

Lecture 02

Network Fundamentals

CS397/497 – Wireless Protocols for IoT
Branden Ghen a – Spring 2022

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

Materials in collaboration
with Pat Pannuto (UCSD)

Administrivia

- Campuswire
 - Everyone should have access to it
 - If you don't, this is the exception when you should email me
- Canvas
 - Most important information is on the Canvas homepage
 - I'm posting slides there too

Today's Goals

- Introduce OSI layer model of communication
- Provide background on Internet layering
- Overview of concerns for the Physical and Data link layers
 - Speak the “lingo” of wireless communication
 - Present technology aspects that we will return to in specific protocols
- Describe Medium Access Control mechanisms

Outline

- **OSI Layers**
- Internet Architecture (Upper Layers)
- Physical Layer
- Data Link Layer

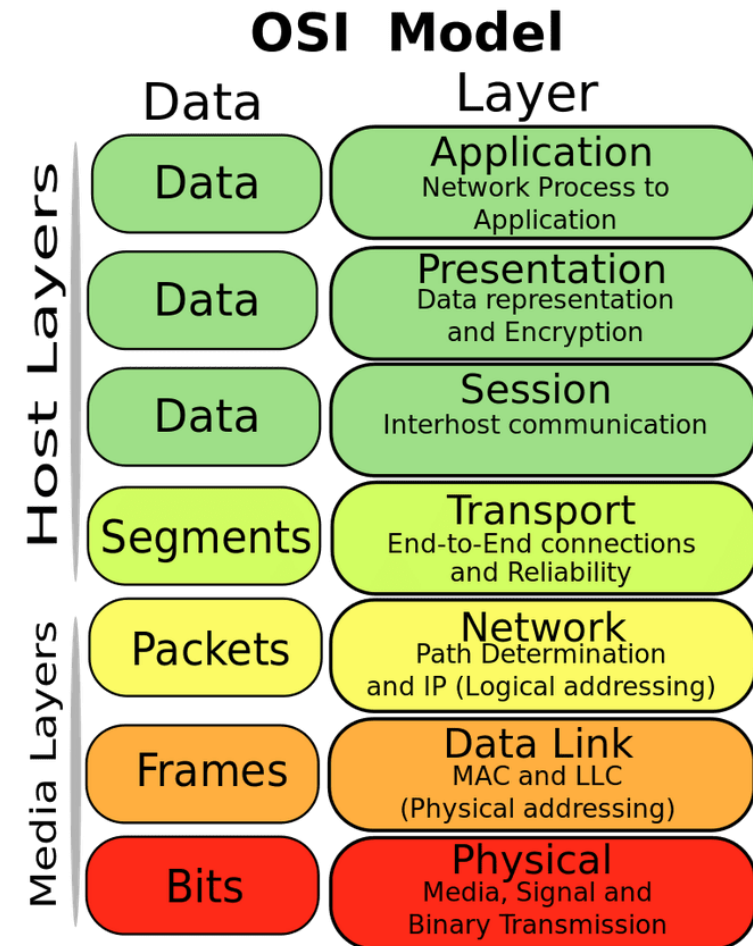
Communication layers

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

What goes on at each of these?

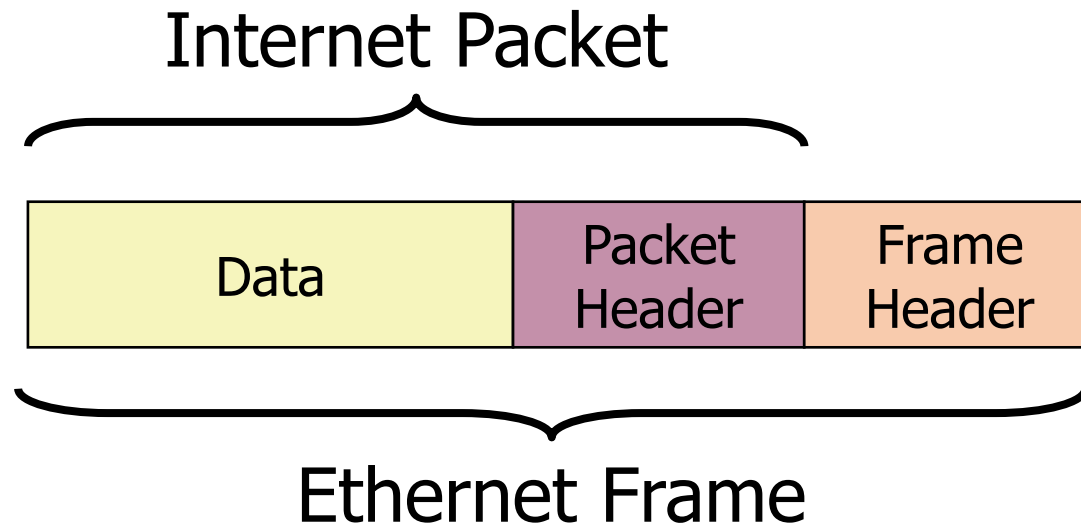
OSI model of communication layers

- Transport
 - How to form connections between computers
 - TCP and UDP
 - CS domain: CS340
- Network
 - How to send packets between networks
 - IP
 - CS domain: CS340
- Data Link
 - How to send frames of data
 - Ethernet, WiFi
 - **Our primary focus** (but we go up & down)
- Physical
 - How to send individual bits
 - Ethernet, WiFi
 - EE domain: EE307, EE380, EE395



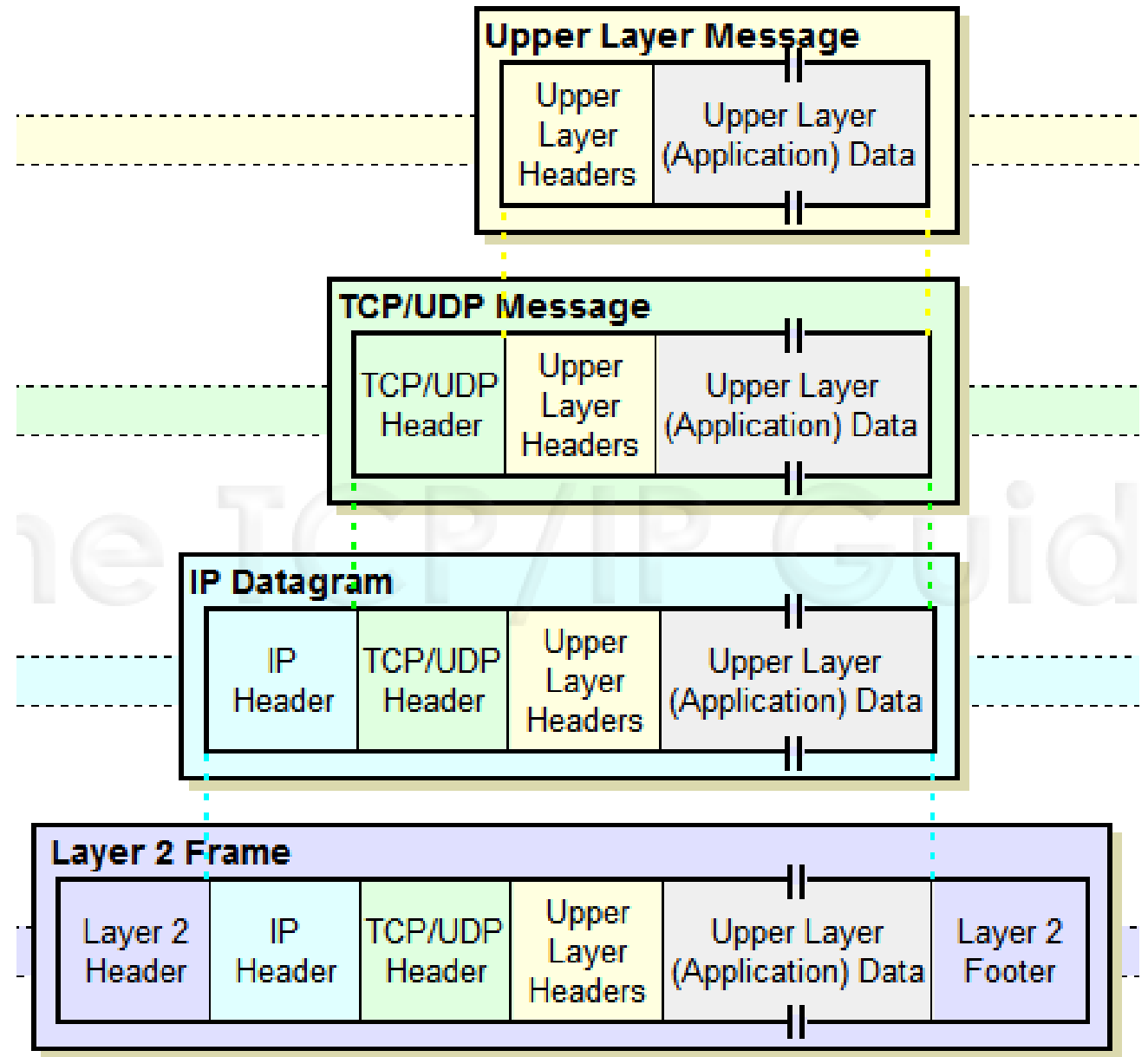
Protocols are “layered”

- Headers for each layer of communication wrap data
 - Data is wrapped with header for the network to make a packet
 - Packet is wrapped with header for the link to make a frame

