CSCI 1680
Physical Layer, Link Layer I

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Based partly on lecture notes by Rodrigo Fonseca, David Mazières, Phil Levis, John Jannotti

Administrivia

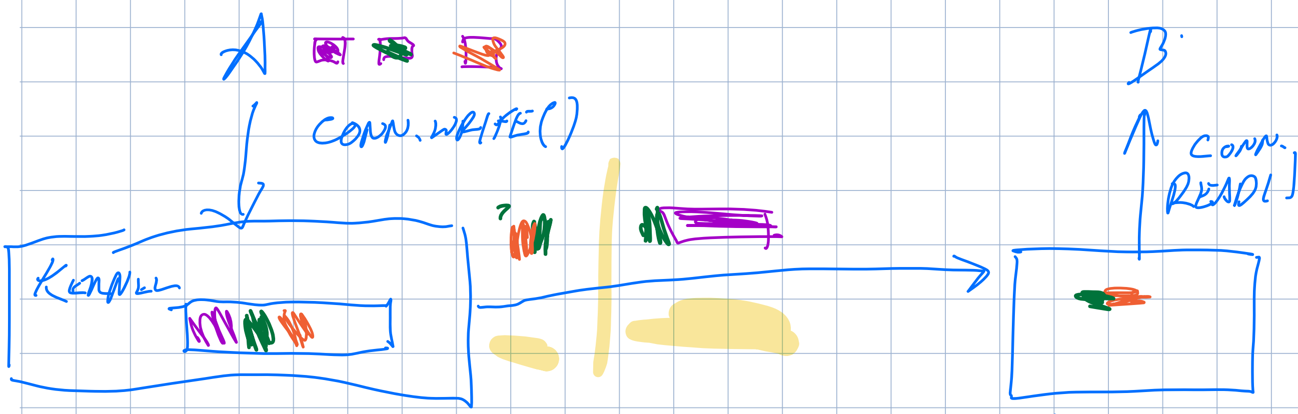
- Snowcast: Milestone due today (ish)
  - Make sure you follow our submission format
  - So long as you pass the tests locally or with reference, you're fine
- Snowcast full submission: due Monday 9/25
- HW1: details soon

Last call for override codes
If you emailed me yesterday, I will respond after class

Roadmap

- One thing on sockets
- Physical layer key points
- Inherent properties of real networks

SENDING DATA W/ TCP




```
FOR {
  BYTES_READ = READ(4)
}
```

When you read on a TCP socket, you might not get back the amount of data you expect => need to check and act accordingly
Idea: call read in a loop until you get back how much you wanted
In Go: io.ReadFull

TCP is designed to provide a STREAM of ordered data => it doesn't care about the separation of individual messages

WHAT HAPPENS IF YOU DON'T KNOW THE SIZE OF THE MESSAGE?

=> PROTOCOL NEEDS TO BE SET UP SO THAT YOU CAN ALWAYS FIGURE OUT HOW MUCH DATA TO READ NEXT.

E.G. | TYPE | LENGTH | STRING . . . |

- LENGTH ↳ LENGTH OF DATA TO FOLLOW
- TYPE ↳ MESSAGE TYPE => SIZE

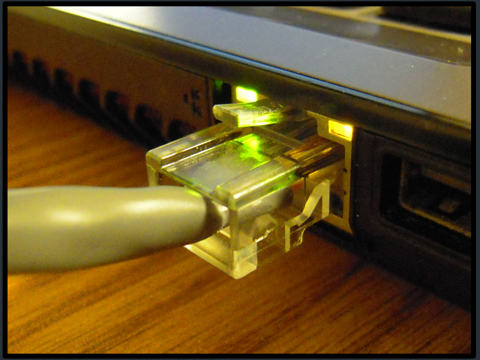
Layers, Services, Protocols

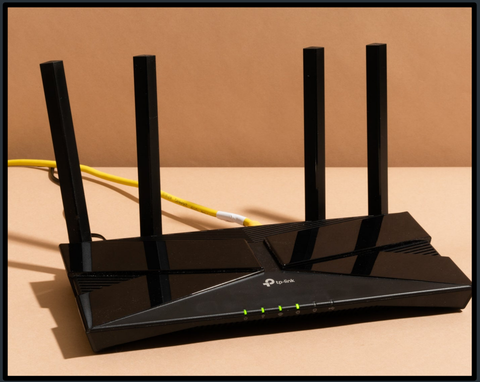
Application	Service: user-facing application. Application-defined messages
Transport	Service: multiplexing applications Reliable byte stream to other node (TCP), Unreliable datagram (UDP)
Network	Service: move packets to any other node in the network IP: Unreliable, best-effort service model
Link	Service: move frames to other node across link. May add reliability, medium access control L2
Physical	Service: move bits to other node across link L1

