge worldwide distributed database called **DNS**
- Conceptually, programmers can view the DNS database as a collection of millions of **host entries**
 - Each host entry defines the mapping between a set of domain names and IP addresses
- A special name: **localhost**
 - Refers back to the computer being used (IP address 127.0.0.1)

3. Internet connections

- A socket is an endpoint of a connection
 - Socket address is an `IPAddress:port` pair
 - IP address identifies the computer
 - Port identifies the process on the computer
- Clients and servers communicate by sending streams of bytes over **connections**. Most connections are:
 - Point-to-point: connects a pair of processes.
 - Full-duplex: data can flow in both directions at the same time,
 - [TCP adds] Reliable: stream of bytes sent by the source is eventually received by the destination in the same order it was sent.

Ports are used to identify services to the kernel



How does the Internet handle routing packets?

- IP layer
 - Describes application connection
 - Packets from my computer <---> Google
- Link layer (Ethernet)
 - Describes individual links
 - Packets from my computer <---> my router
- **Routing**
 - Using link-layer building blocks to get packets from one IP to another

Addressing

- How to solve the routing problem?
 - I need to know how to get data from me to you
- How does the post office work?
 - I know where you live (your address)
 - Zip Code
 - City
 - Street
 - House Number
 - Name

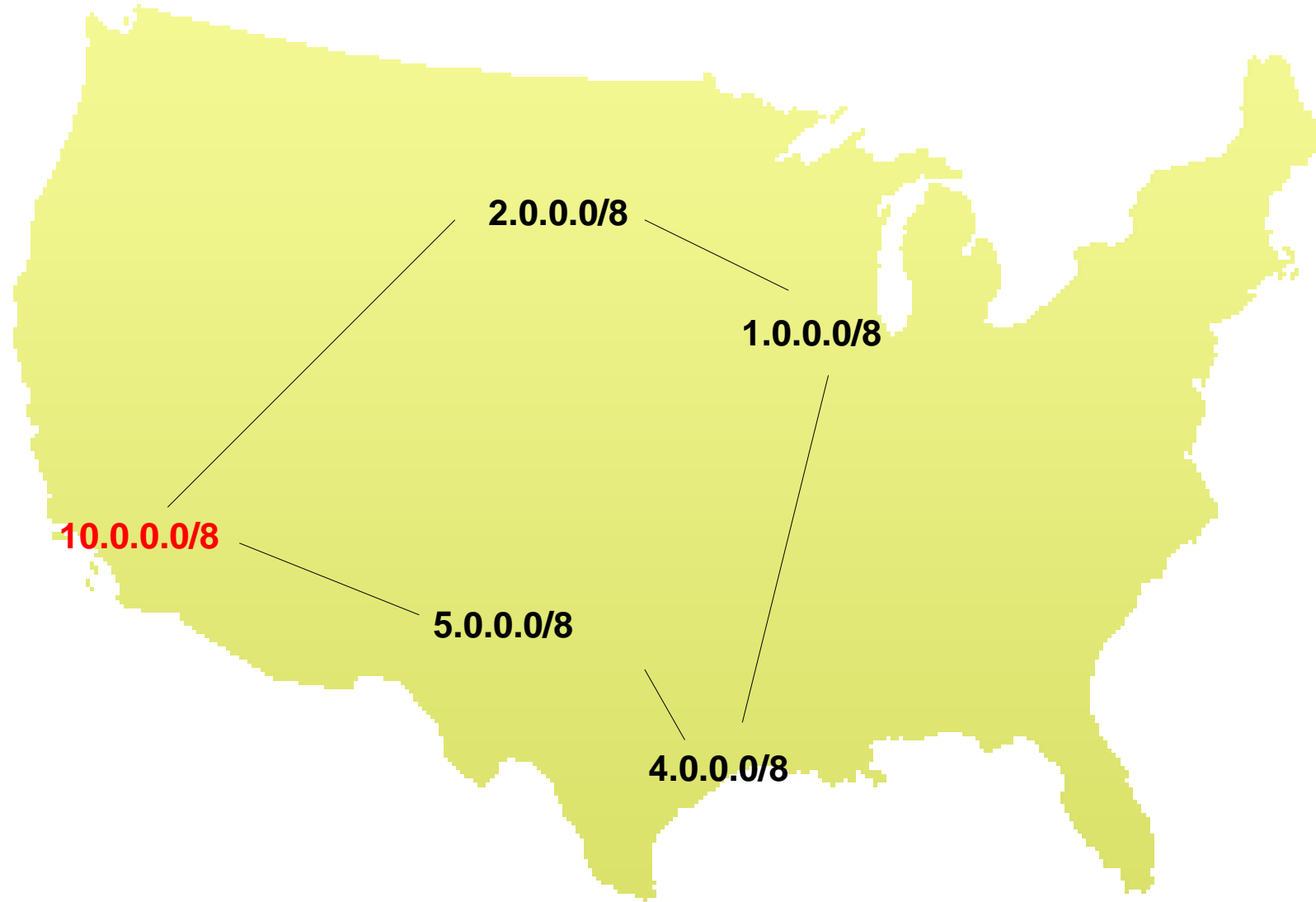
A problem with addressing

- Your computer moves all the time
 - Home, school, Starbucks...

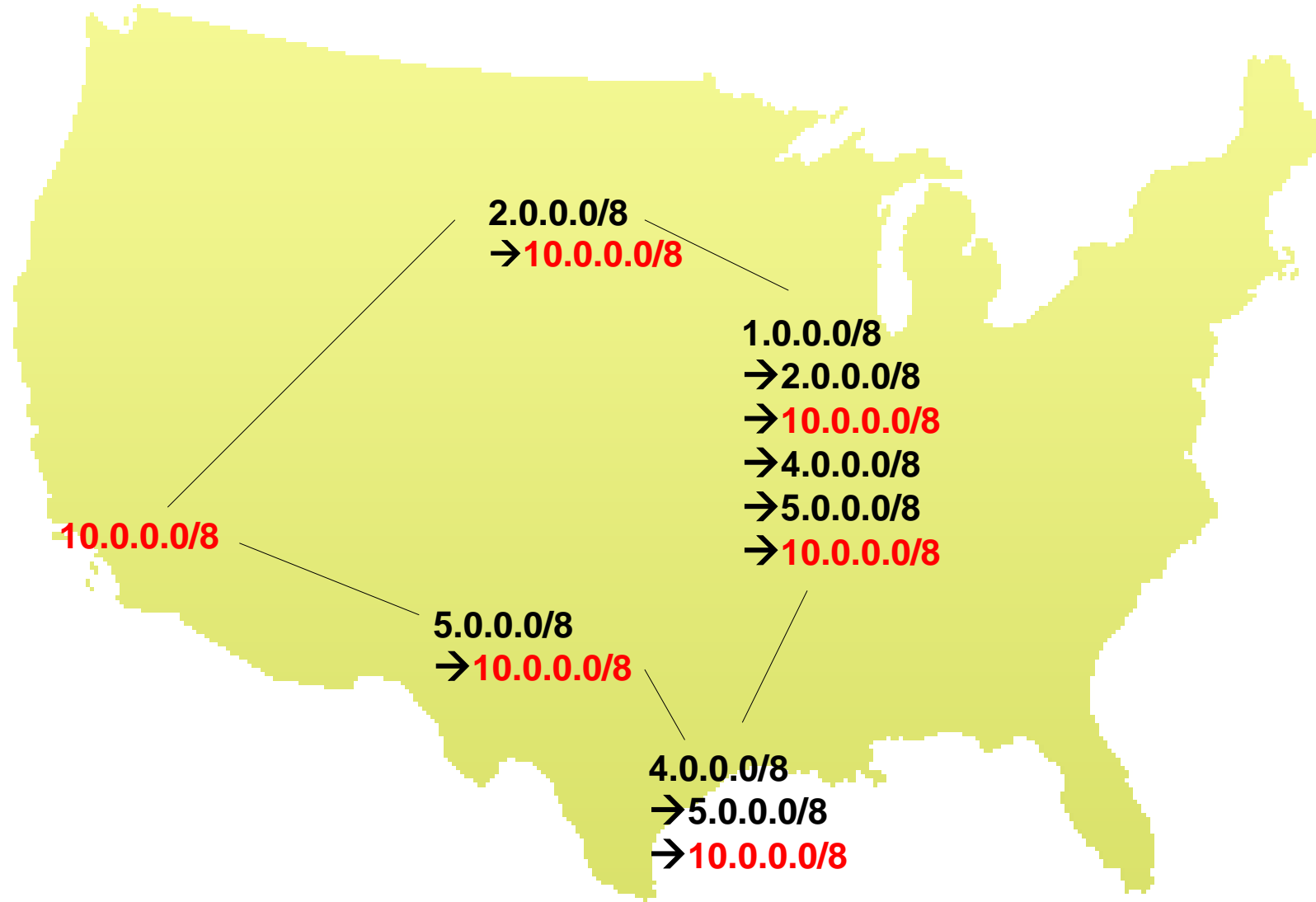
Assigning and finding IP address ranges

- In general, network operators don't change that often
- Solution:
 - Tie IP addresses to network operators
 - Assign computers IPs as they join networks
- Key Point:
 - Networks "own" a block of IP address space
 - "The Internet" is a network of networks