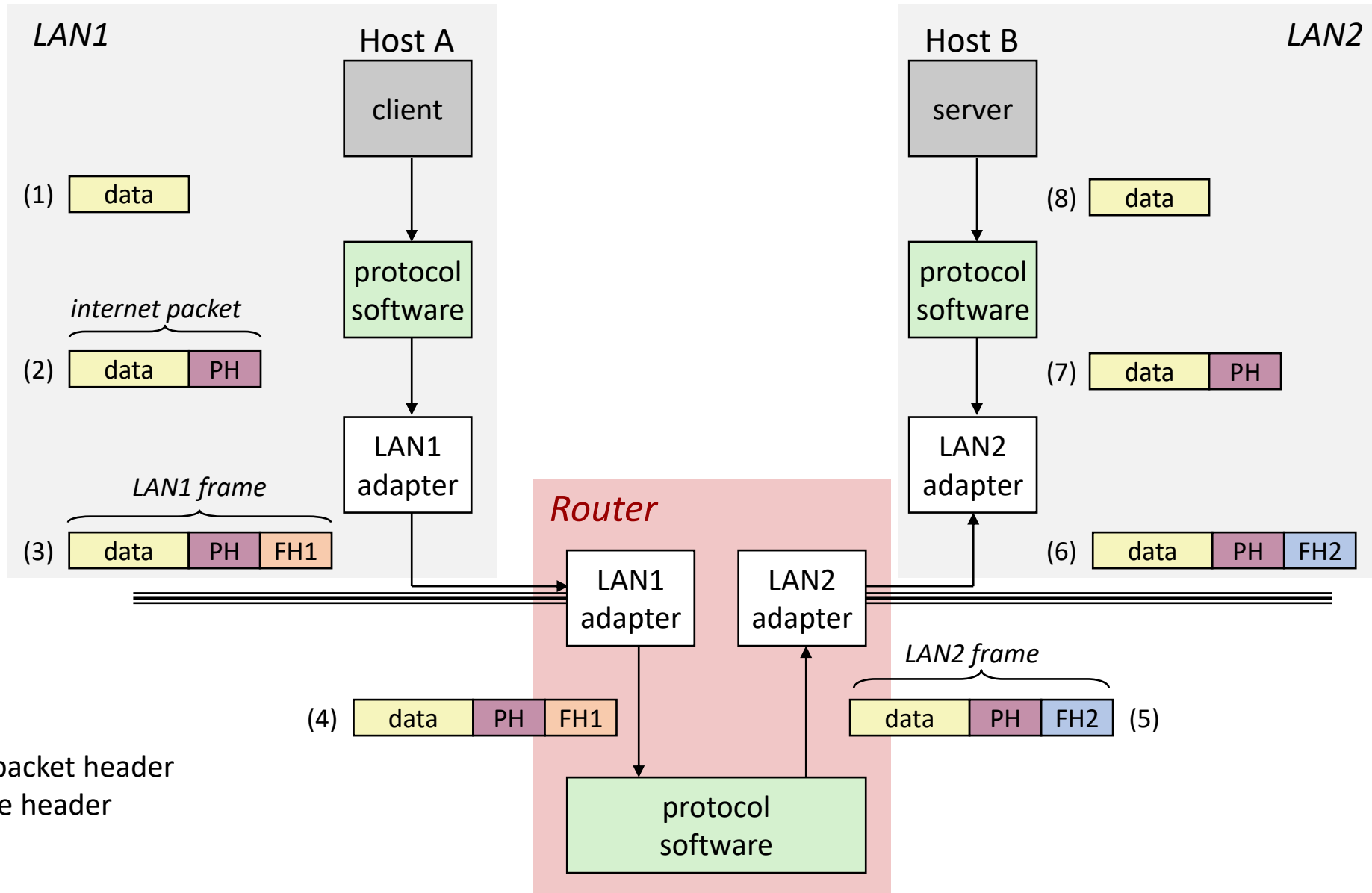


Packet encapsulation

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

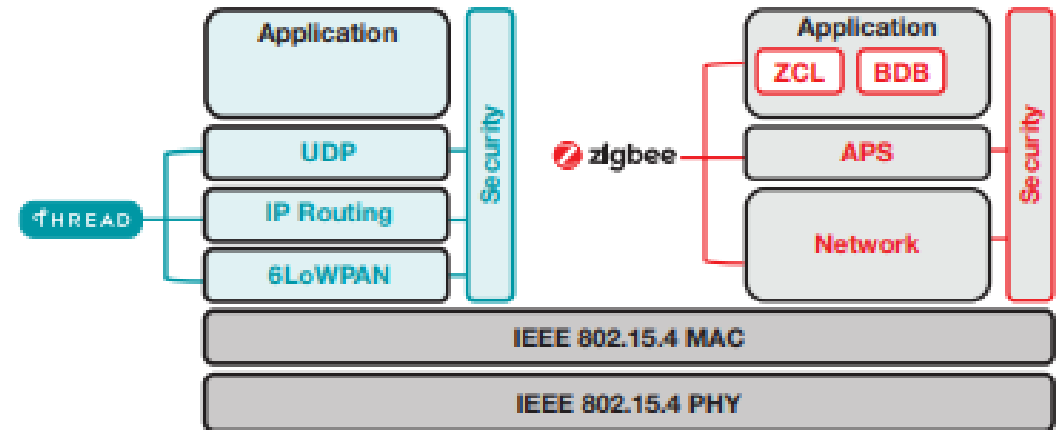
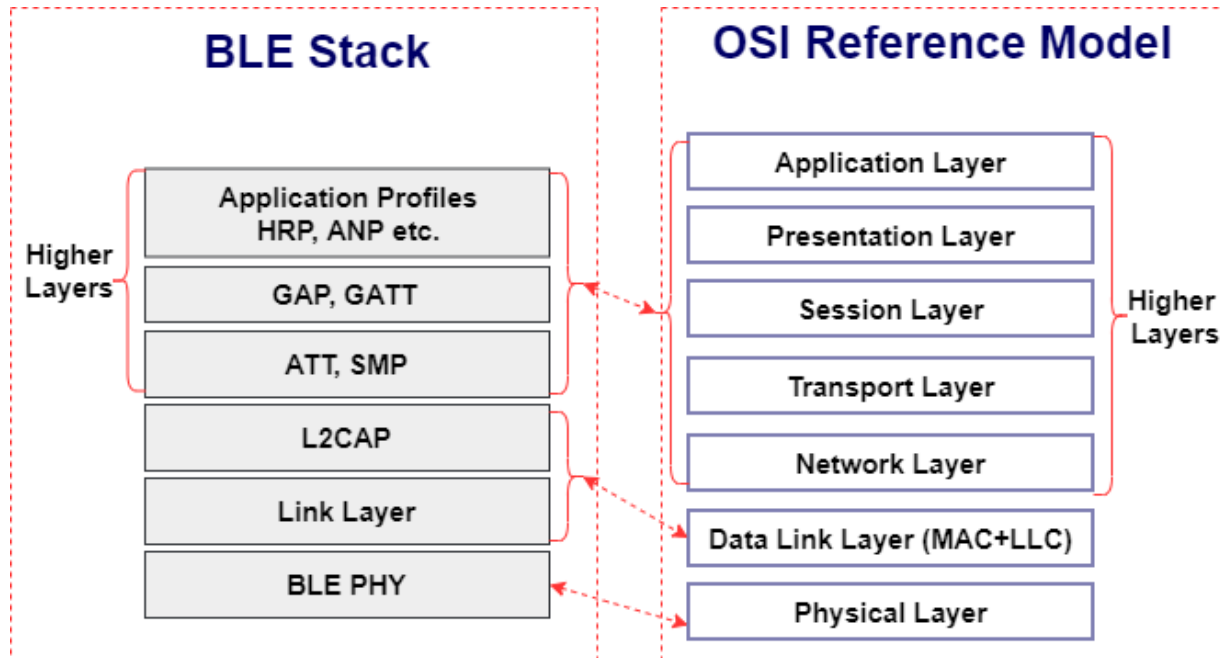


Transmitting data between networks

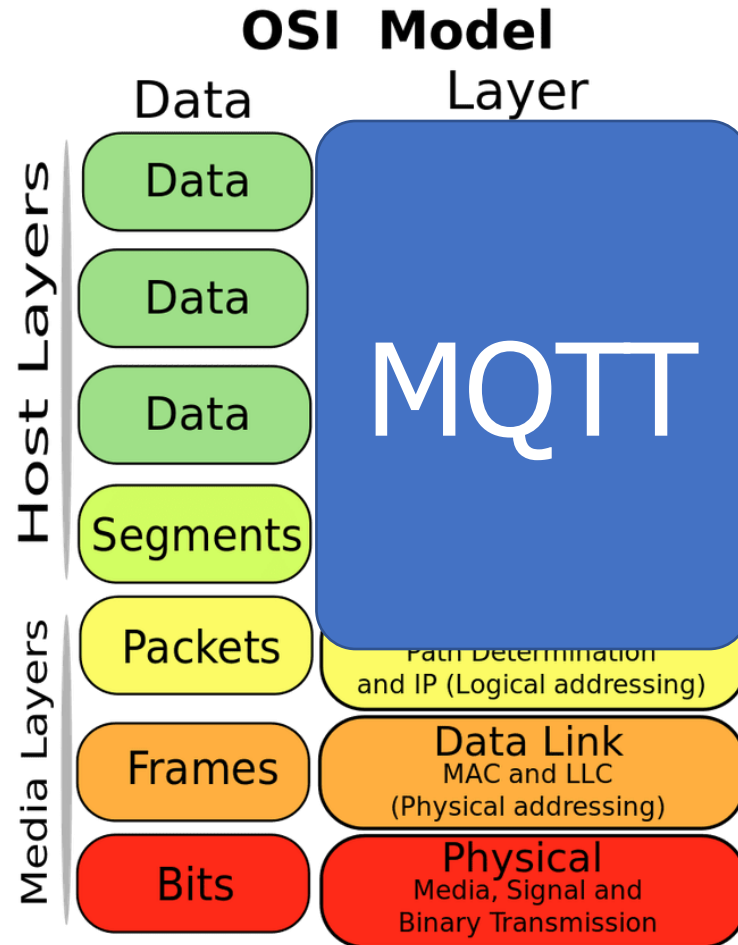


Model does not equal reality

- 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

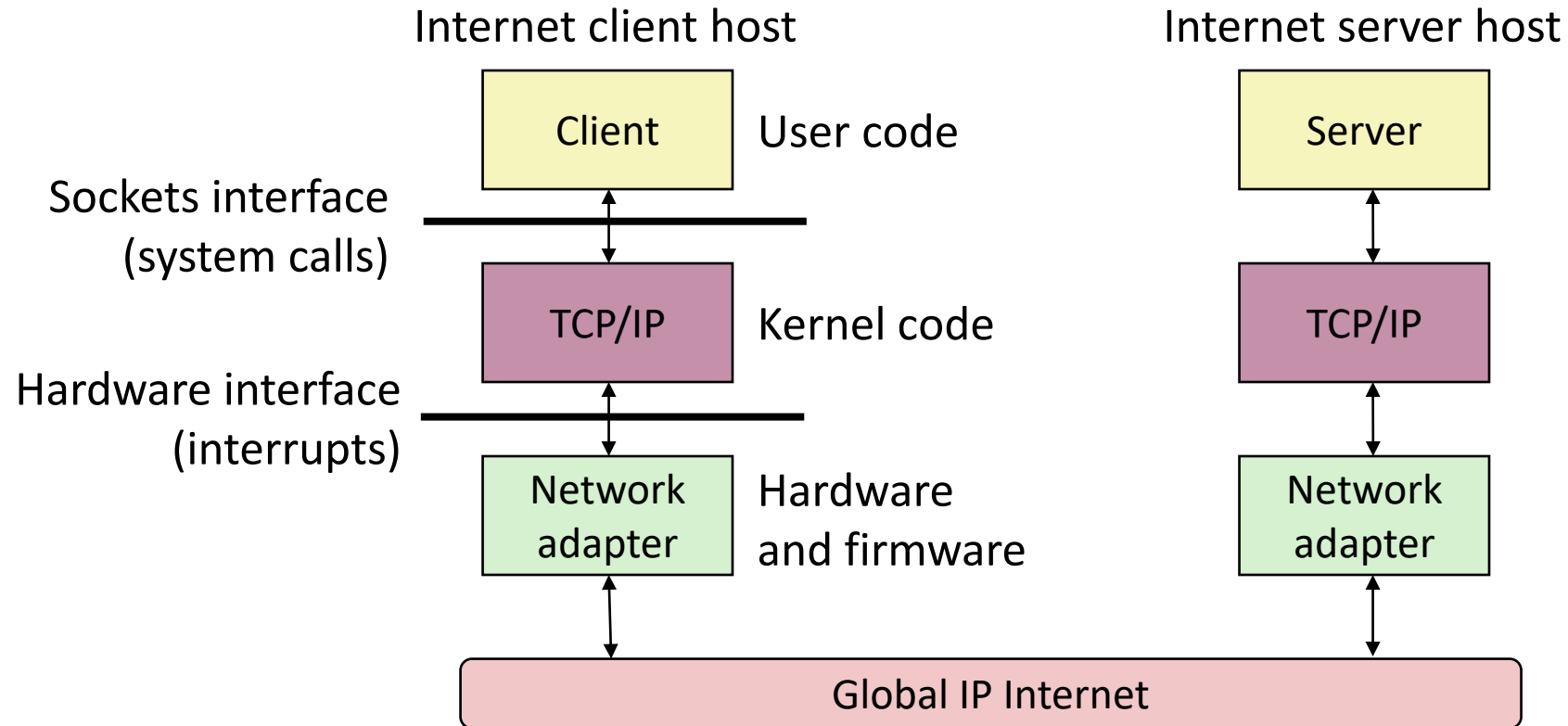
Outline

- OSI Layers
- **Internet Architecture** (Upper Layers)
- Physical Layer
- Data Link Layer

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**

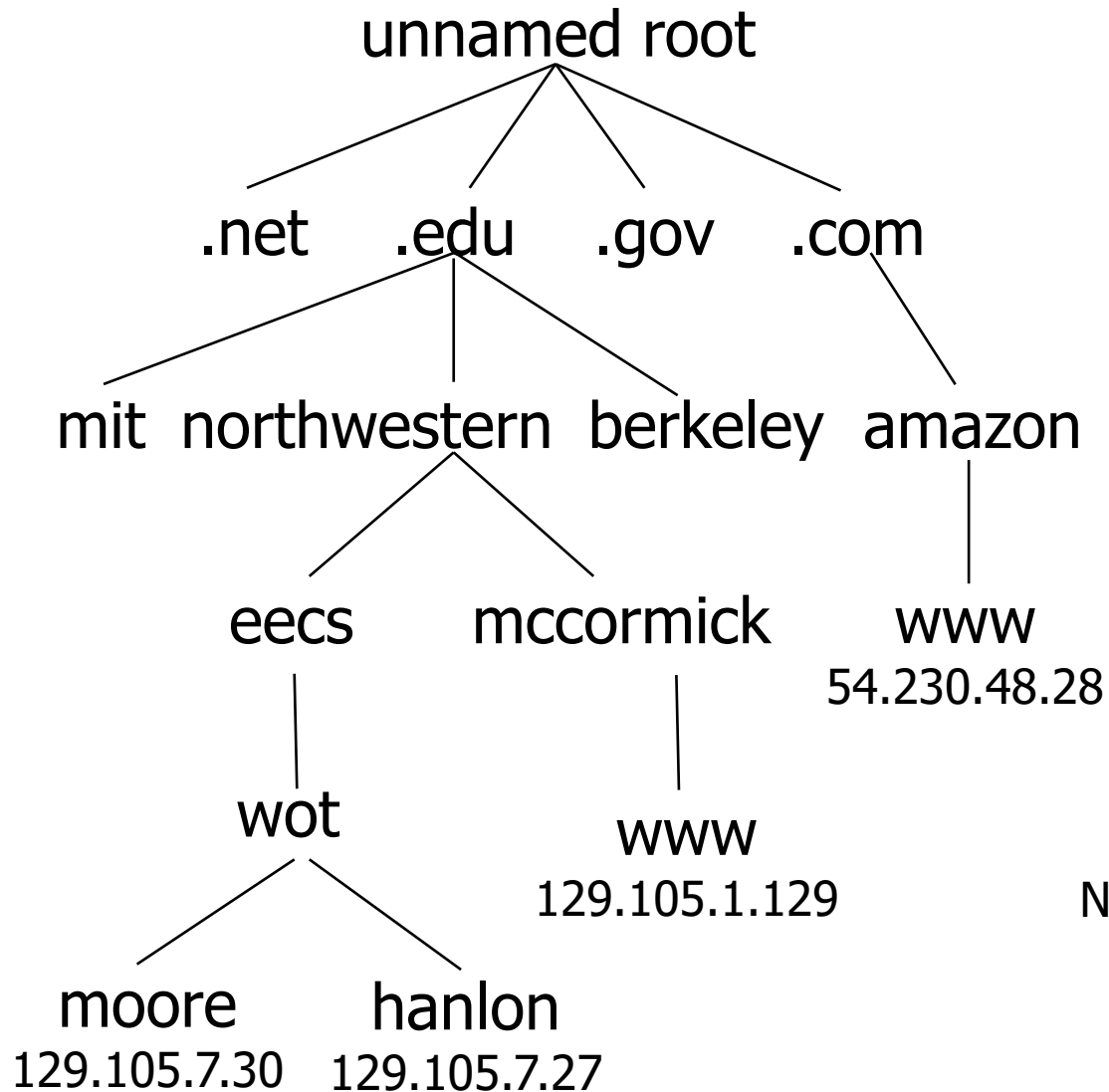
1. IP addresses

- 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

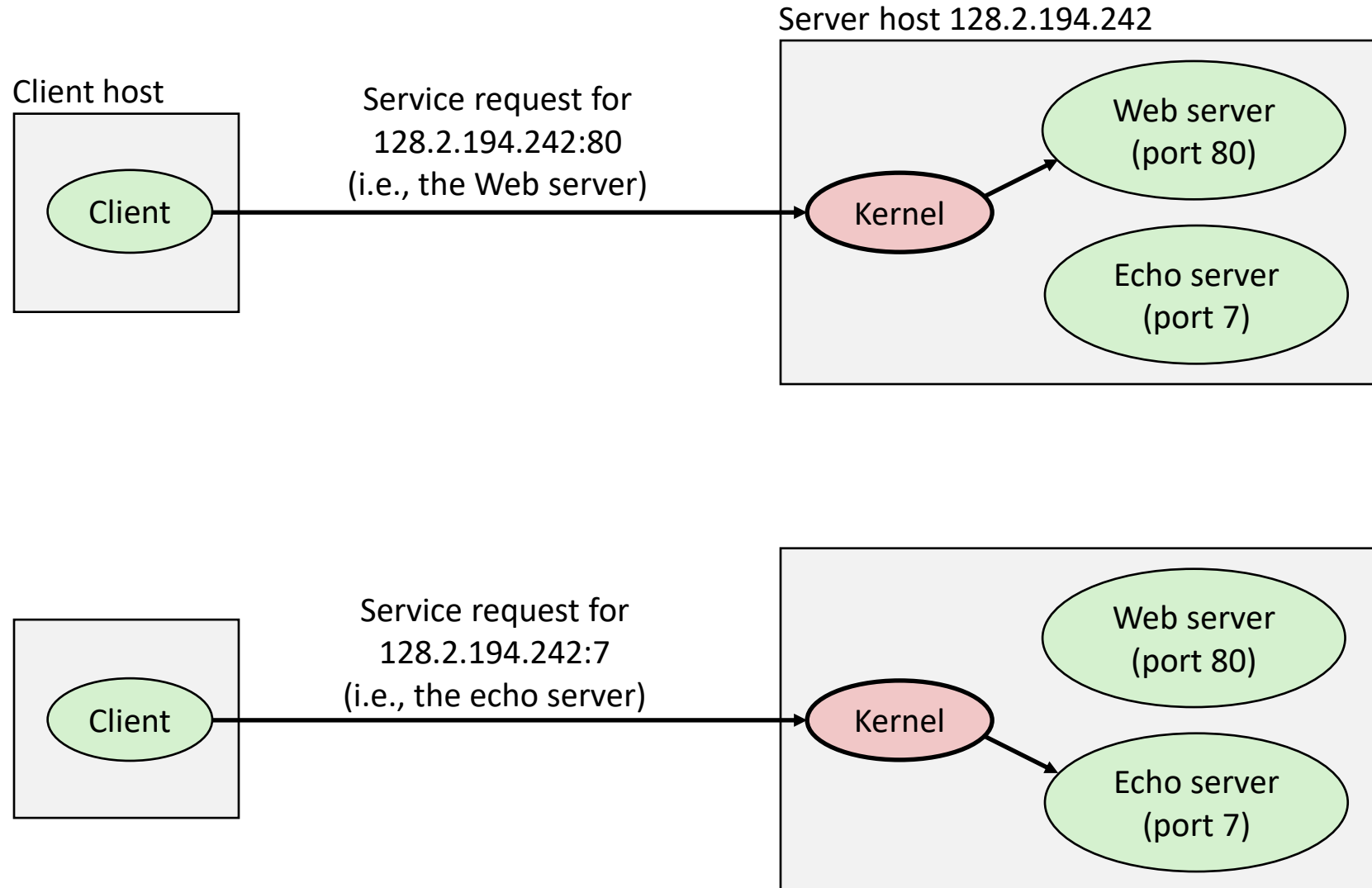
Domain Naming System (DNS)