Physical Layer (Layer 1)

Specifies three things:

- Physical medium: WIFI, ETHERNET, ~~LTE~~ CELLULAR...
- Signaling/modulation: HOW TO SEND 0..1
- Encoding: HOW TO TURN THIS INTO USEFUL INFO

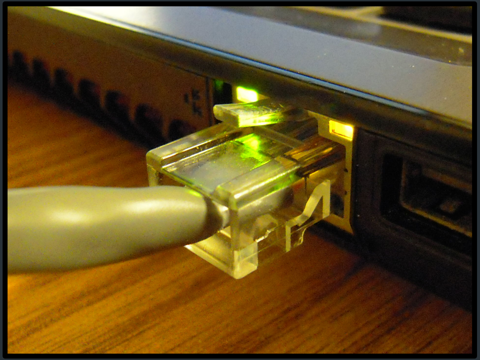


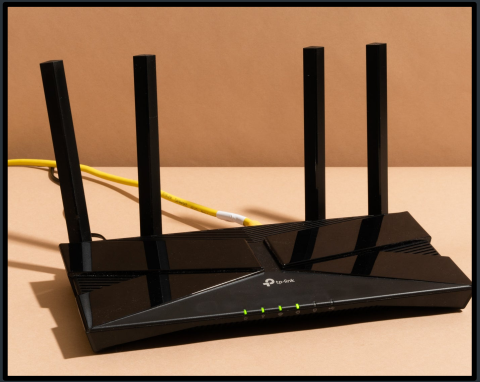


Physical Layer (Layer 1)

Specifies three things:

- Physical medium: cable, fiber, wireless frequency
- Signaling/modulation: how to transmit/receive
- Encoding: how to get meaningful data





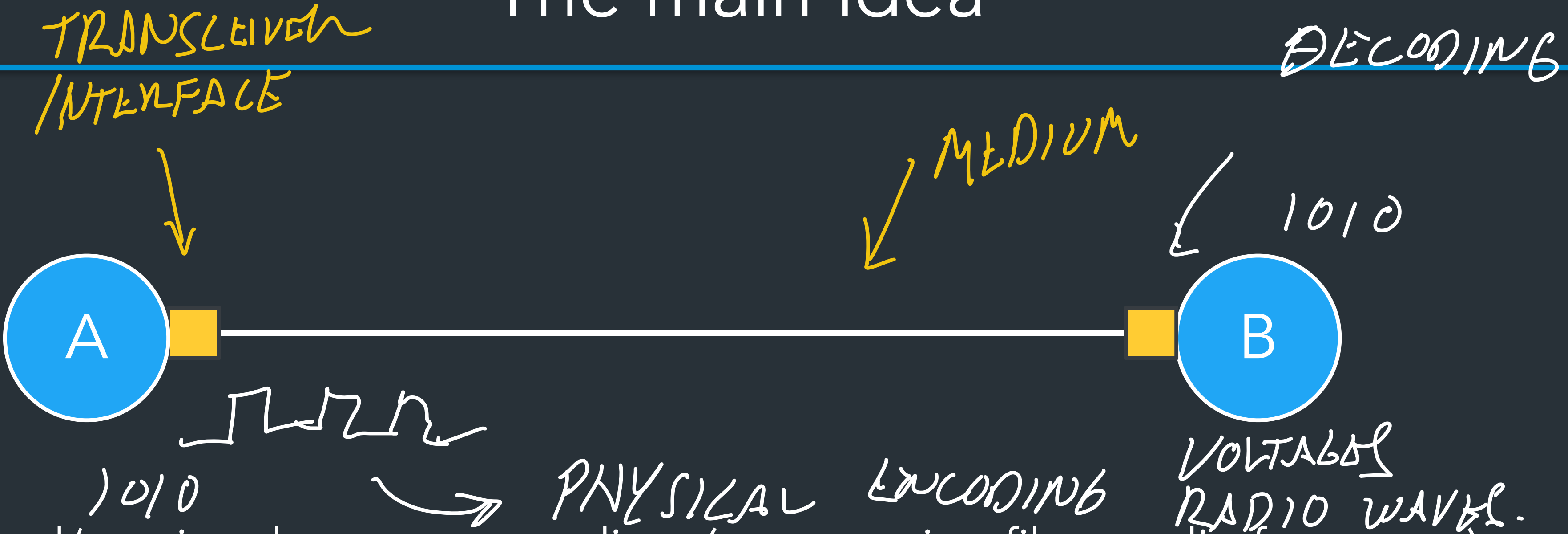
Why should we care?