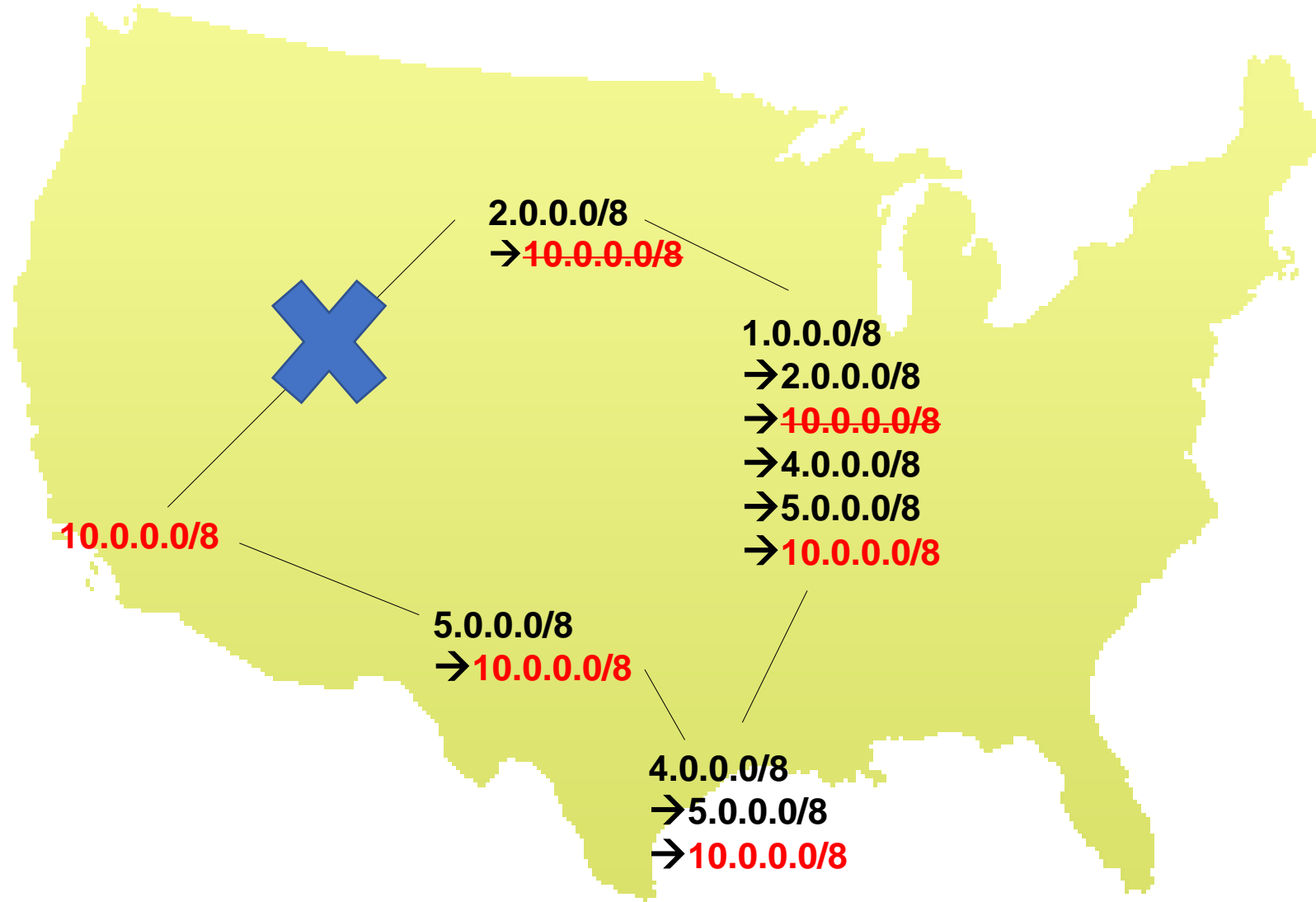
Routing



Routing



Routing Adaptation



Identifying your computer?

- Every network card has its own MAC address
 - IPs are (somewhat) dynamic, "owned" by local networks
 - MACs are hardware and static, "owned" by specific computers
 - Manufacturers own blocks of MACs, "spend" them each time they make a device
- "Connecting" to a network
 - Your computer leases an IP from the local network
 - Only the local router knows your MAC, everyone else sees your IP
 - Note: this overview ignores NATs, which are commonplace today

So how does the Internet of Things fit into the Internet?

- “IP is the Narrow Waist of the Internet”
 - [IP is Dead, Long Live IP for Wireless Sensor Networks](#)
- A recurring theme in this class:
 - How does this actually attach to the Internet
 - Physically, direct IP connection [hello Hue Hub, Wyze Hub, August Hub, ...]
 - Logically, through another device [are BLE devices *really* part of the IoT?]

IP is Dead, Long Live IP for Wireless Sensor Networks

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ABSTRACT

A decade ago an initial sensor network research effort more restricted in its goals obtained the use of IP as an unique and essential element to the success of sensor network research. Since that time the field has matured, standard links have emerged, and IP has evolved. In this paper, we present the design of a concrete IPv6-based network architecture for wireless sensor networks. We validate the architecture with a production-quality implementation that incorporates many techniques pioneered in the sensor network community, including duty-cycled link protocols, router compression, hop-by-hop forwarding, and efficient routing with efficient link estimation. In addition to providing interoperability with existing IP devices, this implementation was able to achieve an average duty cycle of 0.55%, average per-hop latency of 60ms, and a data reception rate of 55.6% over a period of 4 weeks in a real-world home monitoring application where end-nodes generate one application packet per minute. Our results indicate that existing systems that do not adhere to any particular standard or architecture, in light of the demonstration of full IPv6 capability, we believe that the presence of an architecture, specifically an IPv6-based one, provides a strong foundation for various sensor networks going forward.

Categories and Subject Descriptors

C.2.1 [Computer-Communications Networks]: Network Architecture and Design—Wireless communication; C.2.2 [Computer-Communications Networks]: Network Protocols; C.2.3 [Computer-Communications Networks]: Interconnecting—standards

General Terms

Design, Measurement, Performance, Reliability, Security, Standardization

Keywords

network architecture; Internet; Interconnecting; wireless; sensor networks; IPv6; WSN; WSN; WSN; network management

1. INTRODUCTION

As wireless sensor networks (WSNs) research has matured, many researchers in the field agreed that the “narrow waist” of the

known learned that Internet and mobile networks design will be applicable to emerging wireless sensor network applications. ... sensor networks have different security requirements to support monitoring the overall structure of applications and services [13]. The Internet architecture was designed for several reasons including the following [13]:

- The sensor network community may create a new philosophy beyond architecture.
- The sheer numbers of these devices, and their unattended deployment, will probably require the use of a distributed control system to manage the devices and their operation and operation network devices.
- Localized algorithms and network protocols will be required to achieve robustness and scalability.
- Unlike traditional networks, a sensor node may not need an identity (e.g., an address). Naming will be decentralized.
- Traditional networks are designed to accommodate a wide range of applications. WSNs will be tailored to the sensing task at hand.

In addition, it was argued that protocols for all types of WSNs, the traditional Internet and layers of system abstraction should not be assumed [26]. By providing a framework for defining structures and defining the constraints to process, new network abstractions were proposed to emerge [11]. Indeed, by formulating the Active Message Dispatch and the network code through intermediate conceptual levels based on the OS [14] had emerged from the two main areas of protocols developed by the community operating at the link layer, rather than the network layer. The same rationale is a baseline more focused on the use of application level gateway at the top of the WSN, as WSNs were considered to be more similar to 2G, 3G, and USB, rather than an IP network similar to Ethernet or WiFi.

Since these beginnings, the field has matured substantially, a basic collection of protocols have been invented and evaluated, and we have gained experience in how WSNs are used in practice. Over the same period, the Internet has evolved as well. In 1996, RFC 2462 defined IPv6 [12]. The large address space was only prepared for a large number of devices, it obtained many of its architectural constraints. This is what the definition of a unique identifier in RFC 4944 (IPv6 WSN) that control the meaning of IPv6 addresses in sensor networks using small IPv6 (128-bit) short addresses [26]. The IPv6 prefix provided the notion of a subnet. The sensor network was based on IP (IP) discovery, and a network state mechanism used with IPv6 was established with the IPv6 framework and used directly at the core of sensor networks and network devices in a changing environment. Thus, the experience use of options provided for compact headers in the common case,

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Break + Thinking

- What are the steps for viewing a website?

Break + Thinking

- What are the steps for viewing a website?
 1. You enter a domain name for the website
 2. Computer looks up domain name to get IP Address
 3. Computer sends request to IP_address:80
 4. Computer gets back data, which it renders into a website

ALL the layers

- A 'famous' interview question
 - "What happens when you type google.com into your browser's address bar and press enter?"
 - <https://github.com/alex/what-happens-when> (11 pages!)
 - Keyboard events
 - Parsing URL
 - DNS lookup
 - Opening socket
 - HTTP protocol
 - HTML parsing
 - GPU rendering

Outline

- OSI Layers
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- **Physical Layer**
 - **Overview**
 - Signal Strength
 - Signal Frequency and Bandwidth
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Physical Layer

- How bits are transmitted
 - Wireless makes this entirely different from wired cases
- Important considerations
 - Signal strength
 - Modulation
 - Frequency

Why use wireless?

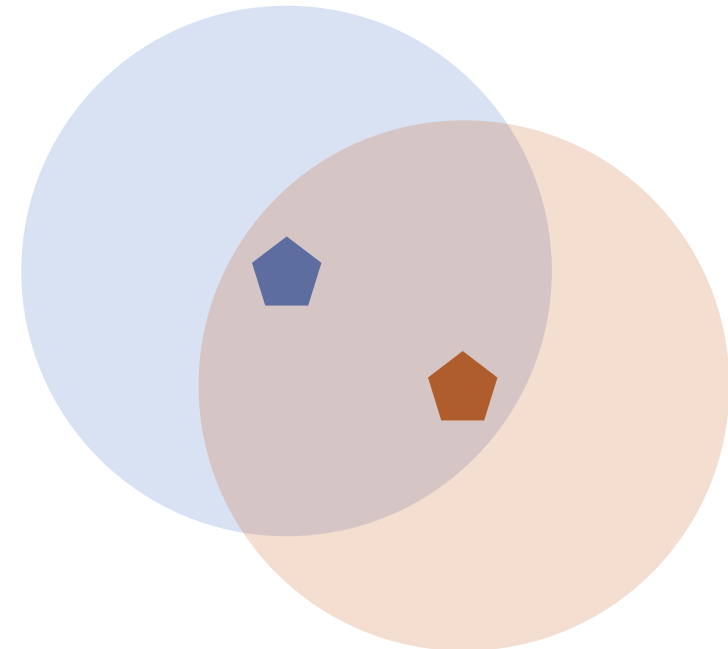
- There are no wires!
- No need to install and maintain wires
 - Reduces cost
 - Simplifies deployment – place devices wherever makes sense
- Supports mobile users
 - Move around office, campus, city
 - Move devices around home