- 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

- Clients and servers communicate by sending streams of bytes over **TCP connections**. Each connection is:
 - Point-to-point: connects a pair of processes.
 - Full-duplex: data can flow in both directions at the same time,
 - Reliable: stream of bytes sent by the source is eventually received by the destination in the same order it was sent.
- 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

Ports are used to identify services to the kernel



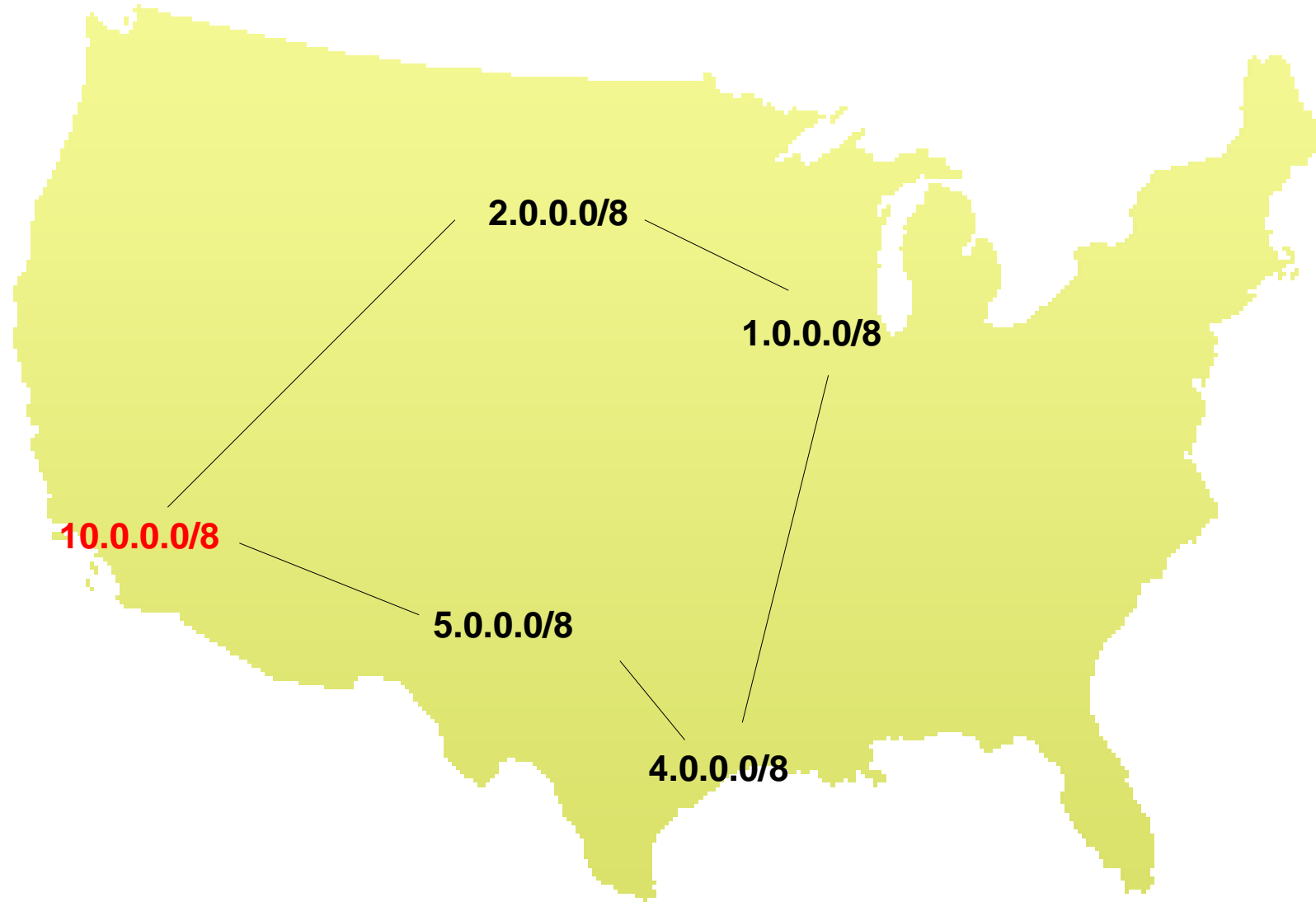
How does the Internet handle routing packets?

- IP layer
 - Describes the overall goal
 - 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

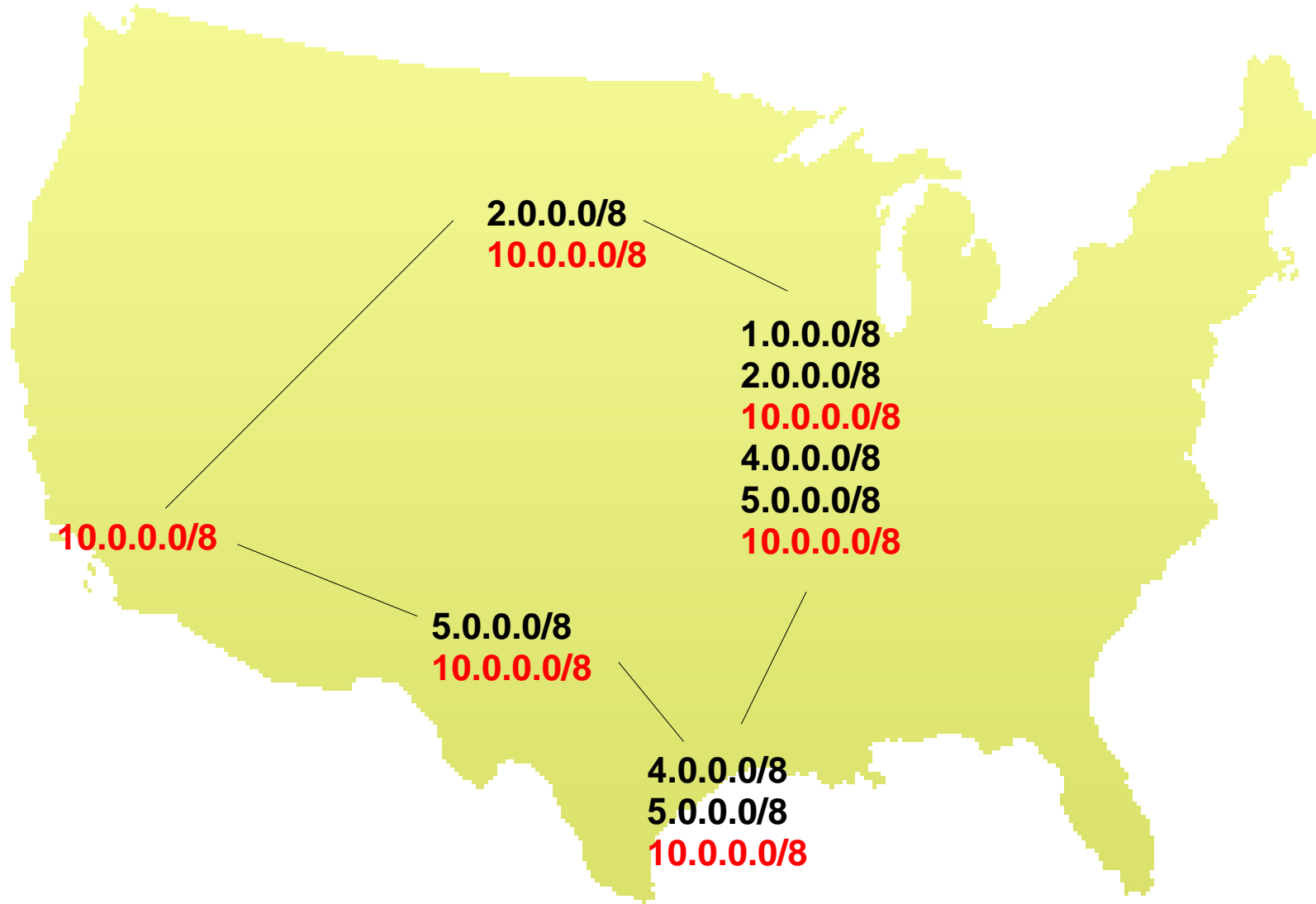
Assigning and finding IP address ranges

- **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

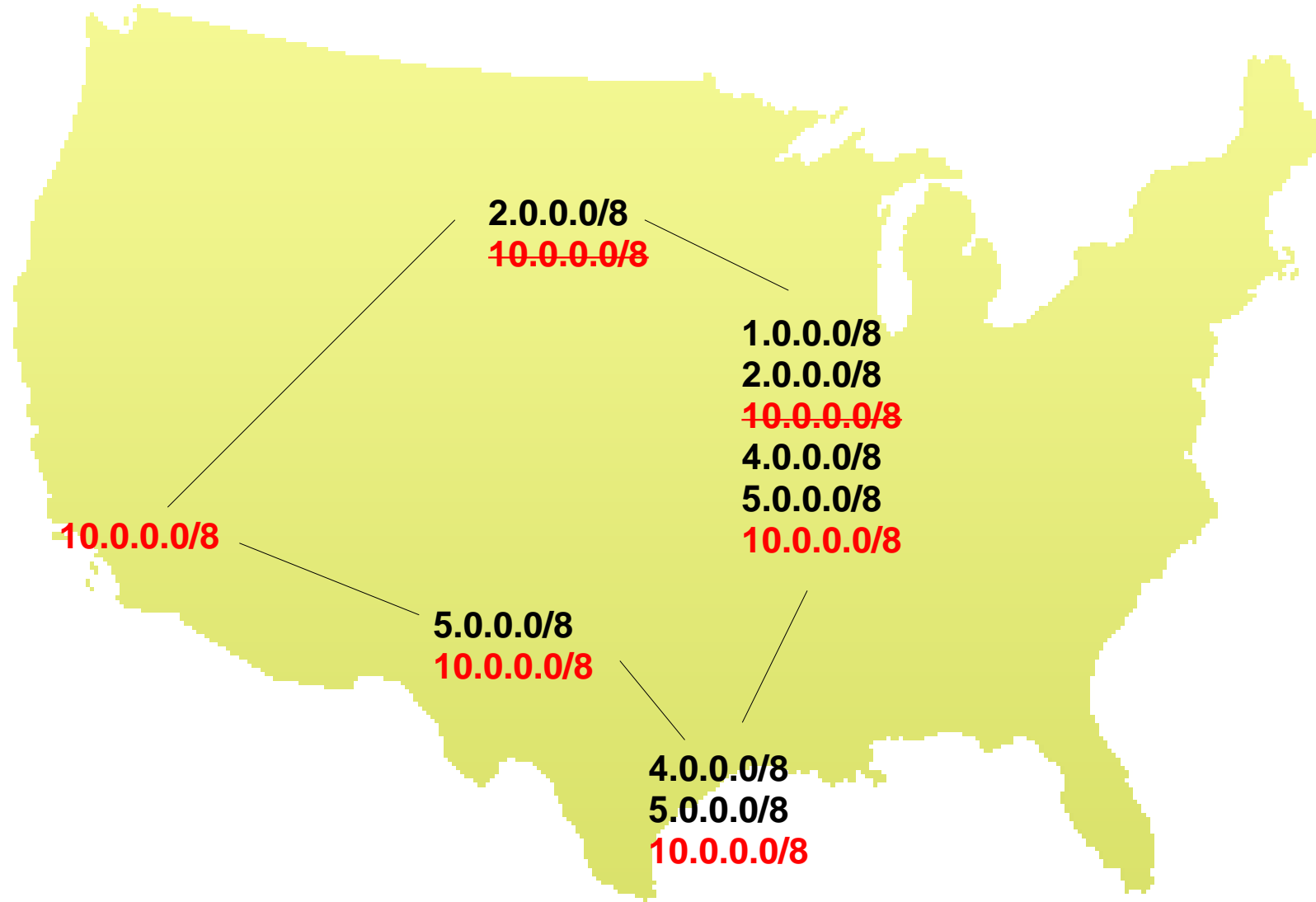
Routing



Routing



Routing – “Adaptive”



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
[hello Hue Hub, Wyze Hub, August Hub, ...]
 - Logically
[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 as wireless sensor network research took off many researchers in the field denounced the use of IP as inadequate and in contradiction to the needs of wireless sensor networking. Since then the field has matured, standard links have emerged, and IP has evolved. In this paper, we present the design of a complete 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, header compression, hop-by-hop forwarding, and efficient routing with effective link estimation. In addition to providing interoperability with existing IP devices, this implementation was able to achieve an average duty-cycle of 0.65%, average per-hop latency of 62ms, and a data reception rate of 99.98% over a period of 4 weeks in a real-world home-monitoring application where each node generates one application packet per minute. Our results outperform existing systems that do not adhere to any particular standard or architecture. In light of this demonstration of full IPv6 capability, we review the central arguments that led the field away from IP. We believe that the presence of an architecture, specifically an IPv6-based one, provides a strong foundation for wireless 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.2.6 [Computer-Communications Networks]: Internetworking—Standards

General Terms
Design, Measurement, Performance, Reliability, Security, Standardization

Keywords
network architecture; internet; internetworking; wireless; sensor networks; IP; IPv6; 6LoWPAN; media management

1. INTRODUCTION
As wireless sensor network (WSN) research took shape, many researchers in the field argued forcefully that “while many of the lessons learned from Internet and mobile network design will be applicable to designing wireless sensor network applications ... sensor networks have different enough requirements to warrant reconsidering the overall structure of applications and services” [19]. The Internet architecture was denounced for several reasons including the following [19]:

- The severe “resource constraints may cause us to give up the layered architecture”.
- “The sheer numbers of these devices, and their unattended deployment, will preclude reliance on a broadcast communication or the configuration currently needed to deploy and operate networked devices.”
- Localized algorithms and in-network processing 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 data-centric.
- “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 to tackle the challenges of WSNs the traditional interfaces and layers of system abstraction should not be assumed [24]. By providing a framework for defining abstractions and allowing the community to progress, new network abstractions were expected to emerge [30]. Indeed, by introducing the Active Message Dispatch ID at the head of each message, rather than a conventional header format, TinyOS [49] lead away from IP. The vast array of protocols developed by the community operate at the link layer, rather than the network layer. The serial interface to a basestation mote favored the use of application level gateways at the root of the WSN, so WSNs were organized in a manner similar to IrDA and USB, rather than an IP subnet similar to Ethernet or WiFi.