This is the line between electrical engineering and computer science

Helpful to understand challenges involved
=> How design/limitations affect our systems

Also: Learn important principles we'll use elsewhere

The main idea



- Send/receive data over a medium (copper wire, fiber, radio frequency)
- Sender encodes message using some format, sends "over the wire"
- Receiver decodes (or recovers) message at the other end

What can go wrong?

- Noise
- Sharing channel: interference from other devices
- Physical distance (attenuation)
- Energy usage
- Security

=> Every medium has its own characteristics, and problems

Key points

- All media have fixed bandwidth => fixed “space” to transmit information

- Sending data takes time! => latency

- All media have (some) errors => how to deal with them?

Bandwidth

Bandwidth

- **Bandwidth** – frequencies that a channel propagates well
  - – Signals consist of many frequency components
- Creates a fixed "space" in which data can be transmitted

=> Wires: defined by physical properties

⇒ Wireless: frequency ranges are regulated

Upper bound on throughput: amount of data we can send per time (bits per second)

UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

- AERONAUTICAL MOBILE
- AERONAUTICAL MOBILE SATELLITE
- AERONAUTICAL RADIONAVIGATION
- AMATEUR
- AMATEUR SATELLITE
- BROADCASTING
- BROADCASTING SATELLITE
- EARTH EXPLORATION SATELLITE
- FIXED
- FIXED SATELLITE
- INTER-SATELLITE
- LAND MOBILE
- LAND MOBILE SATELLITE
- MARITIME MOBILE
- MARITIME MOBILE SATELLITE
- MARITIME RADIONAVIGATION
- METEOROLOGICAL
- METEOROLOGICAL SATELLITE
- MOBILE
- MOBILE SATELLITE
- RADIO ASTRONOMY
- RADIODETERMINATION SATELLITE
- RADIOLOCATION
- RADIOLOCATION SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- SPACE OPERATION
- SPACE RESEARCH
- STANDARD FREQUENCY AND TIME SIGNAL
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