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

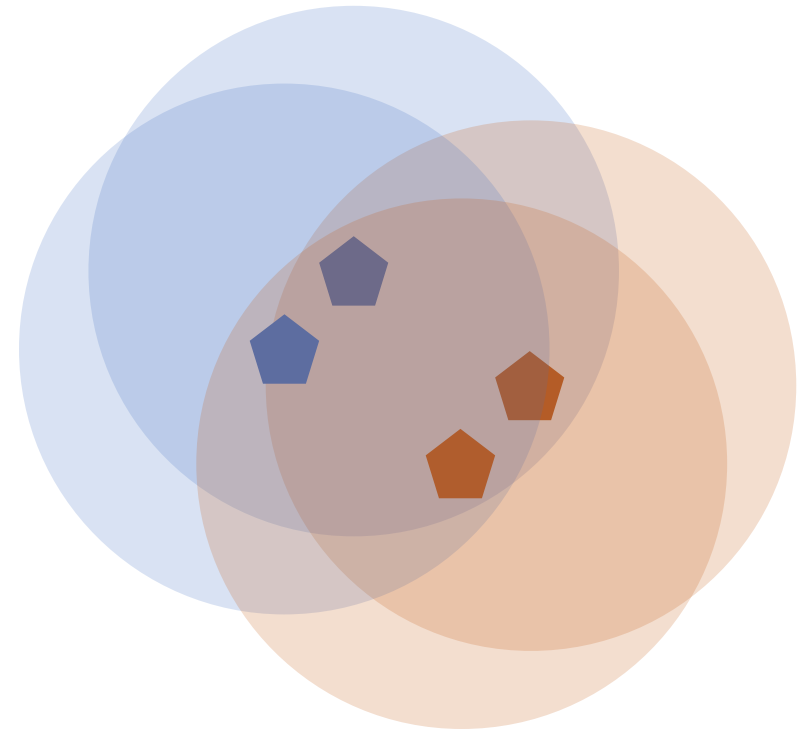
Wireless is a shared medium

- 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



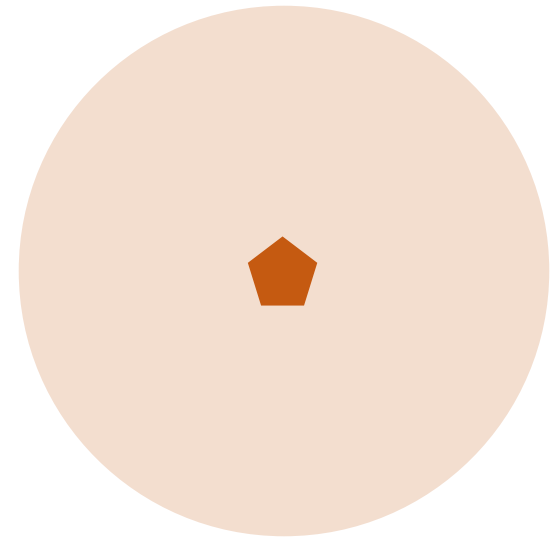
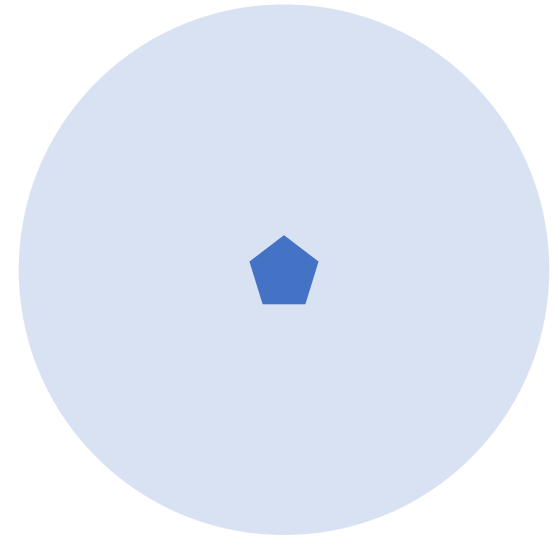
Increasing network capacity is challenging

- 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
- Attenuation with distance
 - Density of energy reduces over time, distance
 - Signal strength is reduced, errors go up
- Two key features
 - Error rates depend on distance
 - Spatial reuse of frequencies



Signal qualities

1. Signal strength

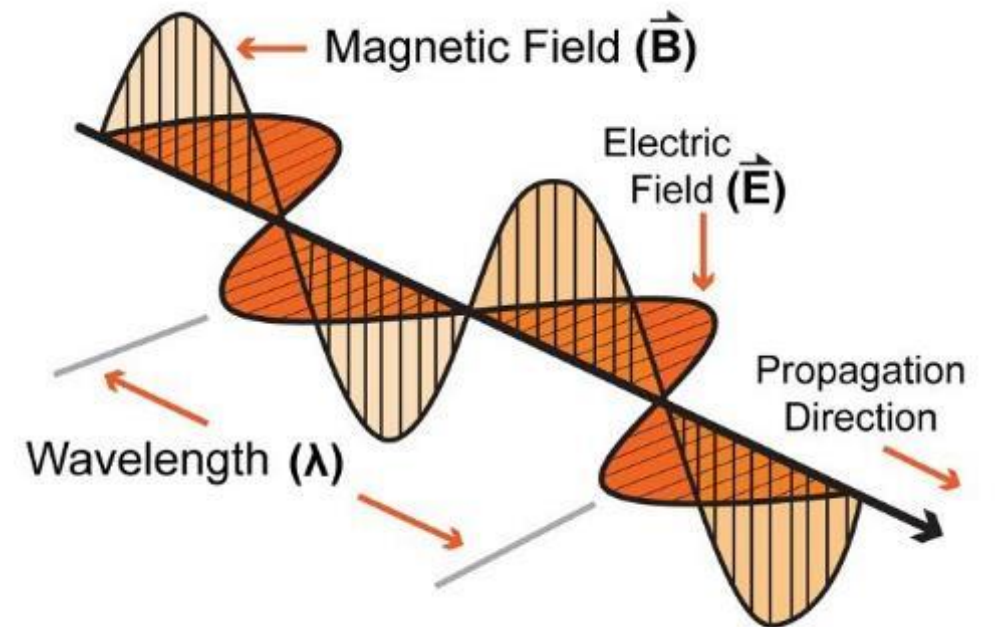
- The amount of energy transmitted/received

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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Signal qualities

1. Signal strength

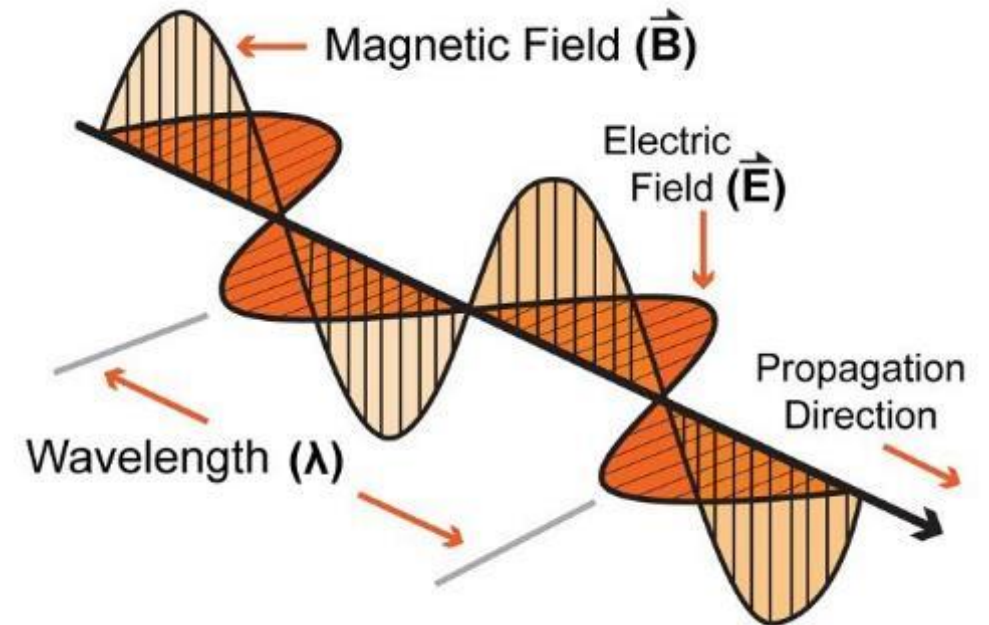
- The amount of energy transmitted/received

2. Signal frequency and bandwidth

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- How data is encoded in the signal



Signal strength is measured in decibels

- Power is measured in Watts or dBw or dBm
 - $Power_{dBw} = 10 * \log_{10}(Power_{Watts})$
 - $Power_{dBm} = 10 * \log_{10}(Power_{milliwatts})$
- dBm is most relevant to the IoT domain
 - 0 dBm equals 1 mW transmit power
 - Example
 - Max BLE transmit power for nRF52840: 8 dBm (6.31 mW)
 - Min BLE receive sensitivity for nRF52840: -95 dBm (316.2 fW)
- Rule of thumb: +3 dB is double the power

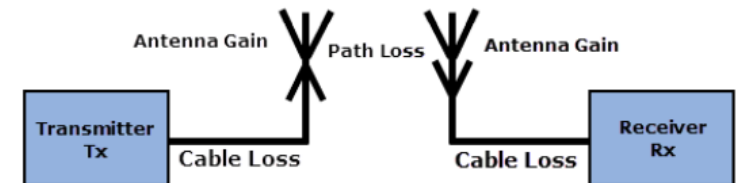
Signal strength varies significantly across technologies

- Bluetooth Low Energy (local area)
 - nRF52840 transmit power: 8 dBm (6.31 mW)
 - nRF52840 receive sensitivity: -95 dBm (316.2 fW)
- LoRa (wide area)
 - SX127X LoRa transmit power: 20 dBm (100 mW)
 - SX127X LoRa receive sensitivity: -148 dBm (1.6 attoWatt)

Propagation degrades RF signals

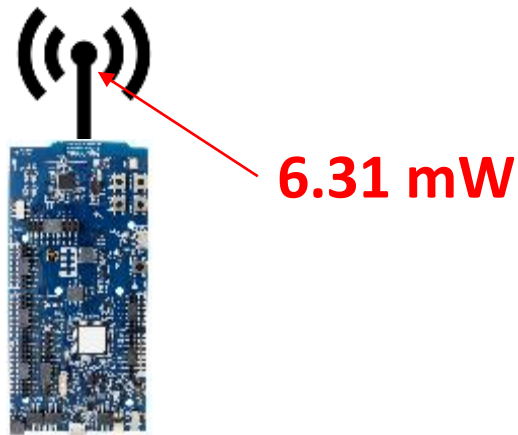
- Attenuation in free space
 - Signals get weaker as they travel over long distances
 - Signal spreads out → Free Space Path Loss (FSPL)

$$FSPL = 20 \log_{10}(d) + 20 \log_{10}(f) + 20 \log_{10}\left(\frac{4\pi}{c}\right) - G_t - G_r$$



Some intuitions for signal propagation, power, gain, etc

- We will use the nrf52840 in lab:
 - Max BLE transmit power for nRF52840: 8 dBm (6.31 mW)
 - Min BLE receive sensitivity for nRF52840: -95 dBm (316.2 fW)



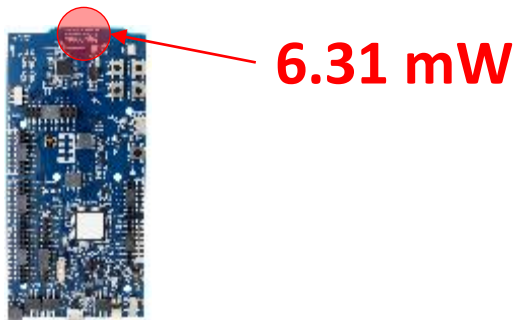
Wait,  is not an antenna

- Indeed, this little strip of metal is the actual antenna
 - Receiver only recovers the part of the signal that hits its antenna (“aperture”)



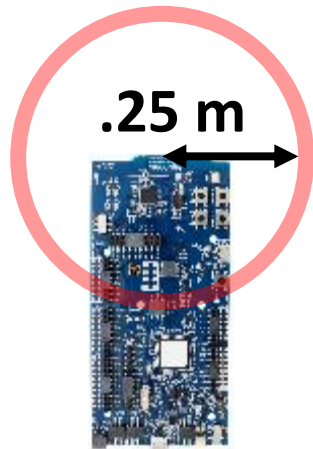
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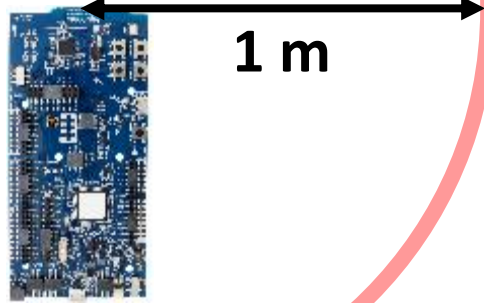
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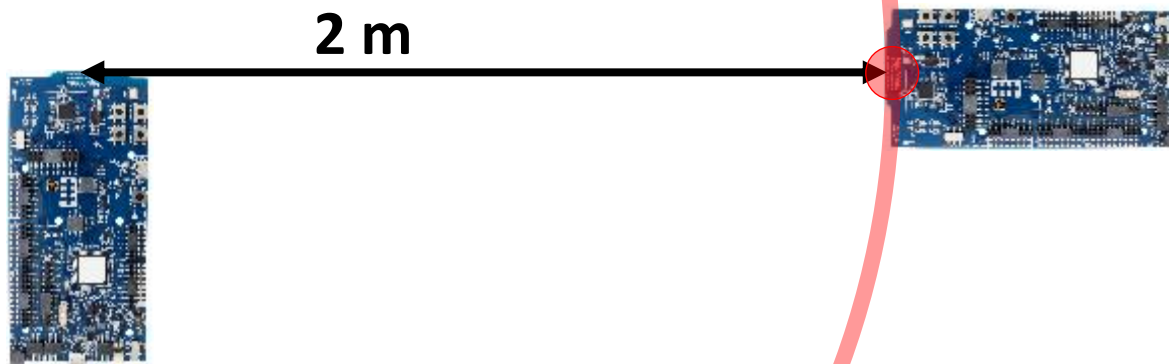
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Some Intuitions for Signal Propagation, Power, Gain, etc.