Since those beginnings, the field has matured substantially, a huge collection of protocols have been invented and evaluated, and we have gained experience in how WSNs are used in practice.

Over this same period, the Internet has evolved as well. In 1998, RFC 2460 defined IPv6 [12]. The large address space not only provided for a huge number of devices, it eliminated many of the artificial naming constraints. This enabled the definition of an adaptation layer in RFC 4944 (6LoWPAN) that carried the meaning of IPv6 addresses in a compact form using small IEEE 802.15.4 short addresses [34]. The IPv6 prefix generalized the notion of a subnet. The various layer-two bootstrapping, discovery, and autoconfiguration mechanisms used with IPv4 were consolidated into the IPv6 framework and went directly at the issue of vast numbers of unattended devices in a changing environment. Finally, the systematic use of options provided for compact headers in the common case,

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Copyright 2008 ACM 978-1-59593-990-6/08/11 ...\$5.00.

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

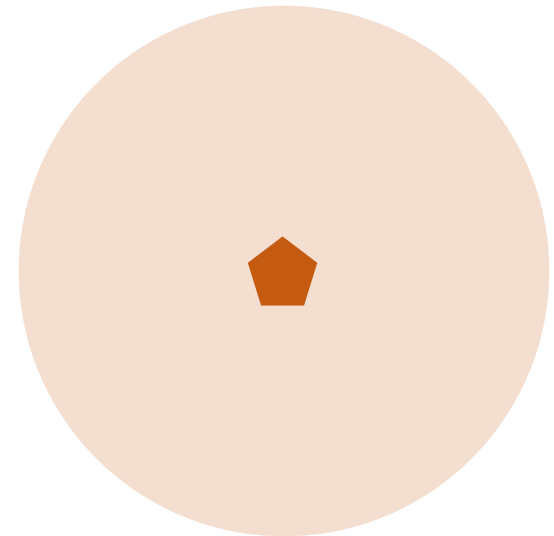
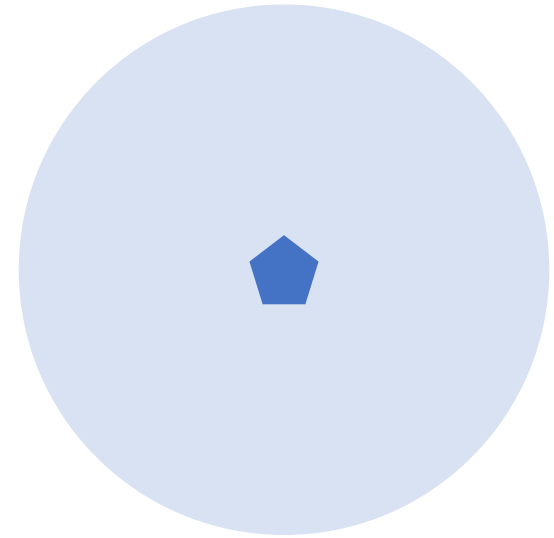
- OSI Layers
- Internet Architecture (Upper Layers)
- **Physical Layer**
- Data Link Layer

Physical Layer

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

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

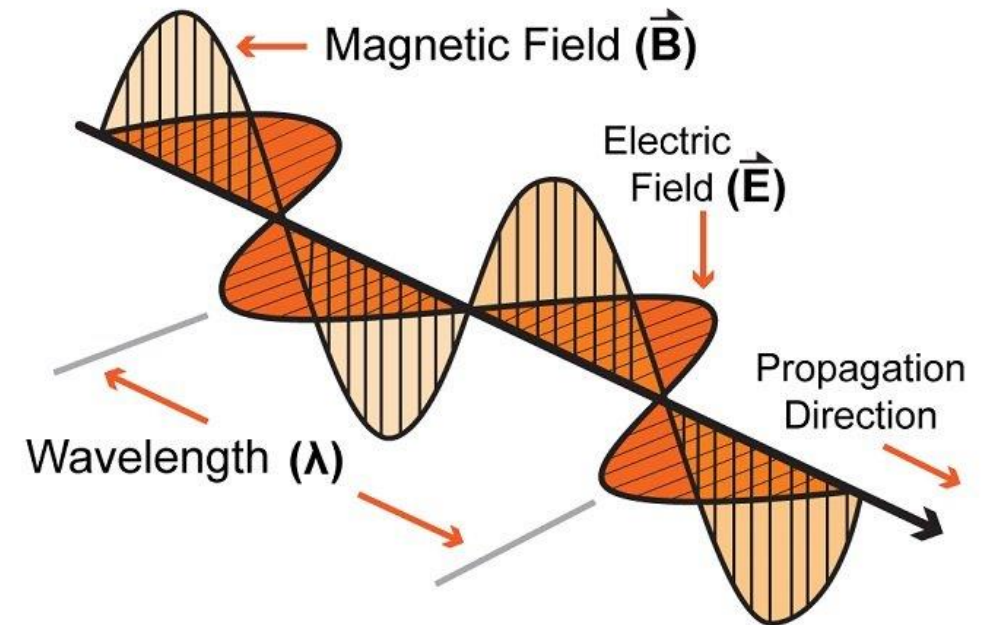
- The amount of energy transmitted/received

2. Signal frequency and bandwidth

- Which "channel" the signal is sent on

3. Signal modulation

- How data is encoded in the signal



Signal qualities

1. Signal strength

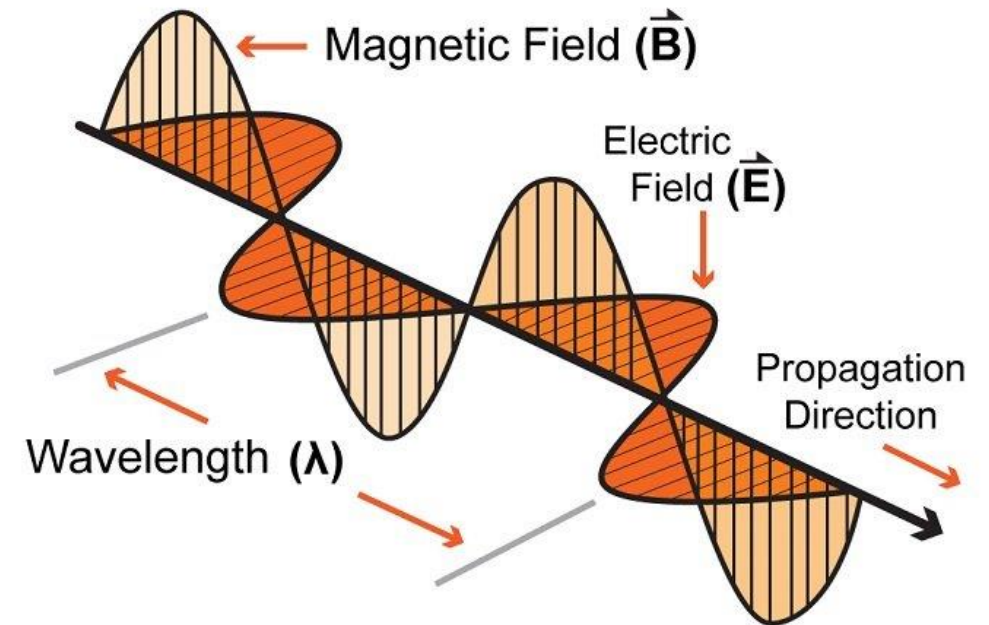
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Signal strength is measured in decibels

- 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
- Obstacles can weaken signal through absorption or reflection
- Important: distance is NOT the only signal strength loss
 - Free space path loss calculation will not give you accurate range for a signal

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.

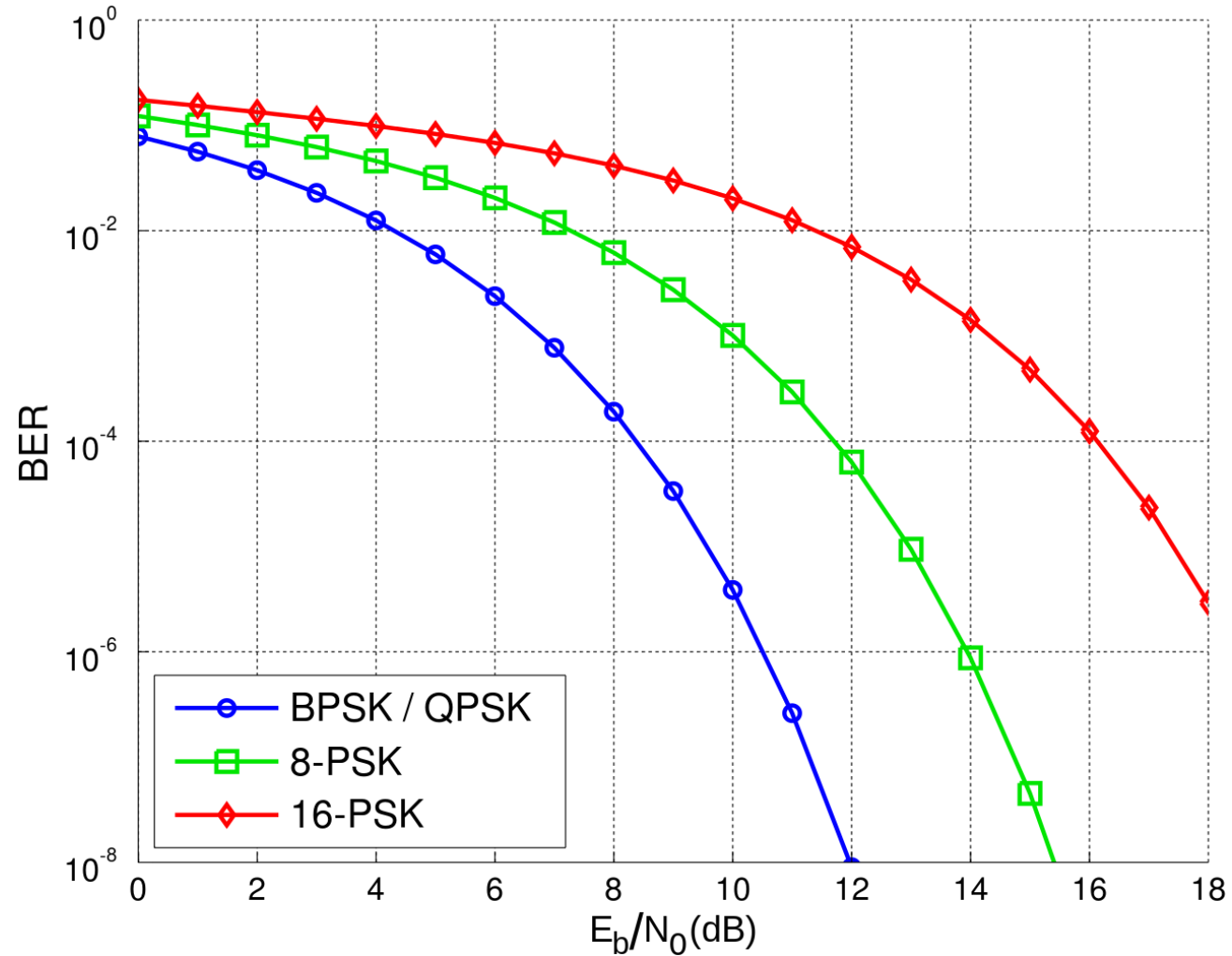
- Models like this are *less bad* than Free-Space Path Loss
 - https://en.wikipedia.org/wiki/ITU_model_for_indoor_attenuation

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

Signal qualities

1. Signal strength

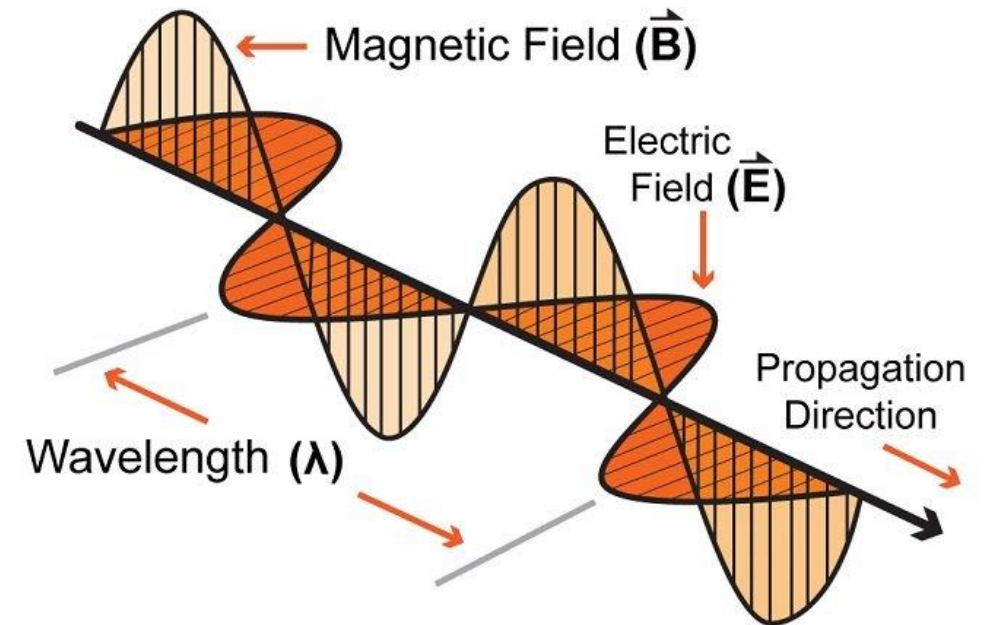
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2. Signal frequency and bandwidth