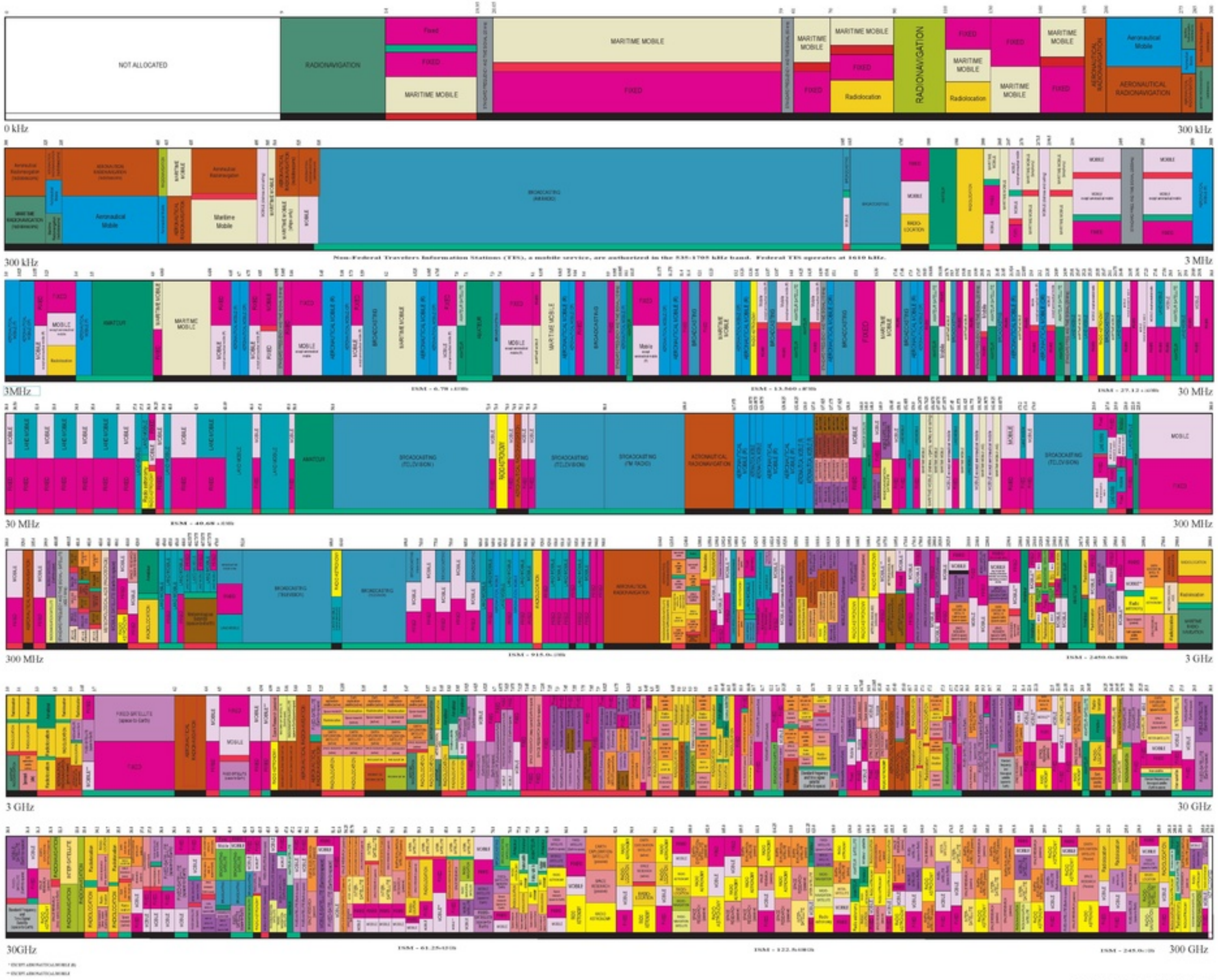
- FEDERAL EXCLUSIVE
- FEDERAL/NON-FEDERAL SHARED
- NON-FEDERAL EXCLUSIVE

ALLOCATION USAGE DESIGNATION

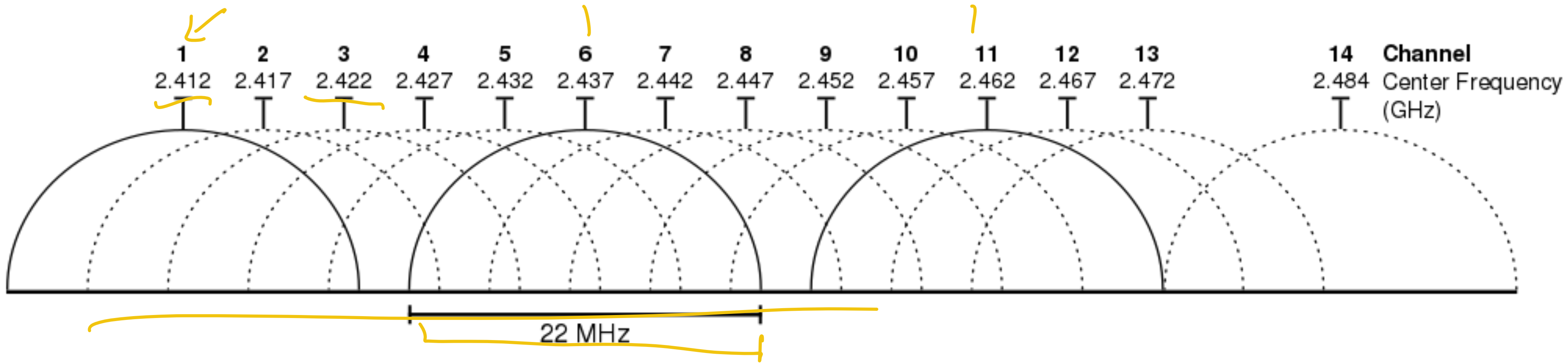
SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