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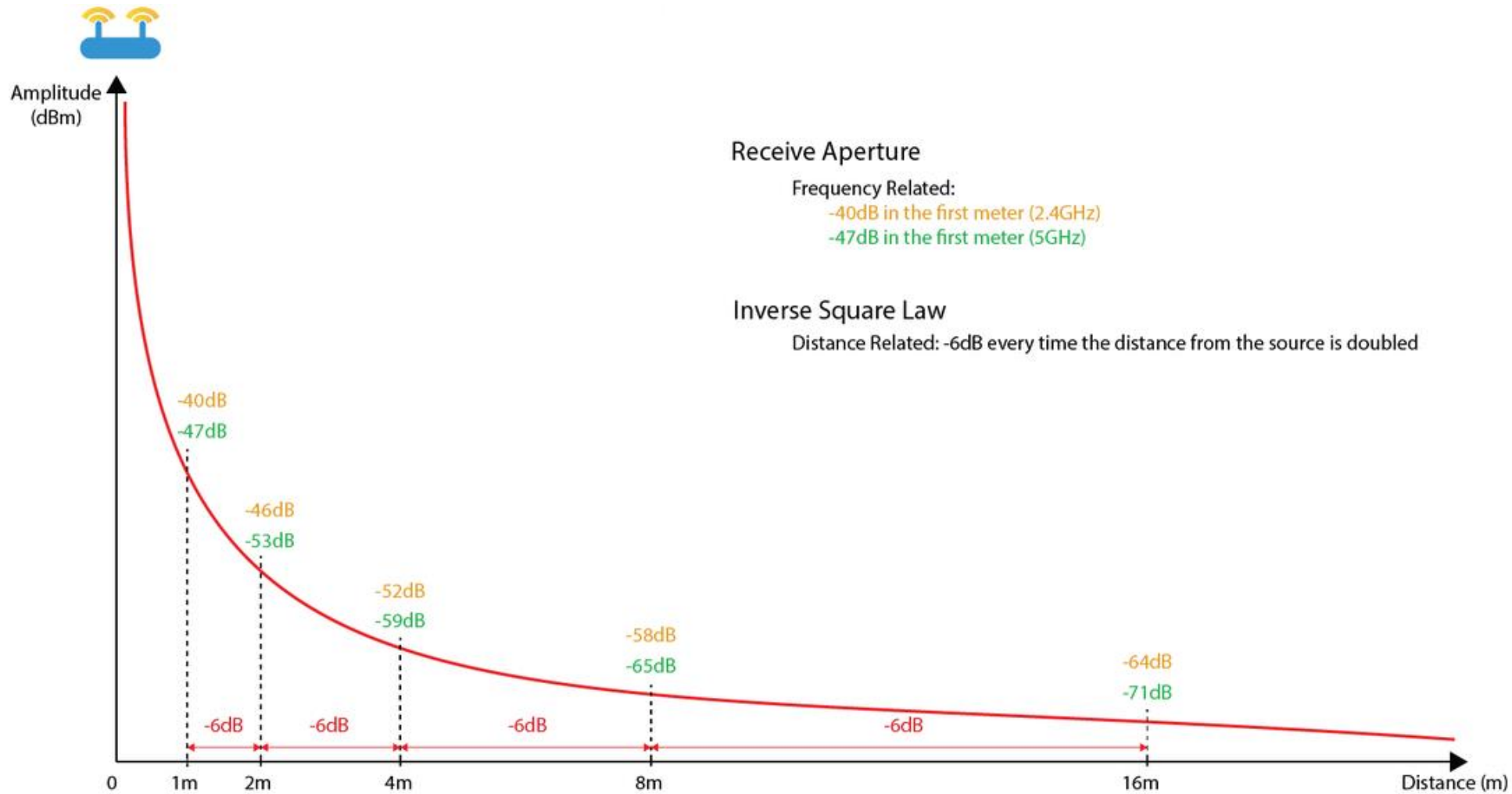


Okay.. So what's the limit?

- We will use the nrf52840 in lab:
 - Max BLE transmit power for nRF52840: 8 dBm (6.31 mW)
 - Min BLE receive sensitivity for nRF52840: -95 dBm (316.2 fW)
- $8 \text{ dBm} - -95 \text{ dBm} = 103 \text{ dB}$ link margin
- For FSPL alone for a 2.4 GHz signal, 103 dB is 1,400 m!

Bluetooth does not go 1.4 km...

Free-Space Path Loss Model



Propagation is *one thing* that degrades RF signals

- Attenuation in free space
 - Signals get weaker as they travel over long distances
 - Signal spreads out -> free space path loss
- Important: distance is NOT the only signal strength loss
 - Free space path loss calculation will not give you accurate range for a signal
- Obstacles can weaken signal through absorption or reflection
 - Precise quantitative details are in the EE domain
 - We'll use examples to develop qualitative instincts in this class

ITU model for Indoor Attenuation

$$L = 20 \log_{10} f + N \log_{10} d + P_f(n) - 28$$

where,

L = the total path loss. Unit: decibel (dB).

f = Frequency of transmission. Unit: megahertz(MHz).

d = Distance. Unit: meter (m).

N = The distance power loss coefficient.

n = Number of floors between the transmitter and receiver.

$P_f(n)$ = the floor loss penetration factor.

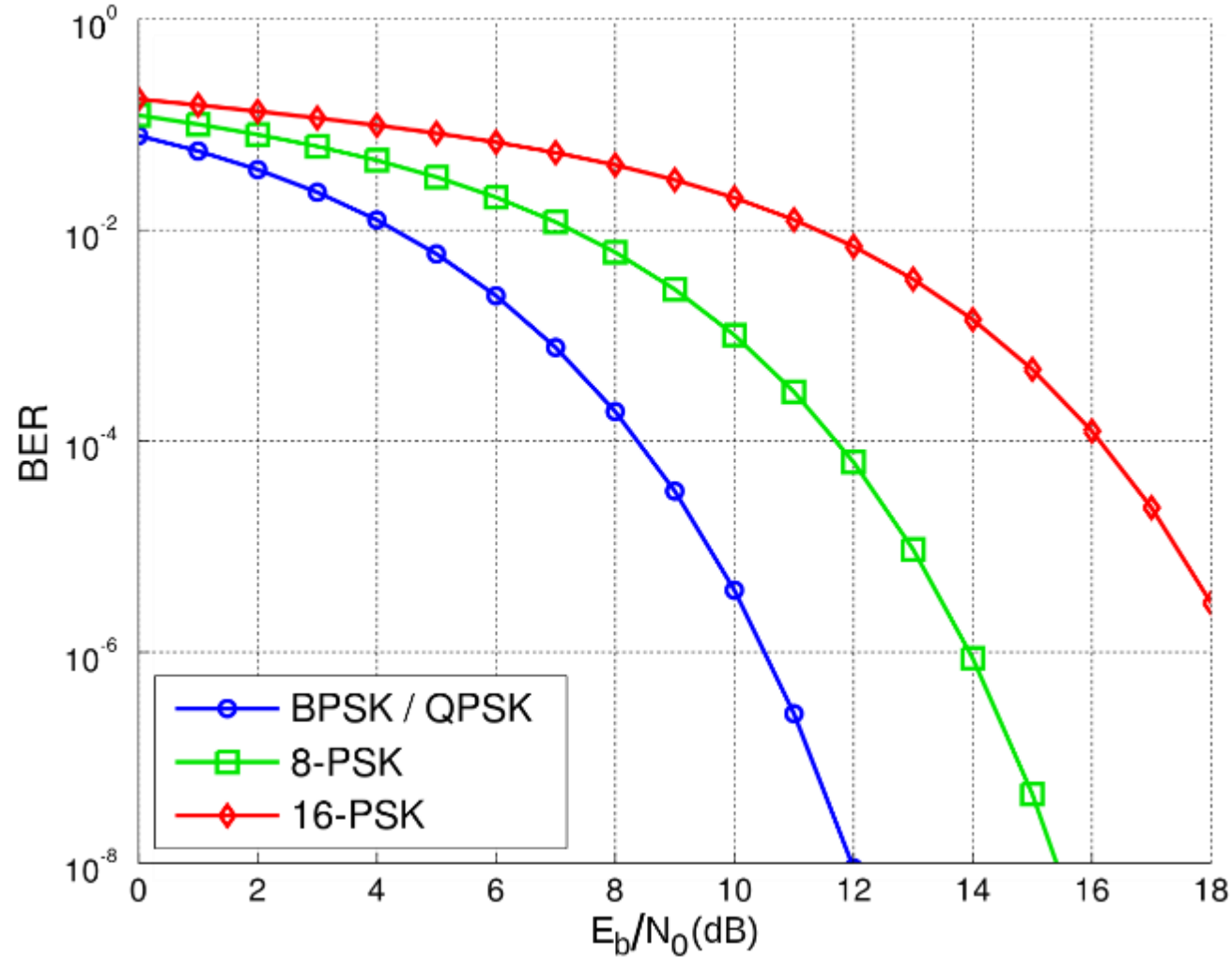
- Models like this are ~~more trustworthy~~ *less bad* than Free-Space Path Loss
 - https://en.wikipedia.org/wiki/ITU_model_for_indoor_attenuation

Lower received energy increases error rates

More Errors



Less Errors



BER:
Bit Error Rate

Odds that a transmitted bit will be received incorrectly

Less Energy Received



More Energy Received

Big Idea: many RF factors are interconnected

- Energy, Distance, Throughput, and Reliability are all interconnected in communication
- Protocols make choices of some and get the results on the others
- To get more distance, choose one or more:
 - Increase energy
 - Communicate slower
 - Accept a higher error rate

Break + Say hi to your neighbors

- Things to share
 - Name
 - Major
 - One of the following
 - Favorite Candy
 - Favorite Pokemon
 - Favorite Emoji