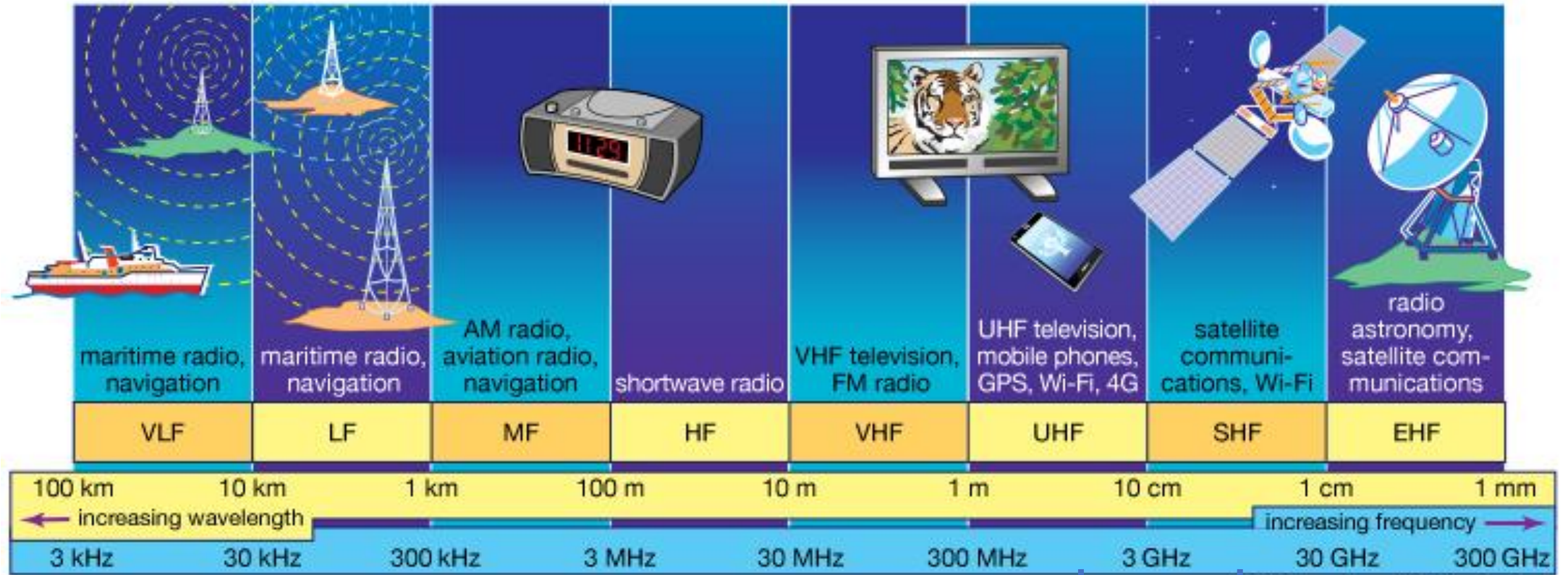
- Which "channel" the signal is sent on

3. Signal modulation

- How data is encoded in the signal



RF communication 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

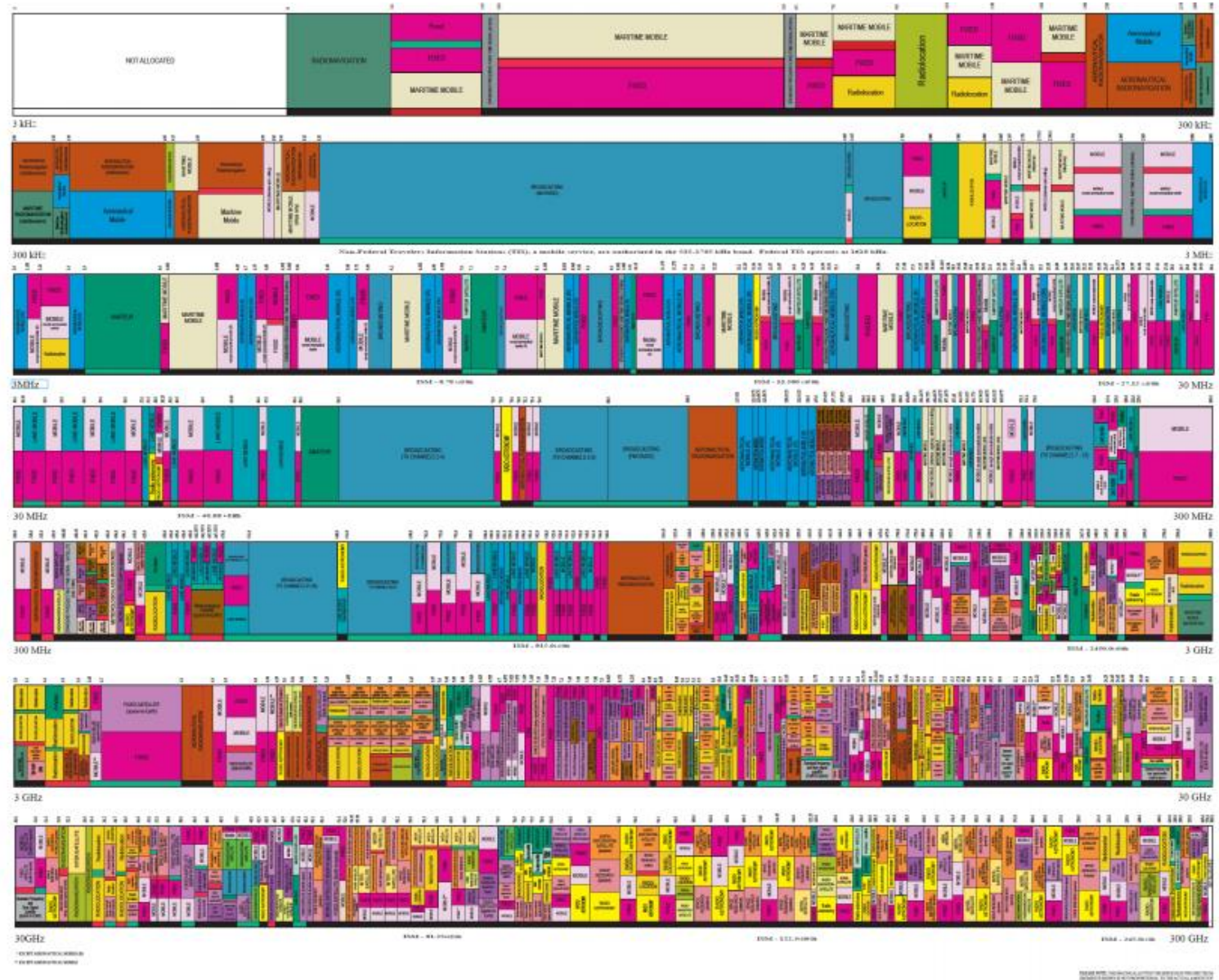
GOVERNMENT USE ONLY	GOVERNMENT-ASSIGNED USES
NON-GOVERNMENT USE ONLY	

ALLOCATION USAGE DESIGNATION

OFFICE	EXAMPLE	DESCRIPTION
Primary	ST25	Land Mobile
Secondary	SM25	Land Mobile (Same use table)

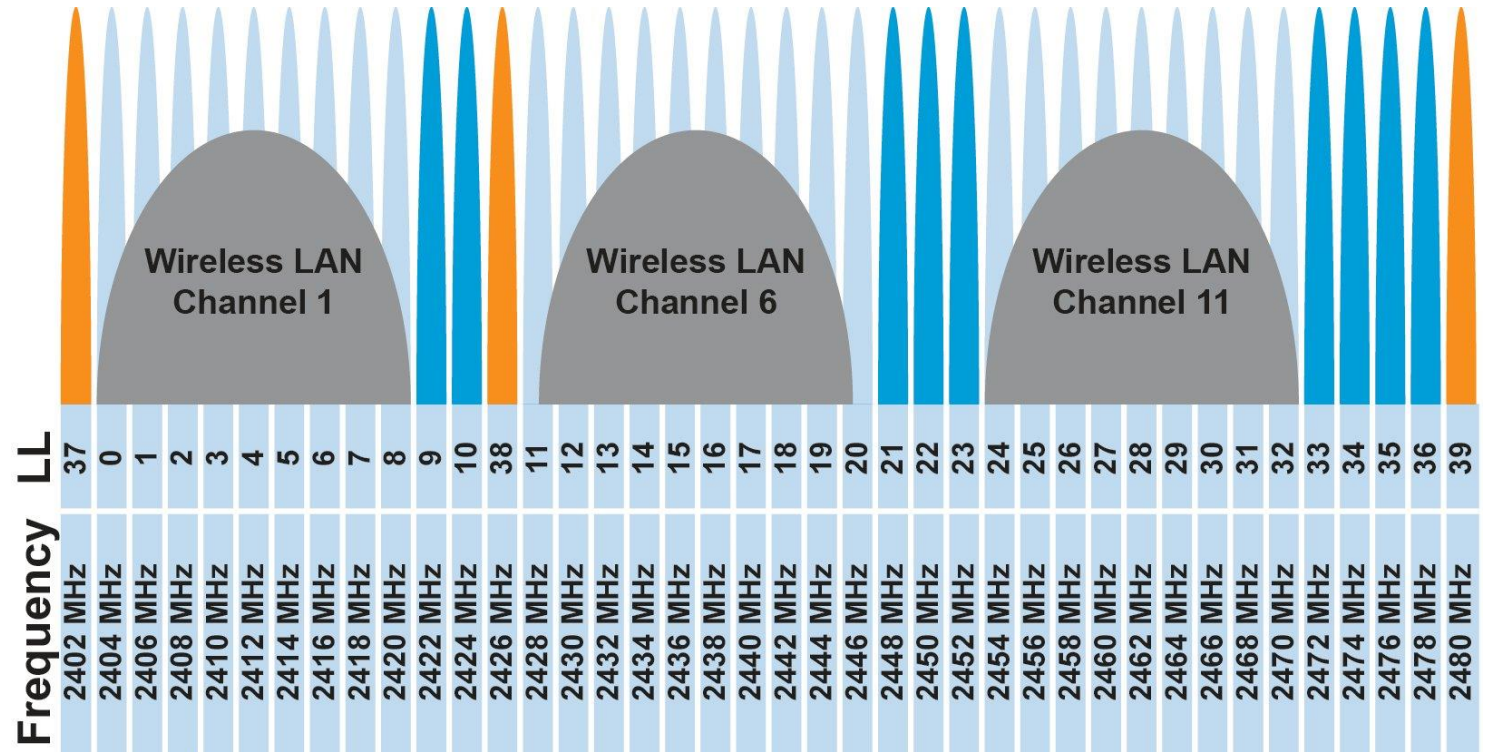
The radio spectrum is a public resource of the United States of America. It is a finite resource and its use is regulated by the Federal Communications Commission (FCC). This chart is a simplified representation of the actual spectrum allocations and is not intended to be used for legal purposes. For more information, please visit the FCC website.