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

JANUARY 2016

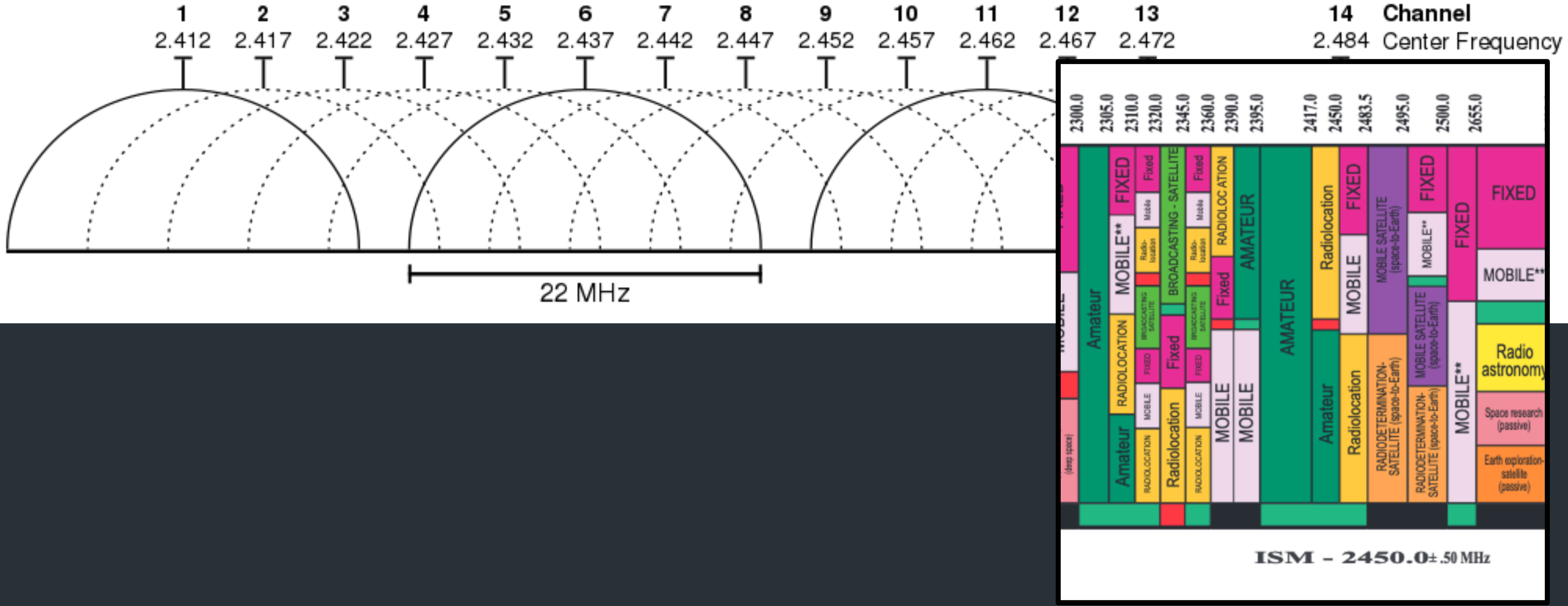


Early IEEE 802.11 (Wifi) channel bandwidth



"UNLICENSED BAND" 2.4 GHz

Early IEEE 802.11 (Wifi) channel bandwidth



Wi-Fi generations

V · T · E

Generation	IEEE standard	Adopted	Maximum link rate (Mbit/s)	Radio frequency (GHz)
Wi-Fi 7	802.11be	(2024)	1376 to 46120	2.4/5/6
Wi-Fi 6E	802.11ax	2020	574 to 9608[41]	6[42]
Wi-Fi 6		2019		2.4/5
Wi-Fi 5	802.11ac	2014	433 to 6933	5[43]
Wi-Fi 4	802.11n	2008	72 to 600	2.4/5
(Wi-Fi 3)*	802.11g	2003	6 to 54	2.4
	802.11a	1999		5
(Wi-Fi 2)*	802.11b	1999	1 to 11	2.4
(Wi-Fi 1)*	802.11	1997	1 to 2	2.4