Break + Say hi to your neighbors

- Things to share
 - Name -Branden
 - Major -EE, CE, and CS
 - One of the following
 - Favorite Candy - Twix
 - Favorite Pokemon - Eevee
 - Favorite Emoji - 🍷

Outline

- OSI Layers
- Internet Architecture (Upper Layers)
- **Physical Layer**
 - Overview
 - Signal Strength
 - **Signal Frequency and Bandwidth**
 - Signal Modulation

Signal qualities

1. Signal strength

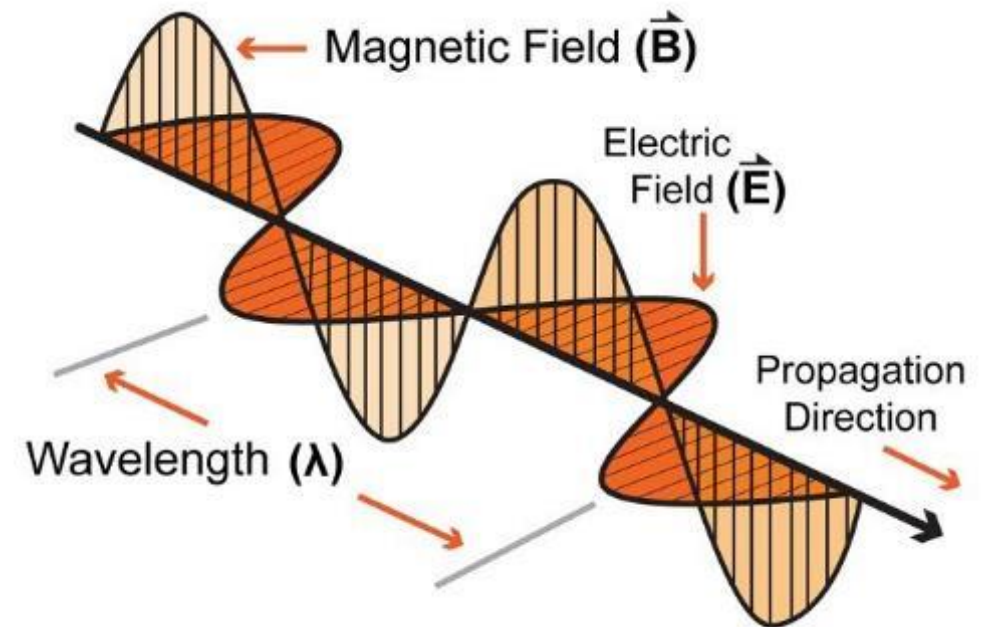
- The amount of energy transmitted/received

2. Signal frequency and bandwidth

- Which "channel" the signal is sent on

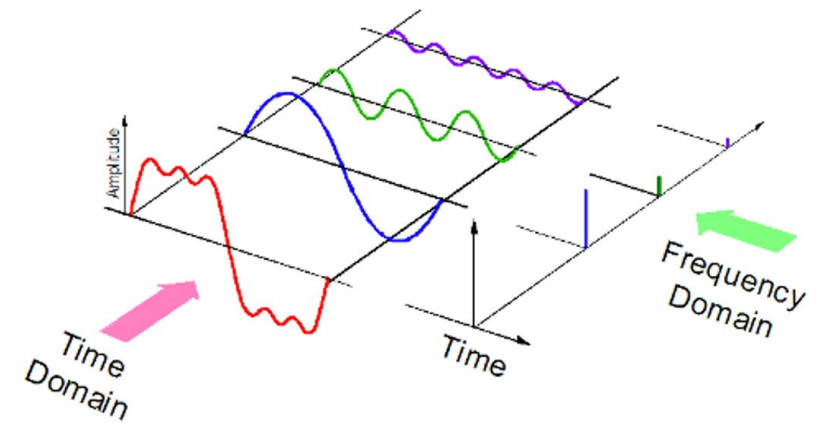
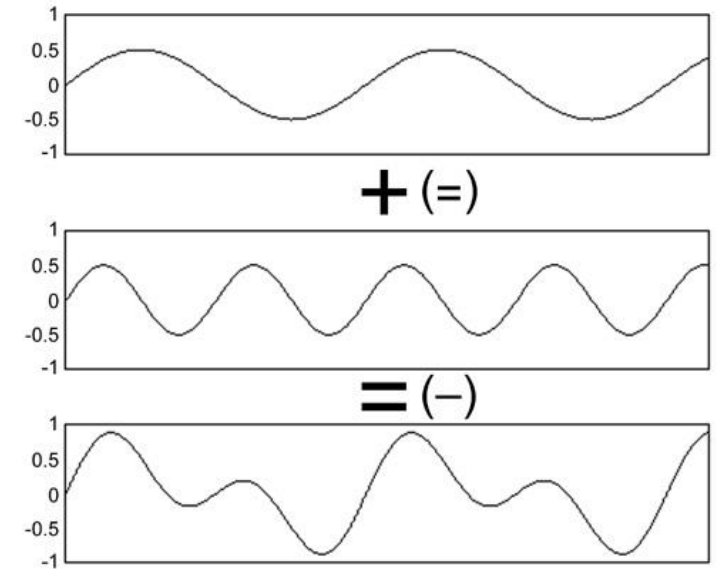
3. Signal modulation

- How data is encoded in the signal



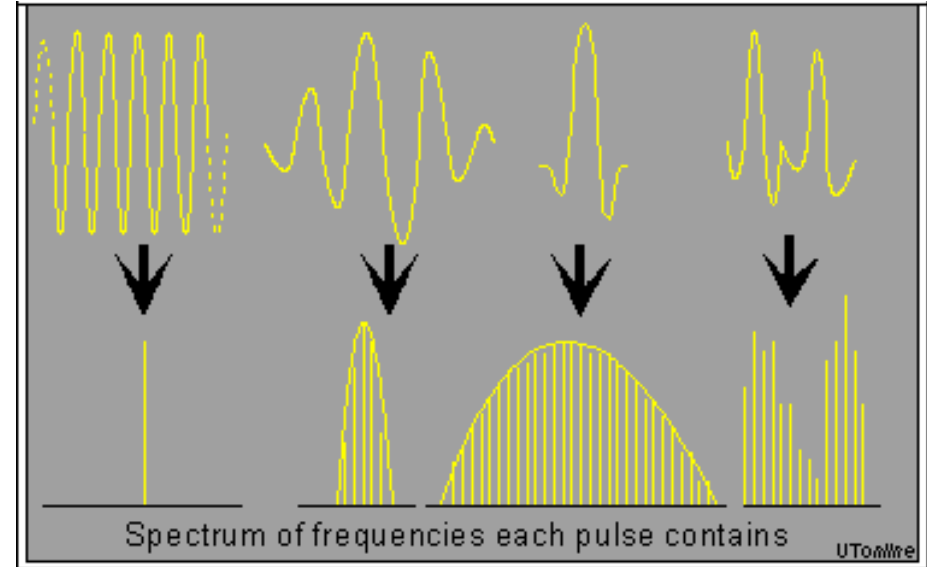
Sum of sinusoids can be reversed

- RF signals are fundamentally sinusoids of electromagnetic energy
- Sinusoids at different frequencies can be combined and pulled apart again later
 - Particularly, it's relatively easy for hardware to determine if there's energy present on a given frequency
 - Although very close frequencies might be difficult to disentangle



Complex waveforms have a center frequency and a width

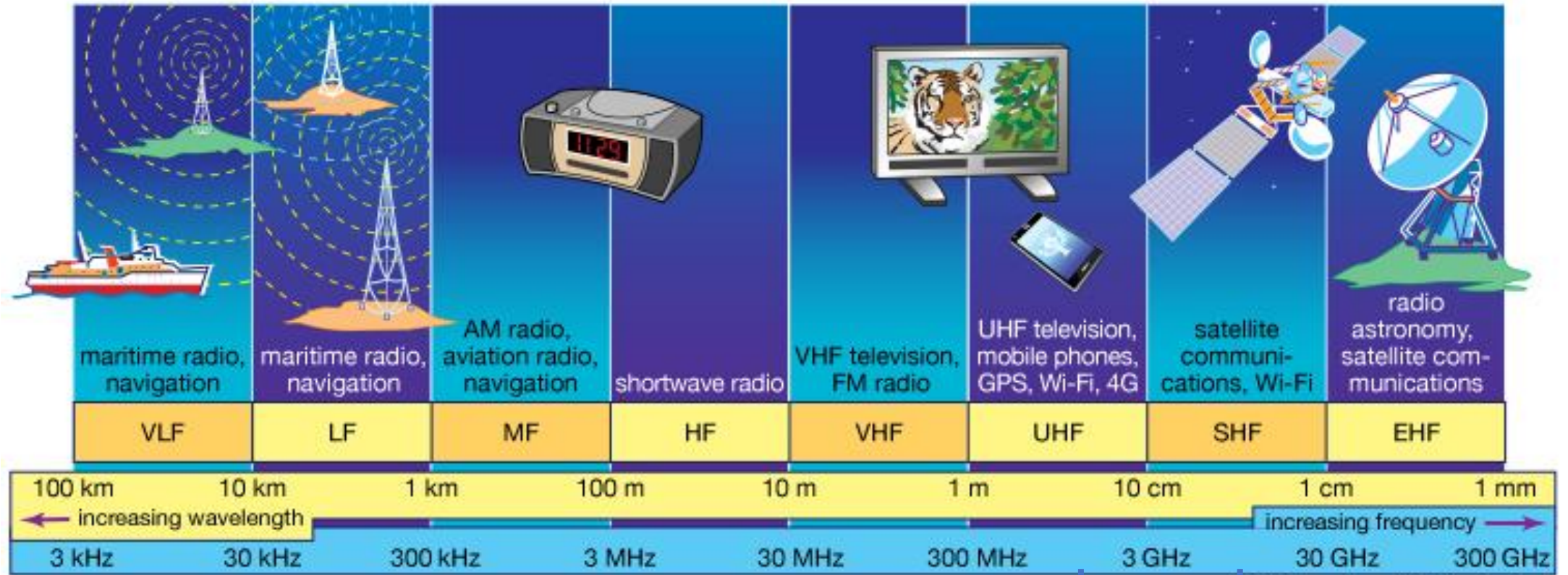
- A pure sinusoid is energy at exactly one frequency
- A messy sinusoid with data layered on top of it has nearby energy
 - There's a center of the signal energy
 - Plus some amount of width, which depends on how complicated the data layered on top is



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 \pm 100 kHz
 - Ranges from 87.6 to 87.8
- Second station is 87.9 MHz \pm 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 frequencies



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IoT focus

Wireless spectrum is allocated to specific uses

UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

AERONAUTICAL MOBILE	BROADCASTING	RADIO AMATEUR
AERONAUTICAL MOBILE SATELLITE	LAND MOBILE	AERONAUTICAL MOBILE SATELLITE
AERONAUTICAL MOBILE SATELLITE	LAND MOBILE SATELLITE	RADIOLOCATION
JOINT USE	MARITIME MOBILE	RADIOLOCATION SATELLITE
AERONAUTICAL SATELLITE	MARITIME MOBILE SATELLITE	RADIOLOCATION
BROADCASTING	MARITIME RADIOLOCATION	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