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



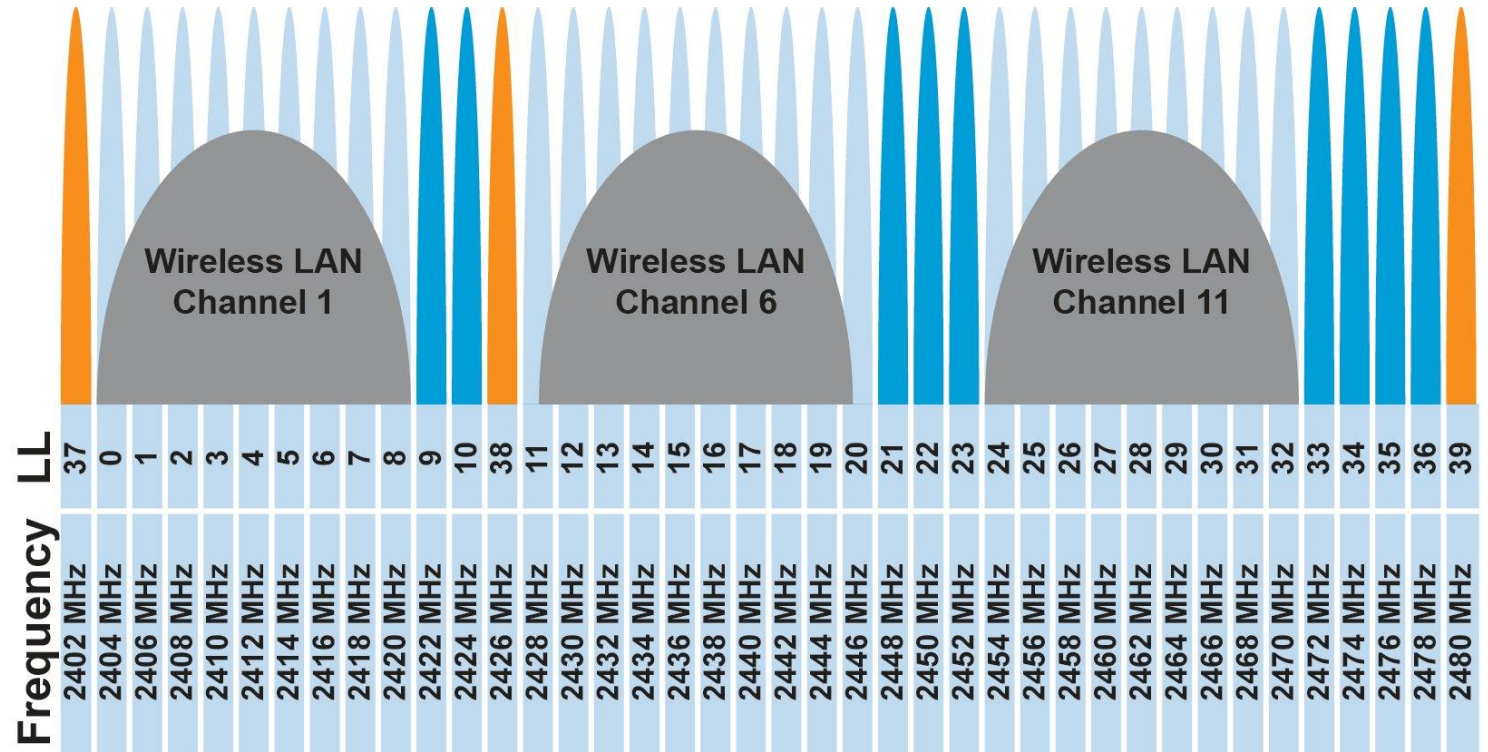
Unlicensed bands are where IoT thrives

- 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?**



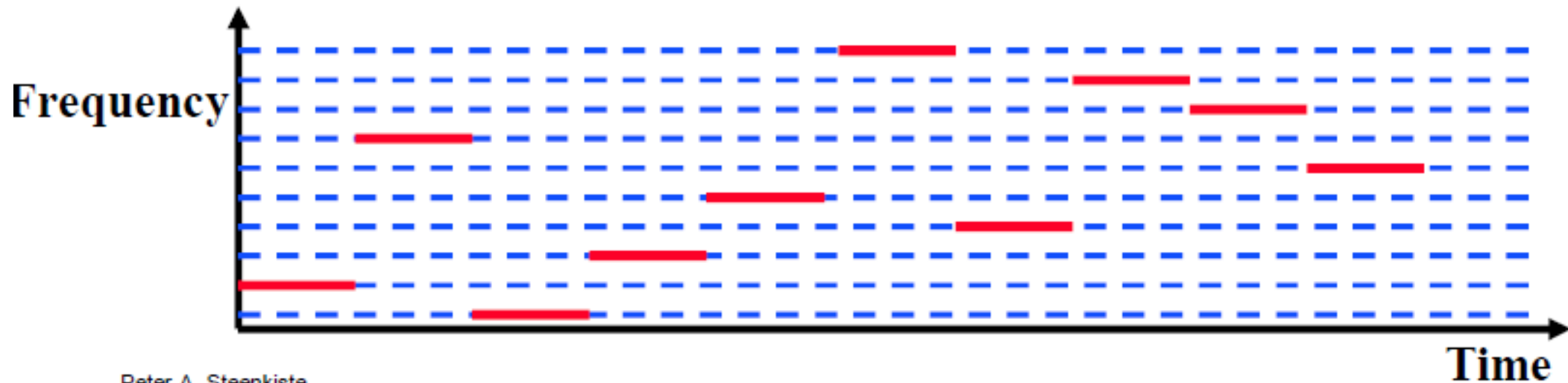
Unlicensed bands are where IoT thrives

- 902 MHz – 928 MHz
 - LPWANs
- 2.4 GHz to 2.5 GHz
 - WiFi, BLE, Thread
- 5 GHz
 - Faster WiFi
- Cellular uses licensed bands at great cost
 - **Why? No interference from other users**



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 and Inventor
 - Designed FHSS with George Antheil during WWII
 - Idea: torpedo control can't be easily jammed if it jumps around

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

Signal qualities

1. Signal strength

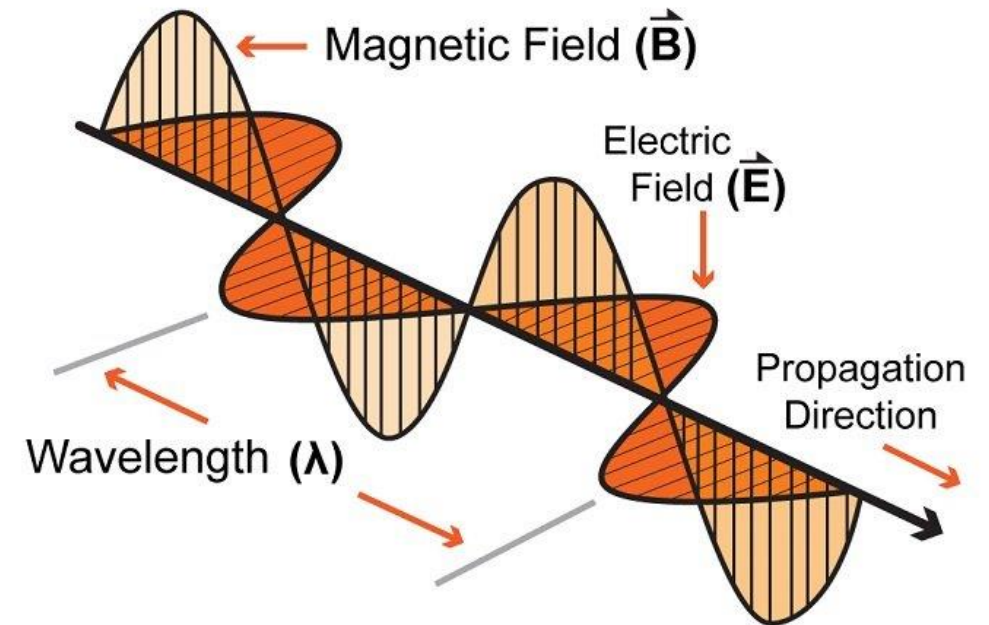
- The amount of energy transmitted/received

2. Signal frequency and bandwidth

- Which "channel" the signal is sent on

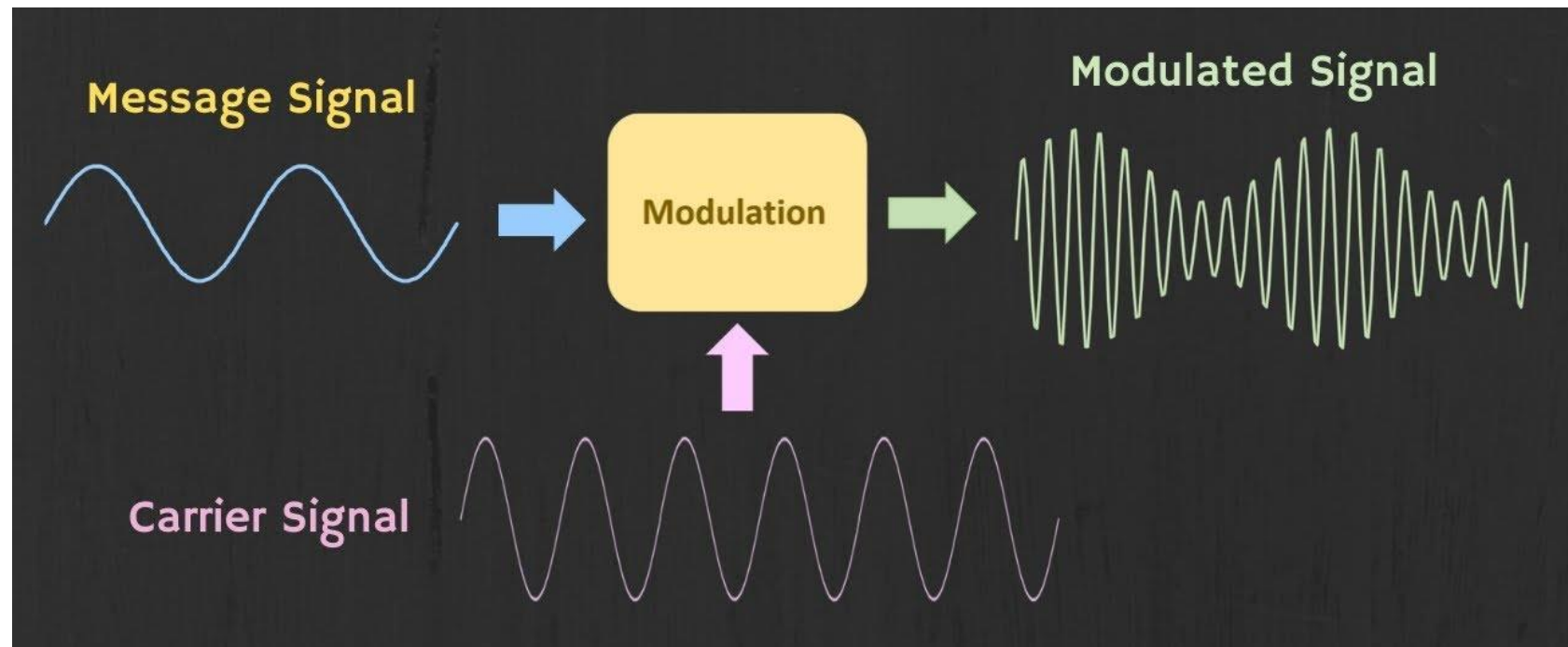
3. Signal modulation

- How data is encoded in the signal



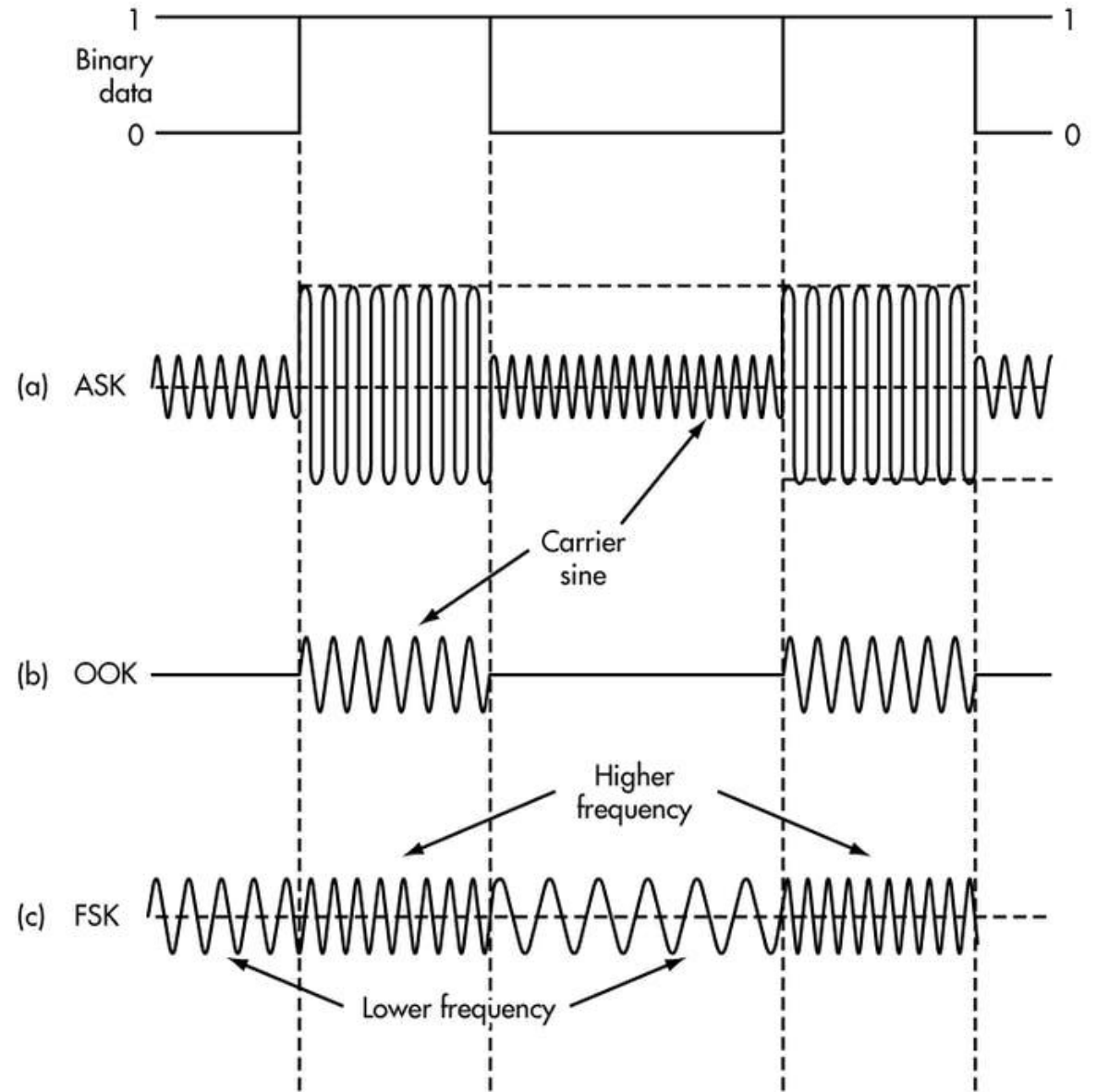
Modulation

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



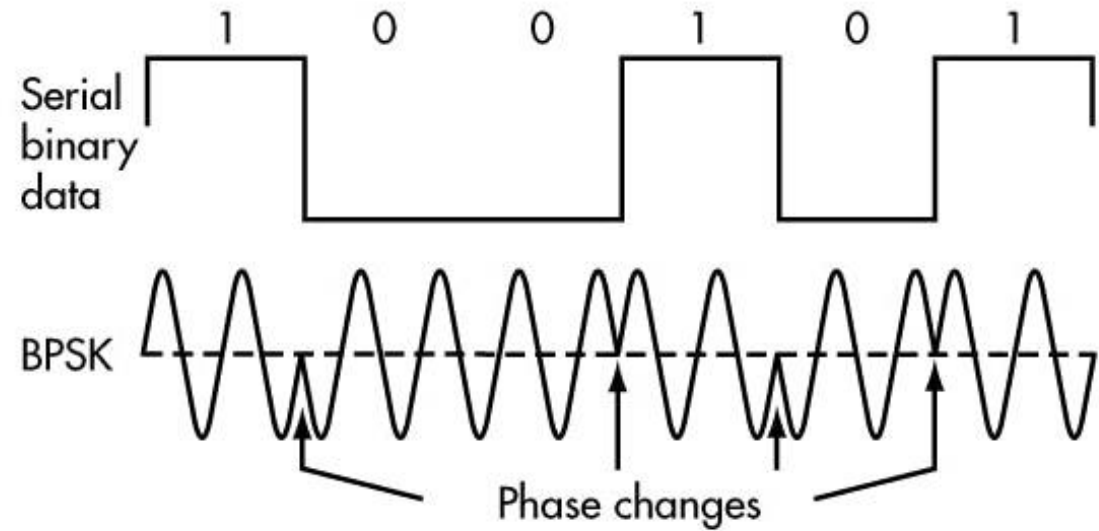
Modulation types

- 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

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
- **Data Link Layer**

Data Link Layer

- Framing
 - Combine arbitrary bits into a “packet” of data
- Logical link control
 - Manage transfer between transmitter and receiver
 - Error detection and correction
- Media access
 - Controlling which device gets to transmit next
- Inherently coupled to PHY and its decisions