*(Wi-Fi 1, 2, and 3 are by retroactive inference) [44][45][46][47][48]

802.11_

THROUGHPUT

BITS/S

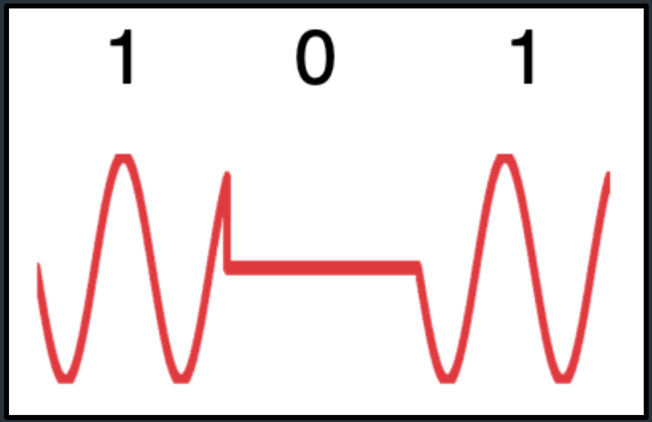
How to actually send stuff?

Modulation: how to vary a signal in order to transmit information

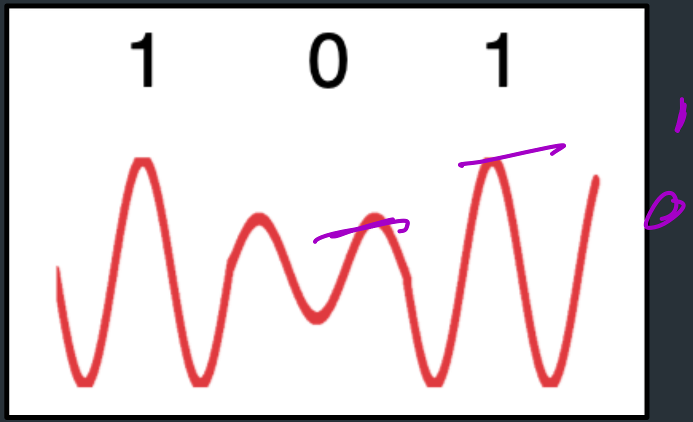
One way: Use Carriers

Start with a carrier frequency, modulate it to encode data:

OOK: On-Off Keying



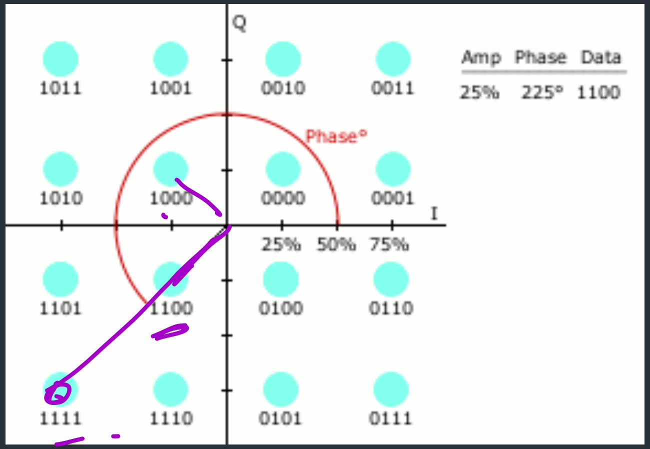
ASK: Amplitude Shift Keying



This can get more complex…

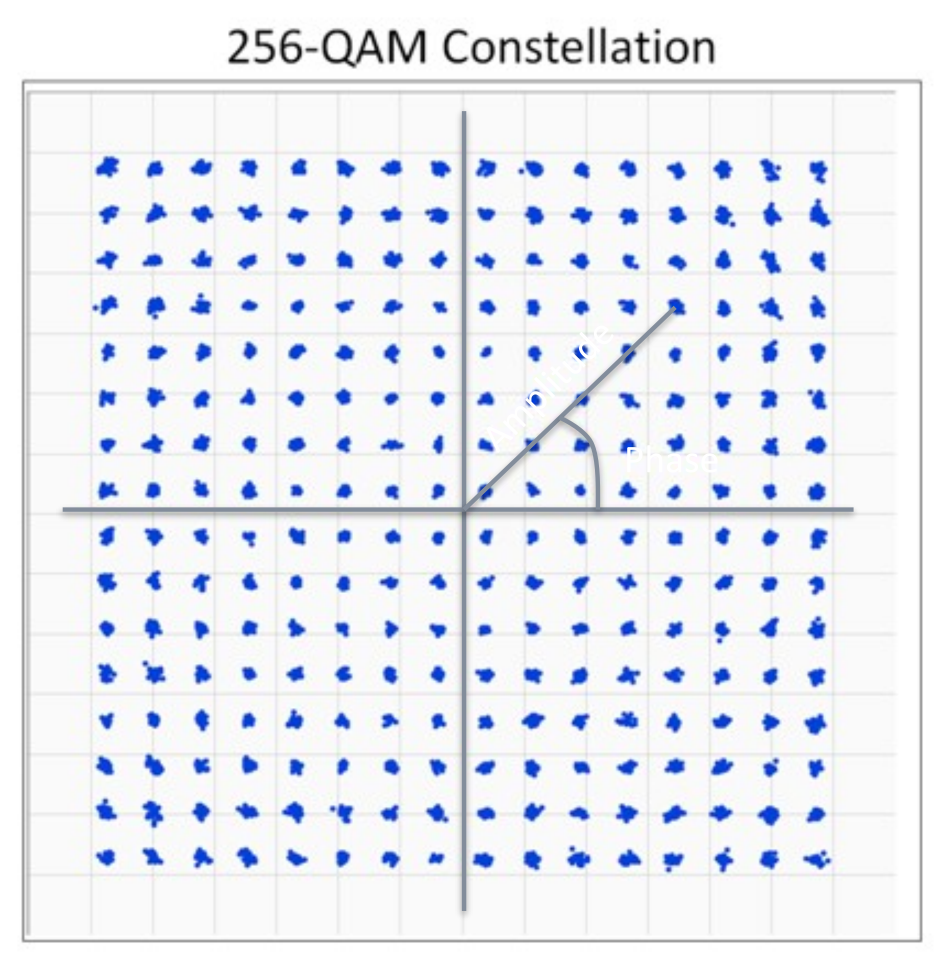
Lots of engineering you can do

- Multiple carriers/frequencies
- Adjust amplitude, phase
- Clever ways to avoid errors
- …



A good animation on Wikipedia

Example: Quadrature Amplitude Modulation (QAM)