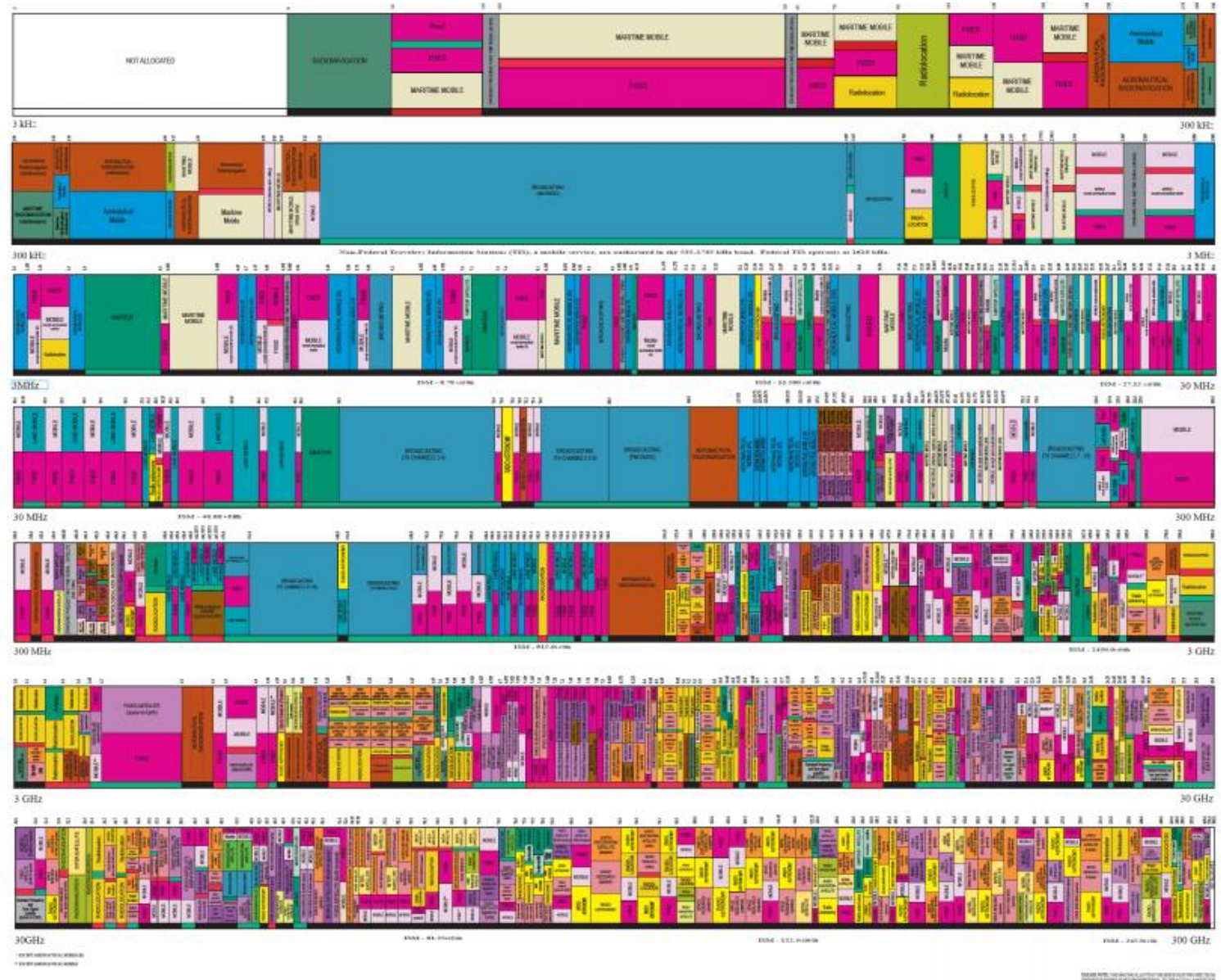
GOVERNMENT USE ONLY	GOVERNMENT-ASSIGNED USES
NON-GOVERNMENT USE ONLY	

ALLOCATION USAGE DESIGNATION

OFFICE	EXAMPLE	DESCRIPTION
Primary	STSD	Land Lines
Secondary	SM	Land Mobile

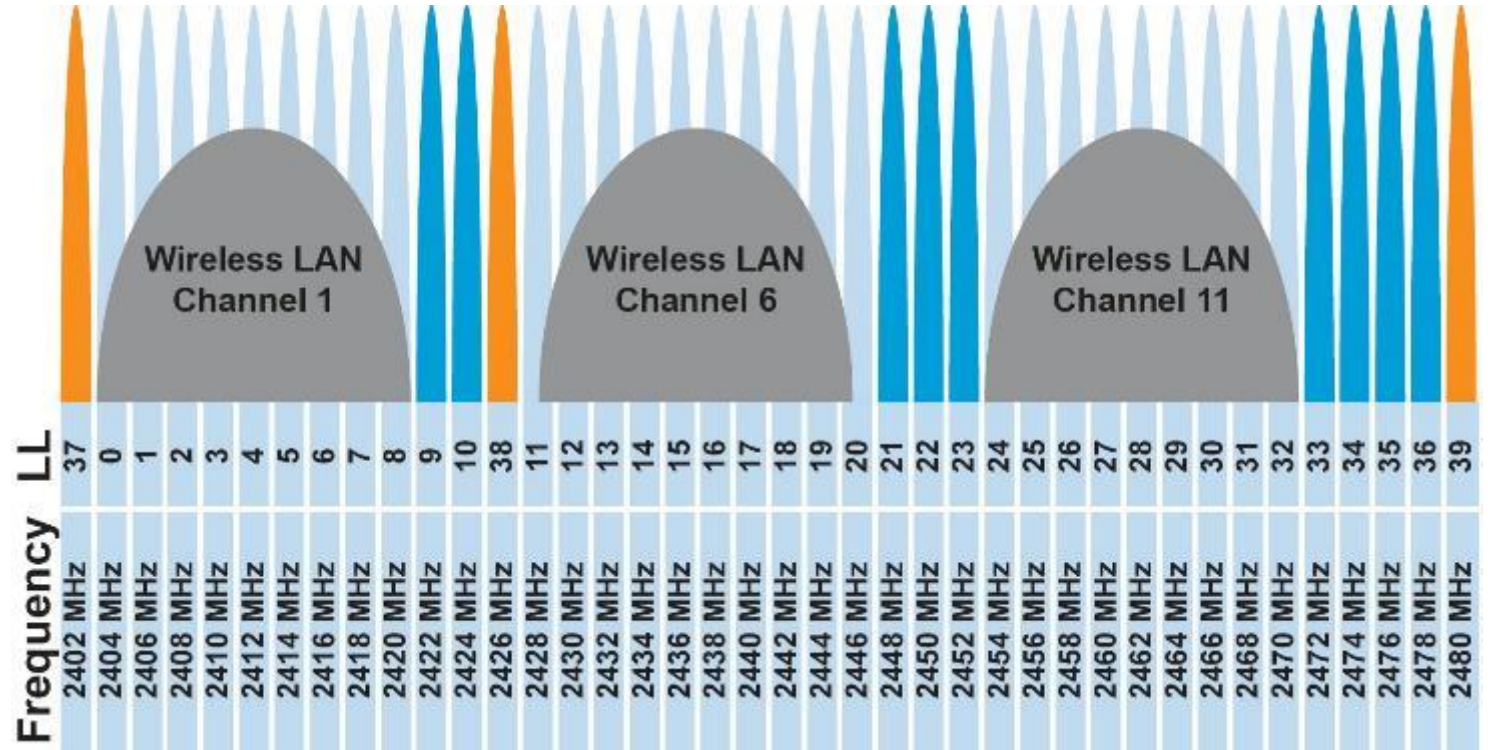
The radio spectrum information presented in this chart is derived from the Federal Communications Commission's (FCC) and the International Telecommunications Union's (ITU) radio frequency allocation tables. It is not intended to be a substitute for the actual regulations governing the use of the radio spectrum. 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