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

Error control: detection and recovery

- Detection: only detect errors
 - Make sure corrupted packets get discarded
 - Cyclical Redundancy Checks
 - Detect single bit errors
 - Detect "burst" errors of several contiguous bits
- Recovery: also try to recover from small bit errors
 - Forward error correction
 - Retransmissions
 - Far more important for wireless because the cost of transmission is higher

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

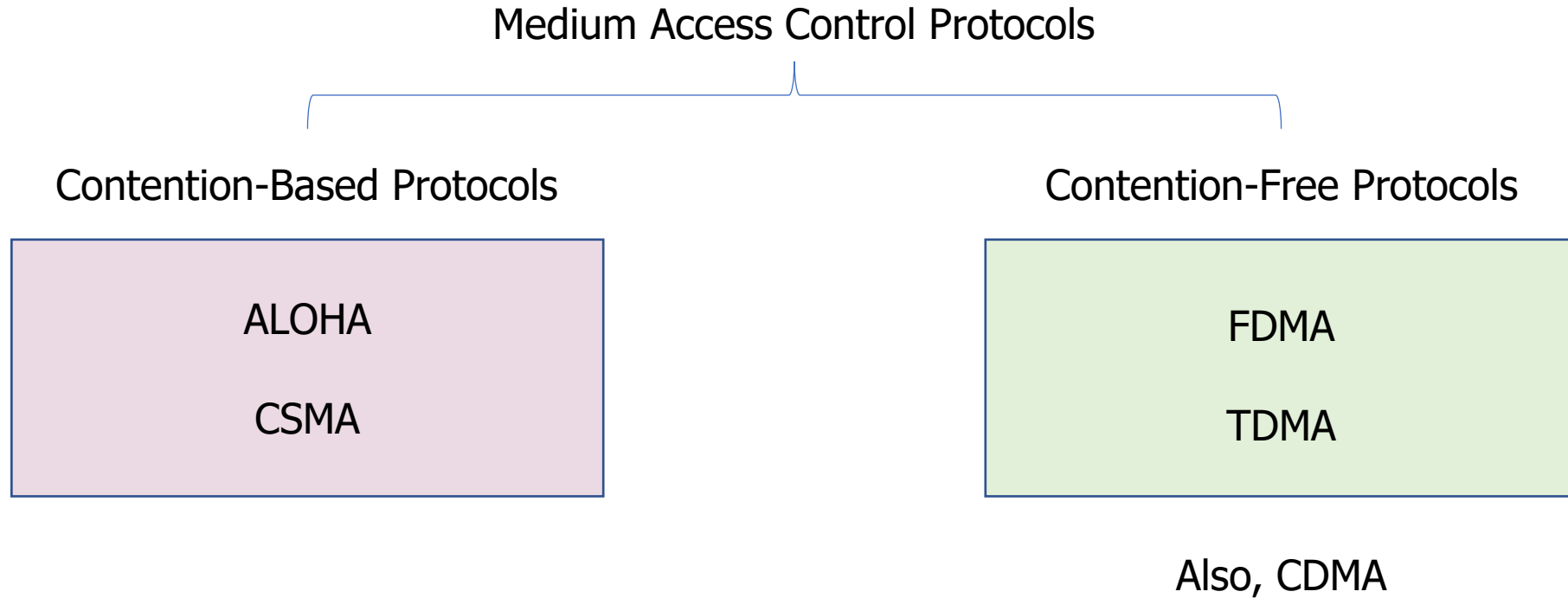
Analogy: wireless medium as acoustic

- **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?

MAC protocol categorization

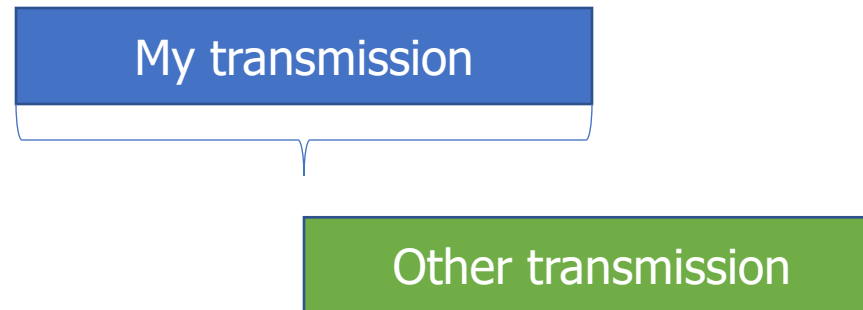


ALOHA

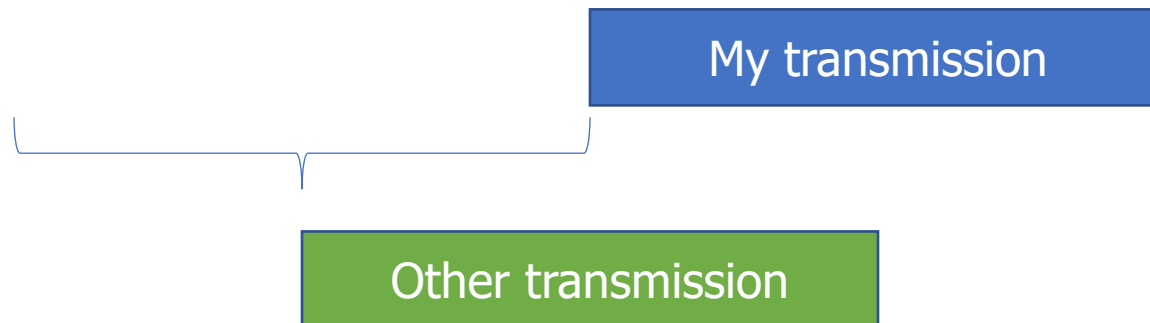
- ALOHAnet (1971)
 - University of Hawaii – Norman Abramson
 - First demonstration of wireless packet network
- Rules
 1. If you have data to send, send it
- Two (or more) simultaneous transmissions will collide and be lost
 - Wait a duration of time for an acknowledgement
 - If transmission was lost, try sending again “later”
 - Want some kind of exponential backoff scheme here

Packet collisions

- Each packet transmission has a window of vulnerability
 - Twice the on-air duration of a packet
 - Transmissions during the packet are bad

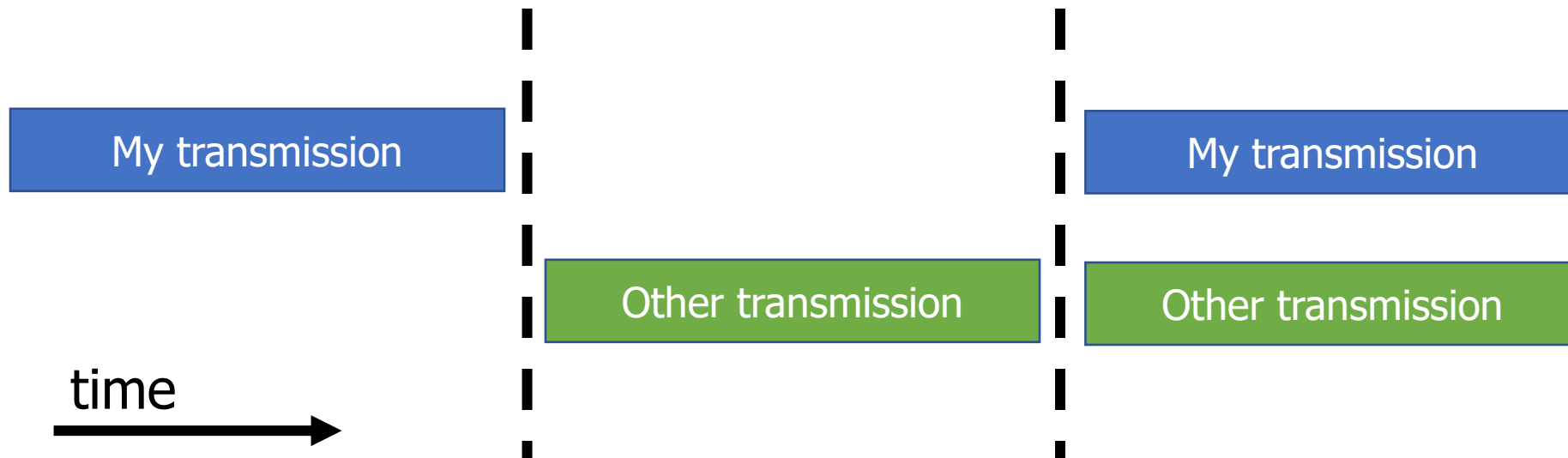


- Transmissions before packet can also be bad



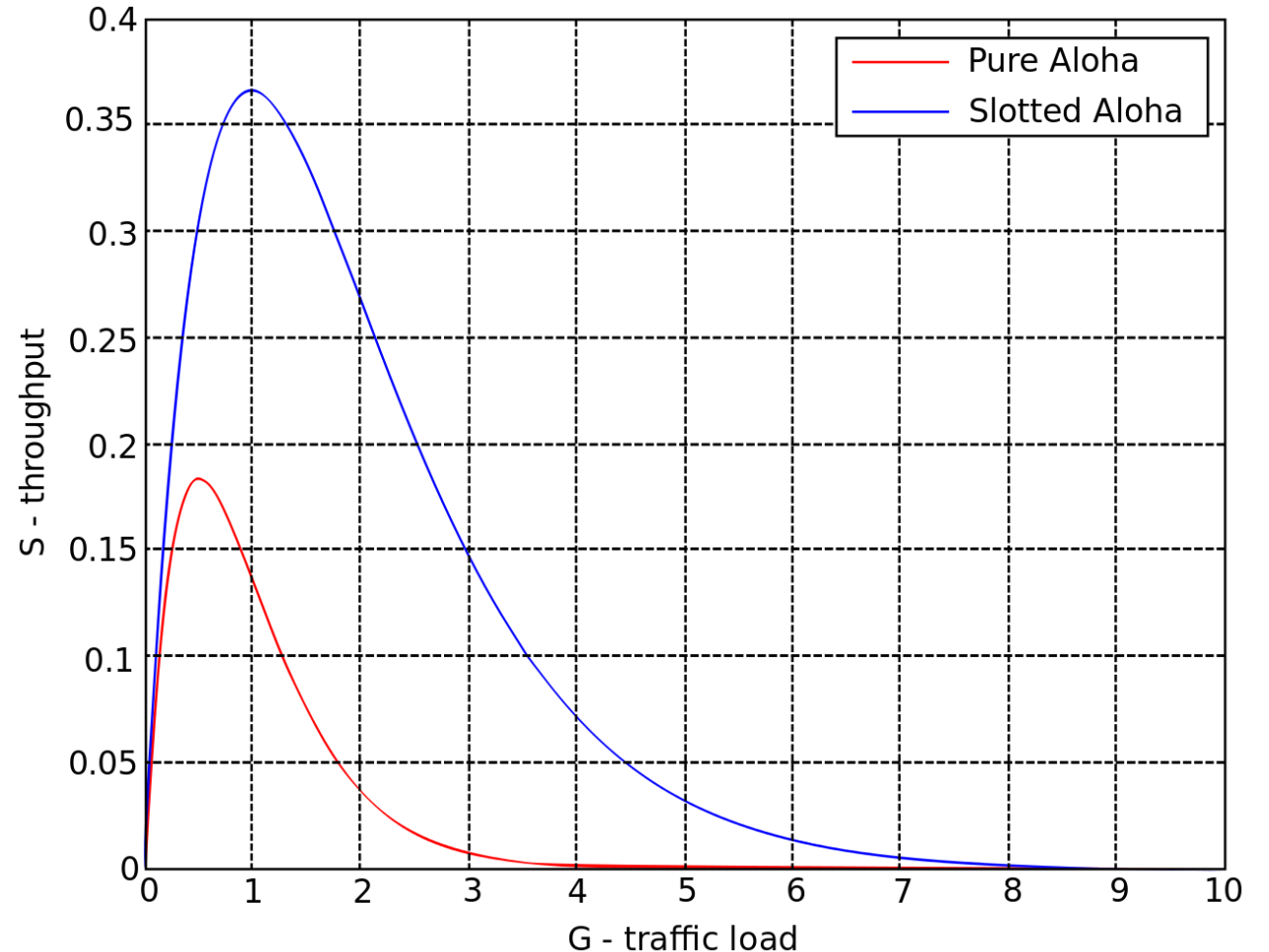
Slotted ALOHA

- Split time into synchronized “slots”
- Any device can transmit whenever it has data
 - But it must transmit at the start of a slot
 - And its transmission cannot be longer than a slot
 - Removes half of the possibilities for collisions!
 - At the cost of some synchronization method



ALOHA throughput

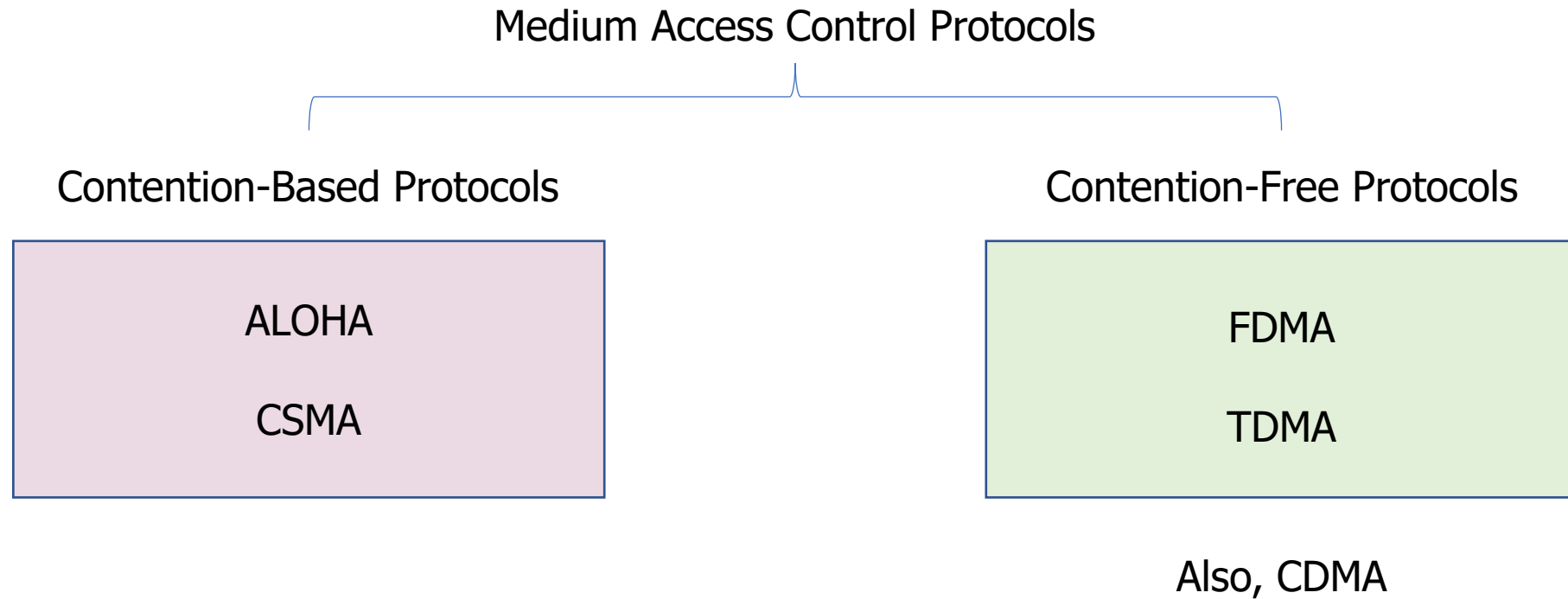
- It can be shown that traffic maxes out at
 - ALOHA: 18.4%
 - Slotted ALOHA: 36.8%
- Assuming Poisson distribution of transmission attempts
- Slotted throughput is double because the “before” collisions can no longer occur



Capture effect

- Actually, two packets at once isn't *always* a total loss
 - The louder packet can still sometimes be heard if loud enough
- How much louder?
 - Ballpark 12-14 dB
- When does this work?
 - Depends on the radio hardware
 - Louder packet first almost always works
 - Louder packet second *sometimes* works

MAC protocol categorization



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”
- Can be combined with notion of slotting
 - If current slot is idle, transmit in next slot
 - If current slot is busy, follow some algorithm to try again later

CSMA/CD – CSMA with Collision Detection

- Detect collisions during your own transmission
 - Works great on wired mediums (Ethernet, I2C)
- Very challenging for wireless systems
 - Transmit and receive are usually the same antenna
 - Receiving while transmitting would be drowned out by transmission
 - Remember: TX at 8 dBm and RX at -95 dBm
- Area of active research!

2017 13th Annual Conference on Wireless On-demand Network Systems and Services (WONS)

On the Feasibility of Collision Detection in Full-Duplex 802.11 Radio

Michele Segata, Renato Lo Cigno

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Abstract—Full-duplex radios are becoming a feasible reality thanks to recent advances in self-interference cancellation. Switching from half- to full-duplex requires a major re-design of many network features and characteristics, including the MAC layer. The literature provides several new proposals or improvements that are applicable in different topologies:

the notion of channel itself becomes blurred, as there is intrinsic spatial reuse and stations very far one another hidden with respect to stations in between. Still, the possibility of detecting collisions and avoid the waste of channel time appealing and has only partially been investigated [5].

2014 IEEE 22nd International Conference on Network Protocols

Concise Paper: Semi-Synchronous Channel Access for Full-Duplex Wireless Networks

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Throughput Analysis of CSMA With Imperfect Collision Detection in Full Duplex-Enabled WLAN

Megumi Kaneko

Abstract—As an alternative to carrier sense multiple access (CSMA) with collision avoidance in half-duplex wireless local area network (WLAN) that incurs heavy control overhead, full-duplex WLANs enabling wireless collision detection (WCD) by simultaneous carrier sensing and data transmission are gath-

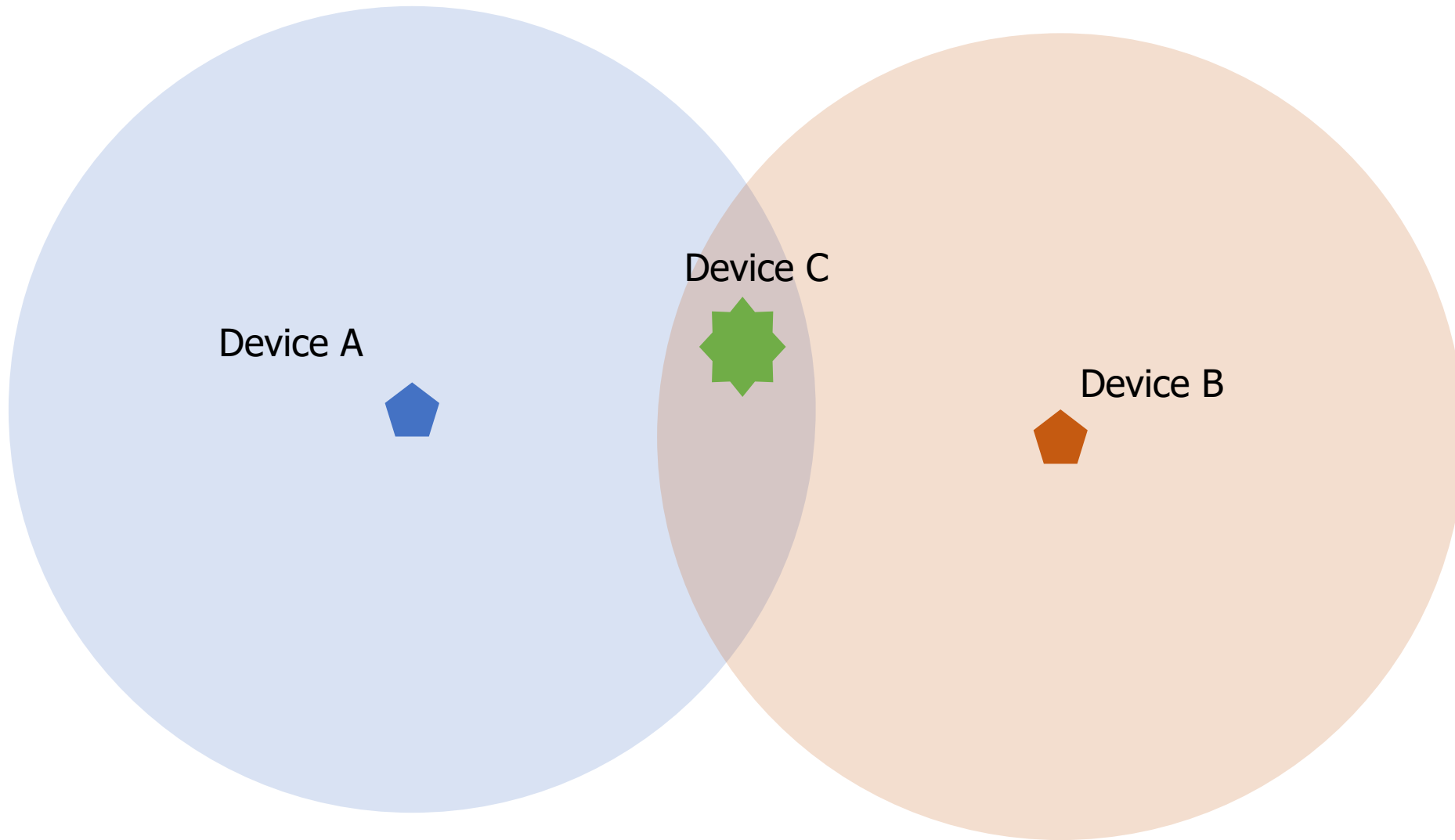
er main reasons. Firstly, a collision detected at the transmitter does not necessarily imply a collision at the receiver due to the nature of wireless channels such as large/small-scale fading. Secondly, detecting simultaneous transmissions during one's own transmission is very challenging, as the transmitter's self-interference signal power is several orders of magnitudes higher than that of collision signals to be detected.

multiple access, wireless collision, full duplex.

work (WLAN) systems are problems due to the ex-

Thus, a number of PHY layer WCD schemes have been proposed [7], [8]. A MIMO-based scheme is designed in [7] for detecting an interfering preamble signal at one of the transmit antennas, and a self-interference canceller is designed in [8] which enables the transmitter to detect simultaneous transmissions even under very high self-interference. Such schemes allow the UTs to detect potential collisions during transmission, and hence to immediately revert to the retransmission process without any delay, leading to large throughput improvements compared to CSMA/CA [3]. Note that [3] assumed an ideal WCD where any collision can be perfectly detected at the transmitter. In [9], the impact of interference on full-duplex transmitter-receiver pairs in ad-hoc

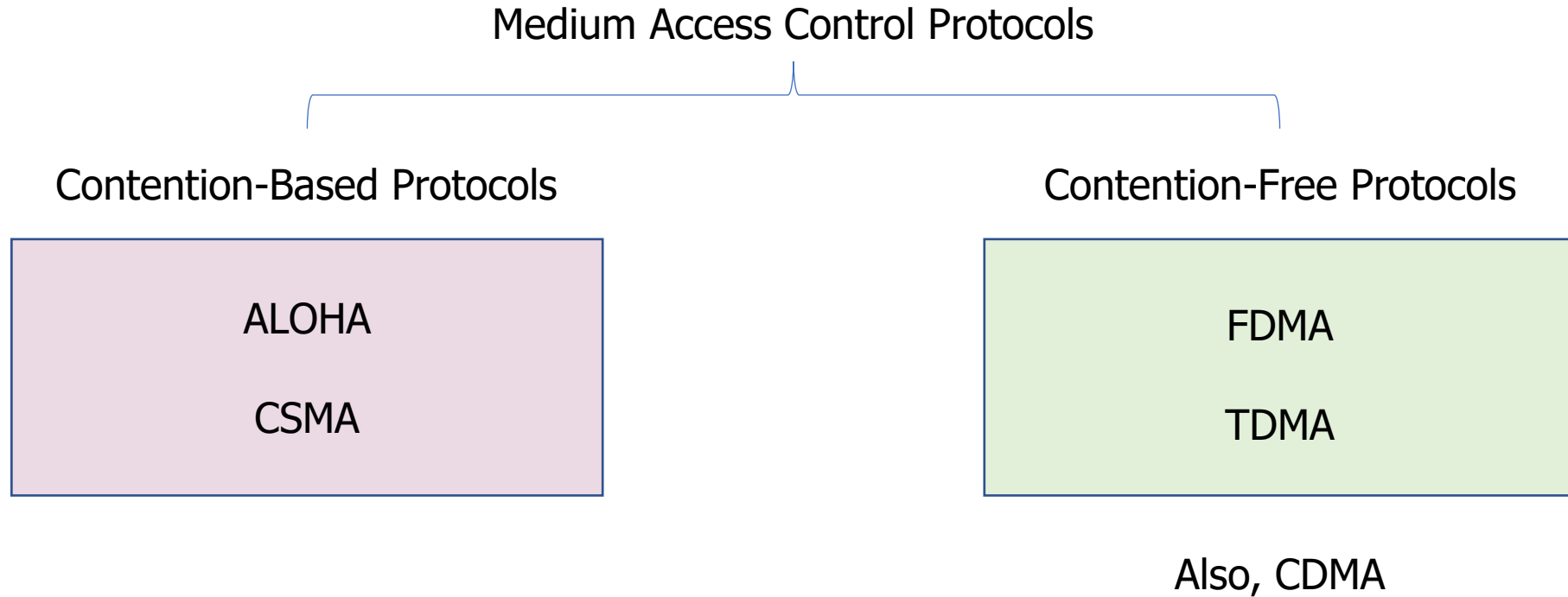
Hidden terminal problem



CSMA with RTS/CTS

- Hidden terminal problem means that two transmitters might never be able to detect each other's transmissions
- A partial solution
 - When channel is idle, transmitter sends a short Request To Send (RTS)
 - Receiver will send a Clear To Send (CTS) to only one node at a time
 - RTS collisions are faster and less wasteful than hidden terminal collisions
 - Downside: overhead is high for waiting for CTS when contention is low

MAC protocol categorization

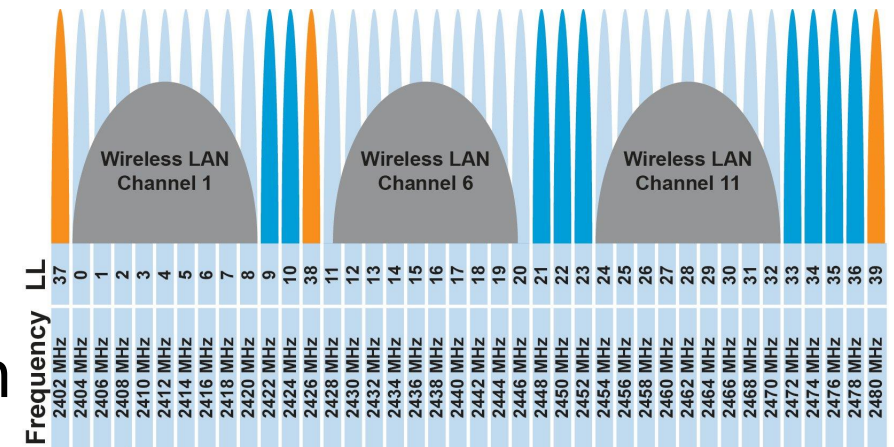


Contention-free access control protocols

- Goal: split up communication such that devices will not conflict
- Can be predetermined or reservation-based
 - Devices might request to join the schedule and be given a slot
 - Devices lose their slot if it goes unused for some amount of time
 - Reservations often occur during a dedicated CSMA contention slot
 - Assignment of schedules can be complicated
- Really efficient at creating a high-throughput network
 - Assuming they are all following the same protocol
 - Otherwise, interference can be very problematic

FDMA – Frequency Division Multiple Access

- Split transmissions in frequency
 - Different carrier frequencies are independent
 - Fundamentally how RF spectrum is split
- Technically, each device uses a separate, fixed frequency
 - Walkie-talkies
- Conceptually, how RF channels work
 - WiFi networks pick different bands
 - 802.15.4 picks a channel to communicate on



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

Real-world protocol access control

- ALOHA
 - BLE advertisements
 - Unlicensed LPWANs: Sigfox, LoRaWAN
- CSMA
 - WiFi (slotted, CSMA/CA)
- TDMA
 - BLE connections
 - Cellular LPWANs: LTE-M and NB-IoT

Outline

- OSI Layers
- Internet Architecture (Upper Layers)
- Physical Layer
- Data Link Layer