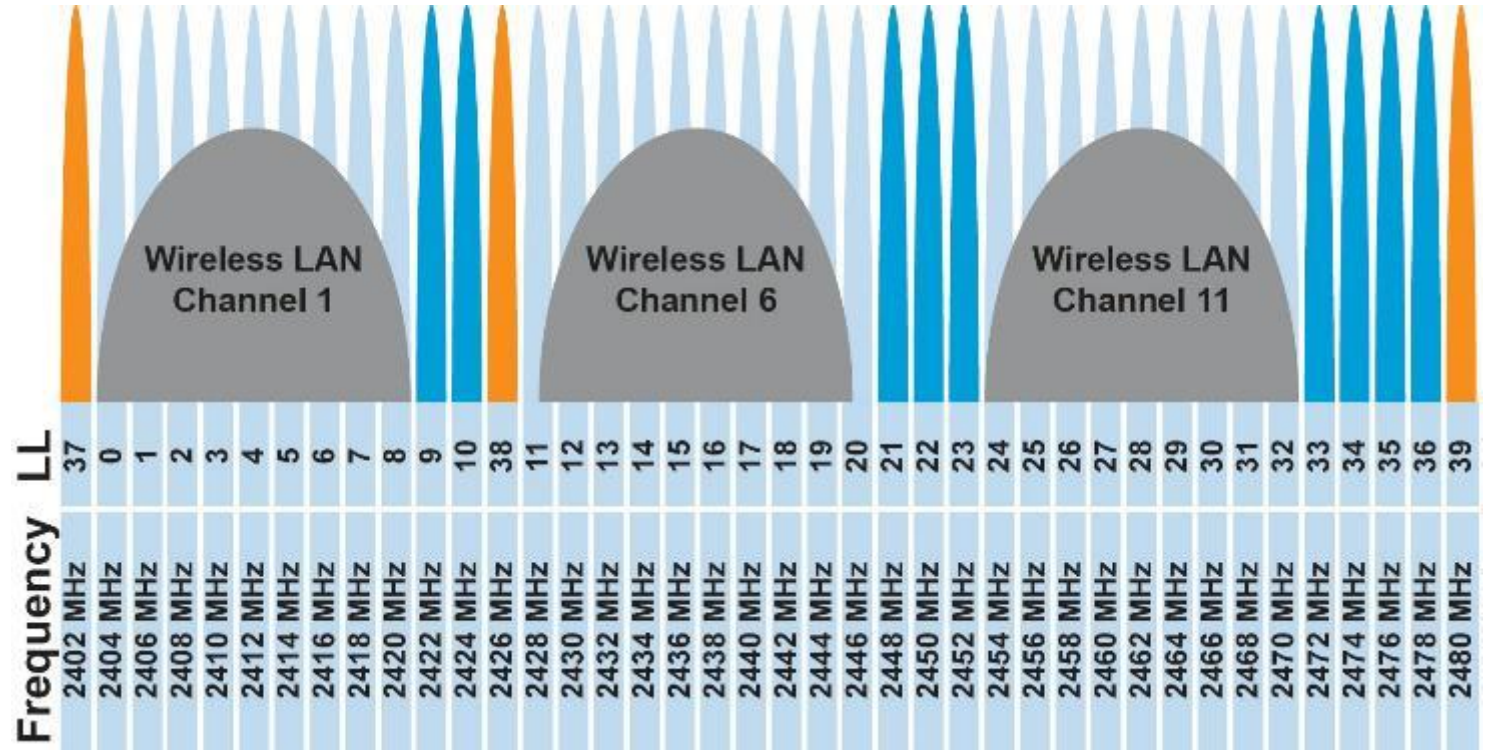
Unlicensed bands are where IoT thrives

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



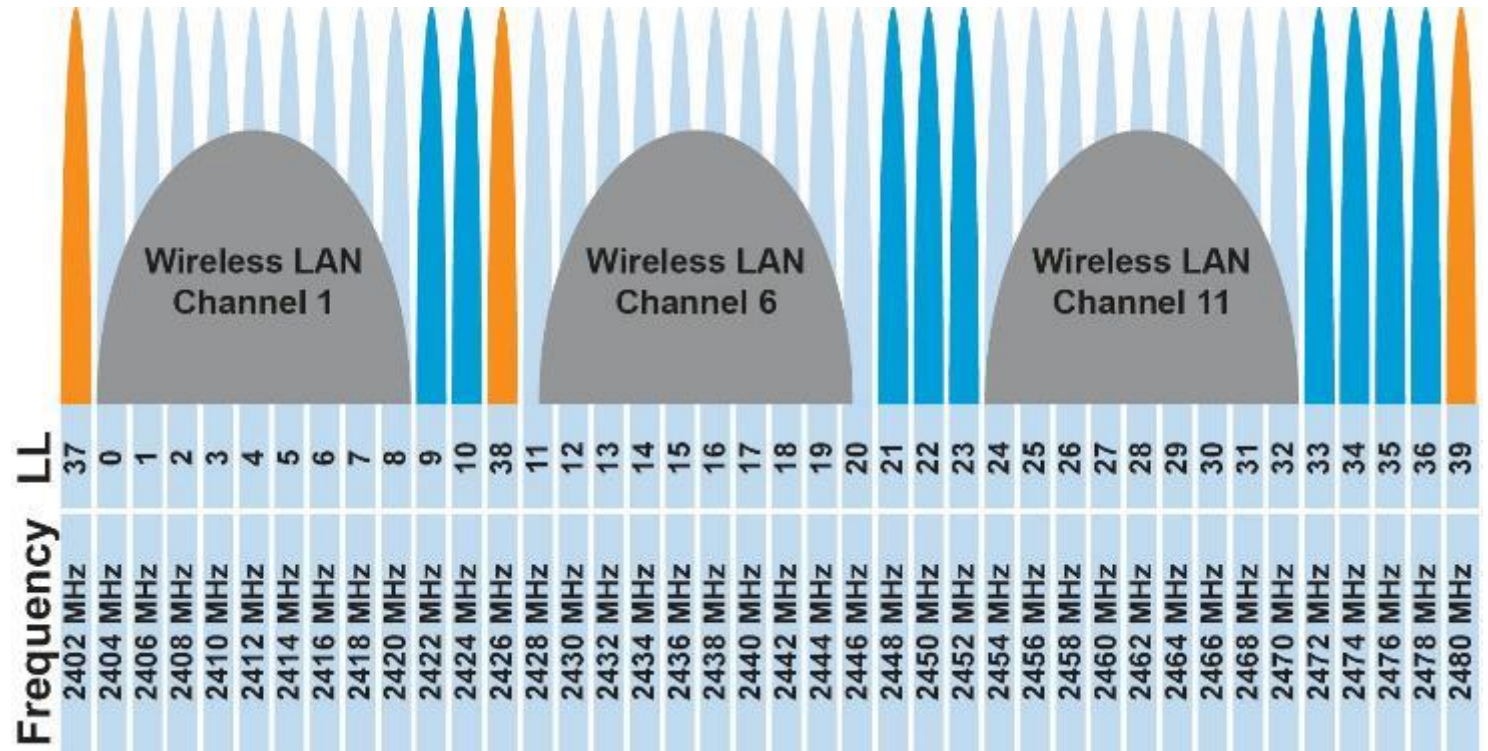
Unlicensed bands are where IoT thrives

- 902 MHz – 928 MHz
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- 2.4 GHz to 2.5 GHz
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- 5 GHz
 - Faster WiFi
- Cellular uses licensed bands at great cost
 - **Why?**

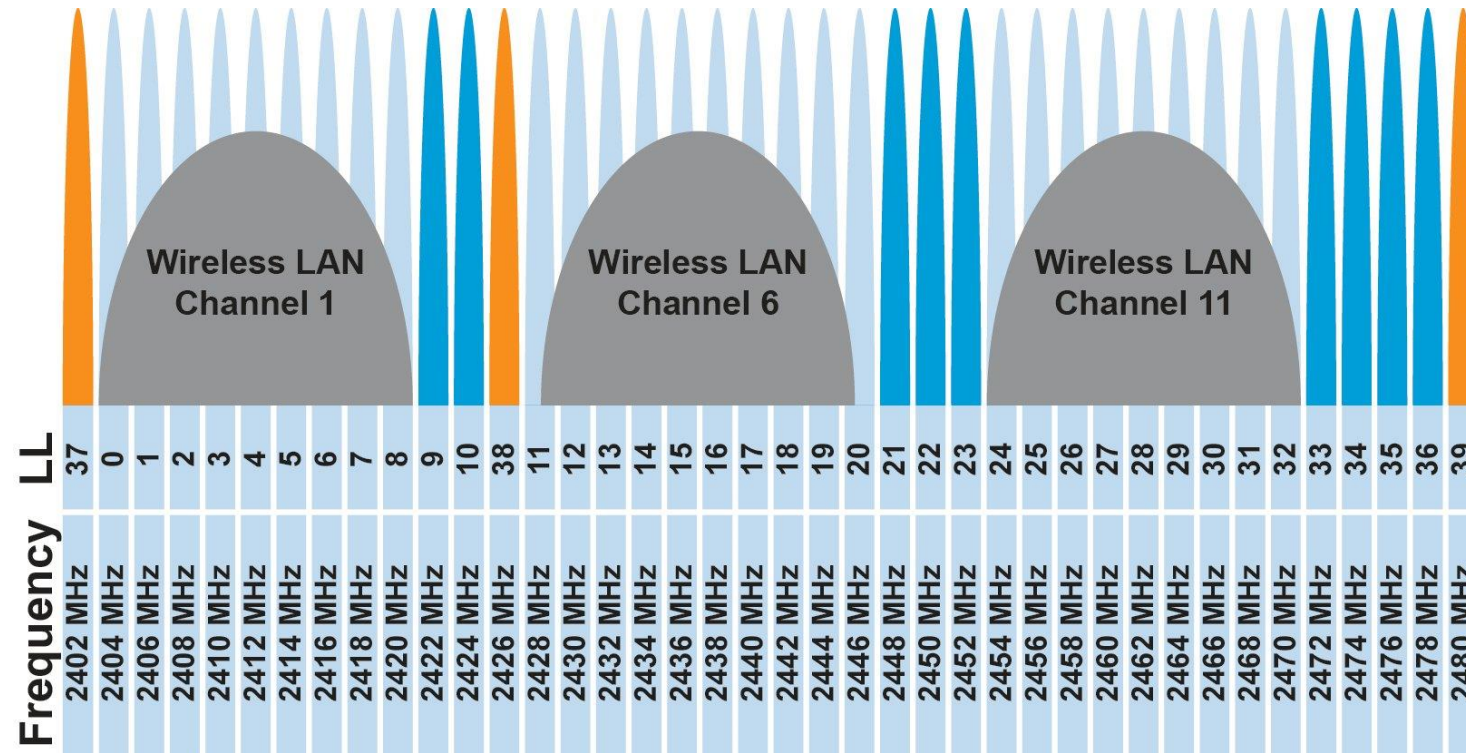


Unlicensed bands are where IoT thrives

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



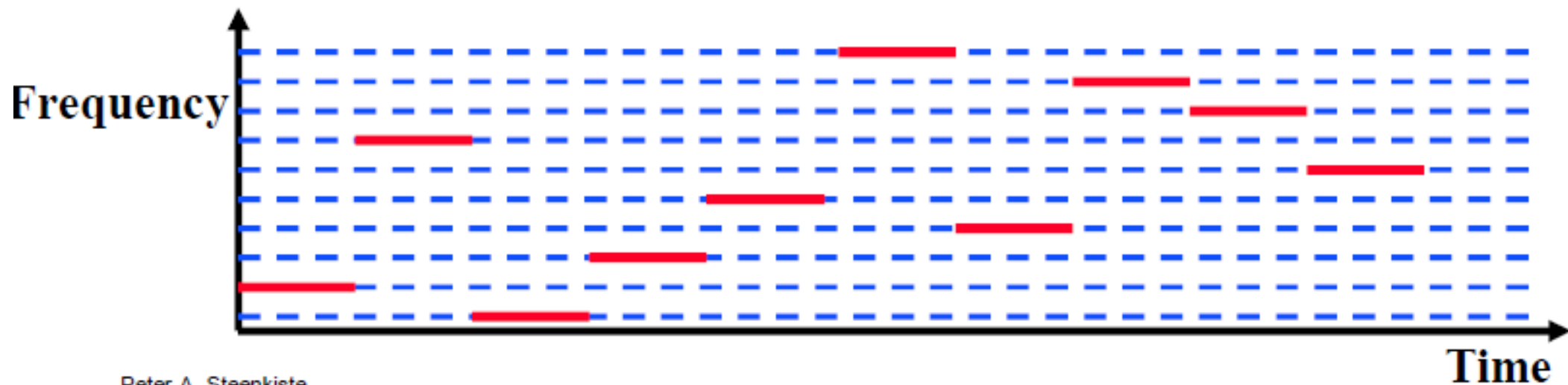
Different technologies use spectrum in different ways



- How spectrum is used affects: cost (\$), robustness, throughput...
 - We will talk about how each technology uses spectrum, and implications
- This graphic shows how BLE and WiFi interoperate; more on this next week

Frequency Hopping Spread Spectrum

- Transmitter hops through a sequence of transmit channels
 - Spend some "dwell time" on each channel before hopping again
 - Receiver must know the hopping pattern
- Avoid causing or receiving prolonged interference



Peter A. Steenkiste

Sidebar: inventor of FHSS – Hedy Lamarr

- Actress, inventor, and all-around badass
 - Designed FHSS with George Antheil during WWII based on music ideas
 - Idea: torpedo control can't be easily jammed if it jumps around

- https://en.wikipedia.org/wiki/Hedy_Lamarr#Inventing_career

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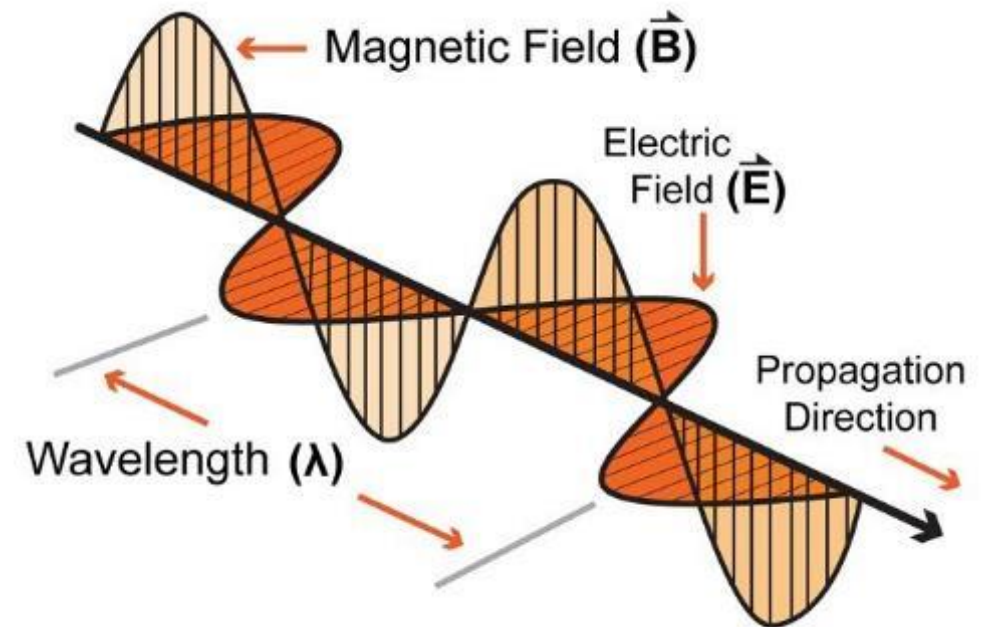
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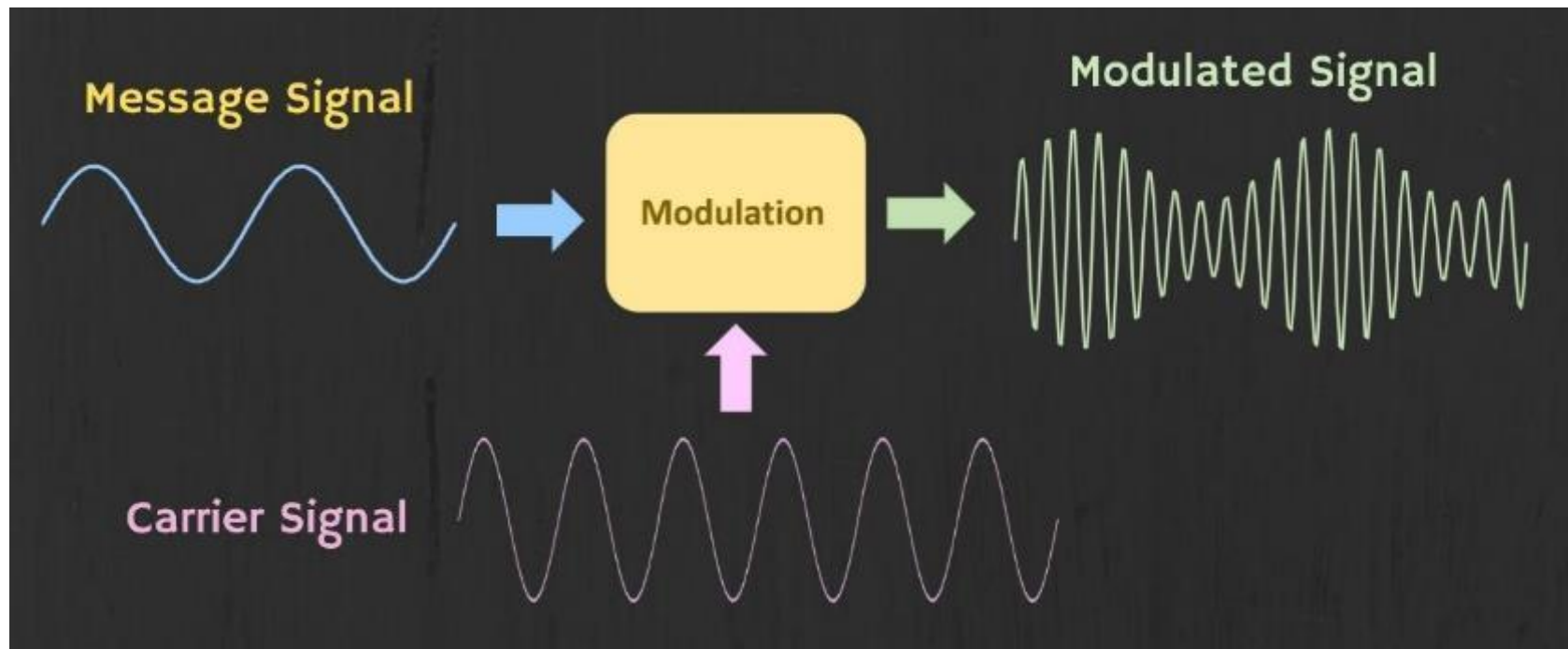
3. Signal modulation

- How data is encoded in the signal



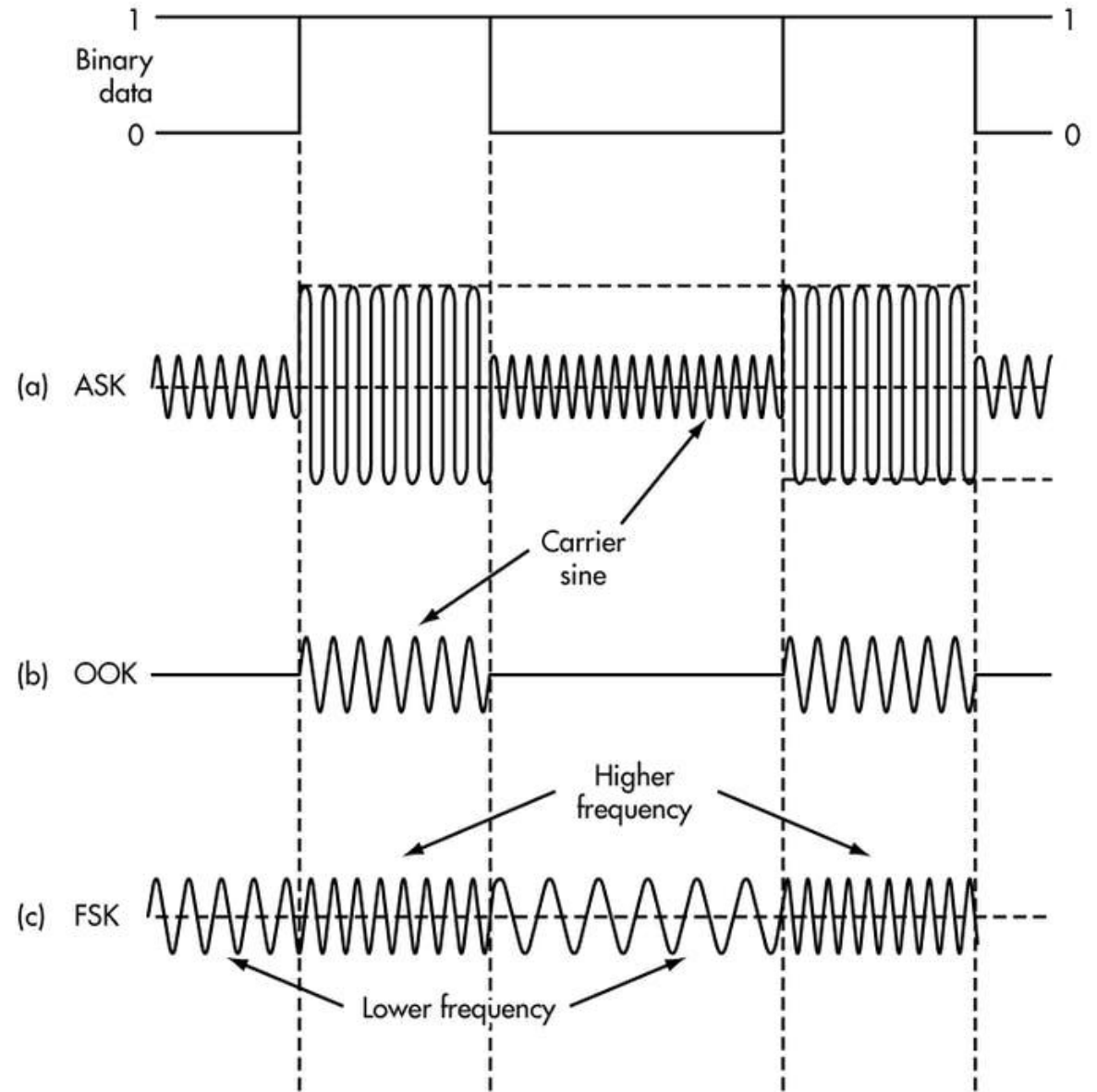
Modulation

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



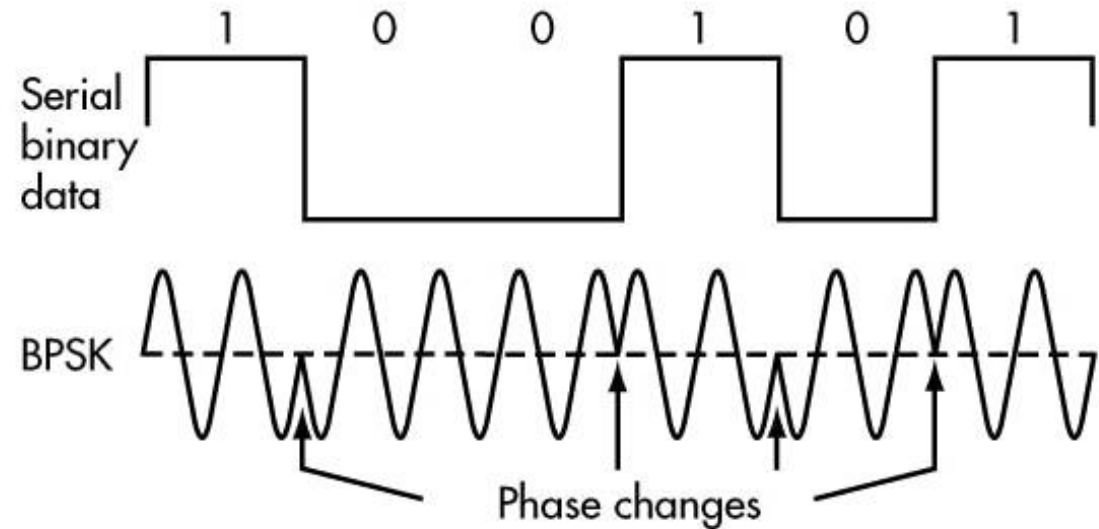
Modulation types

- 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
 - Usually 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"

Modulation tradeoffs

- Various tradeoffs between different modulation schemes
 - Bandwidth requirements, transceiver hardware, immunity to noise, etc.
- ASK (amplitude) is simple but susceptible to noise
 - Noise exists in the real world
- FSK (frequency) is relatively simple and robust to noise, but uses more bandwidth
 - Bandwidth is limited, but still commonly used
- PSK (phase) energy efficient and robust, but more complex hardware
 - More expensive hardware, but very commonly used

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