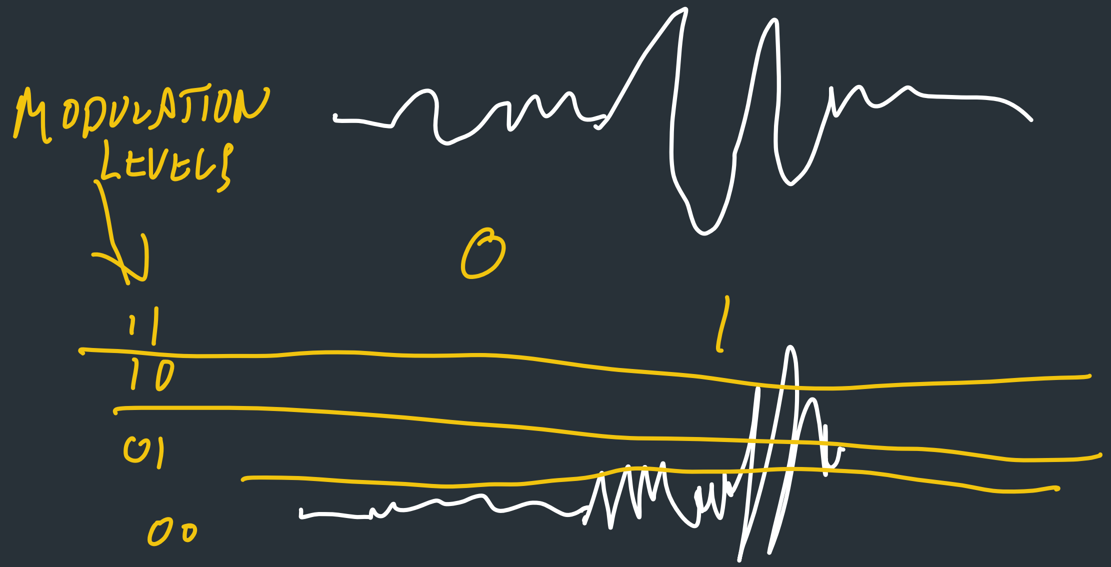


Modulation schemes in action

- https://www.youtube.com/watch?v=vvr9AMWEU-c

Sounds great, right?

- Problem: noise limits the number of modulation levels (M)



Sounds great, right?

- Problem: noise limits the number of modulation levels (M)

Shannon's Law: $C = B \log_2(1 + S/N)$

- C: channel capacity in bits/second ← THROUGHPUT
- B : bandwidth in Hz
- S, N: average signal, noise power

AMOUNT OF INFORMATION WE CAN FIT IN A CHANNEL: BANDWIDTH

SIGNAL/NOISE RATIO

Sounds great, right?

- Problem: noise limits the number of modulation levels (M)

Shannon's Law: $C = B \log_2(1 + S/N)$

- C: channel capacity in bits/second
- B : bandwidth in Hz
- S, N: average signal, noise power

=> For any medium, need to design encodings based on bandwidth, noise characteristics

Medium	Bandwidth	Throughput
Dialup	8 kHz	56 Kbit/s
Early Wifi (802.11g)	20 MHz	54 Mbit/s
Modern Wifi (802.11ax)	20-40 MHz	Up to 9 Gbps
Ethernet	62.5 MHz (1Gbps version)	1Gbit/s (common) Up to 100Gbps
3G cellular	Depends on carrier	2 Mbit/s
5G cellular	Depends on carrier	> 1 GBps

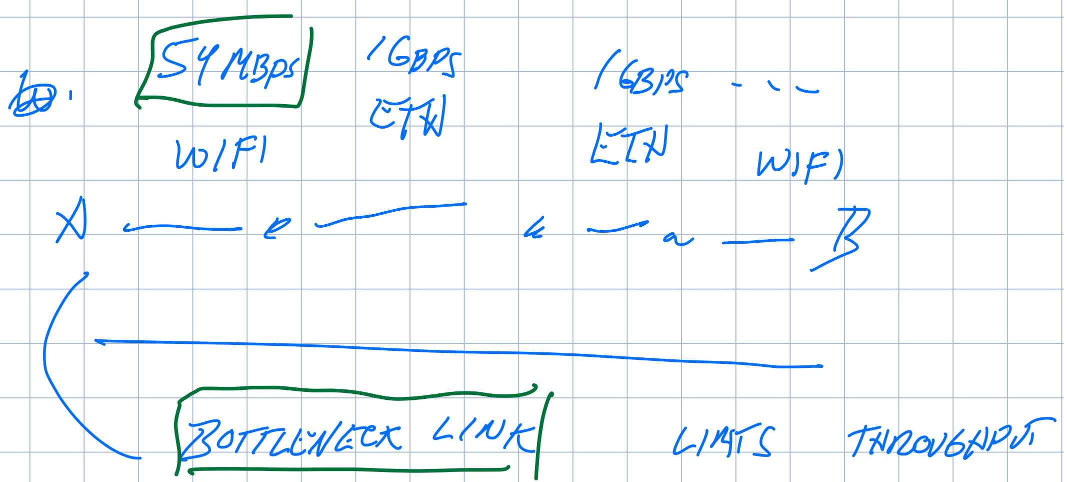
=> Does this mean wifi is the best?

10^{-9}

NOISE
INTERFERENCE
ETC...

10^{-12}

WHAT IF YOU HAVE MULTIPLE LINKS OF DIFFERENT SPEEDS?

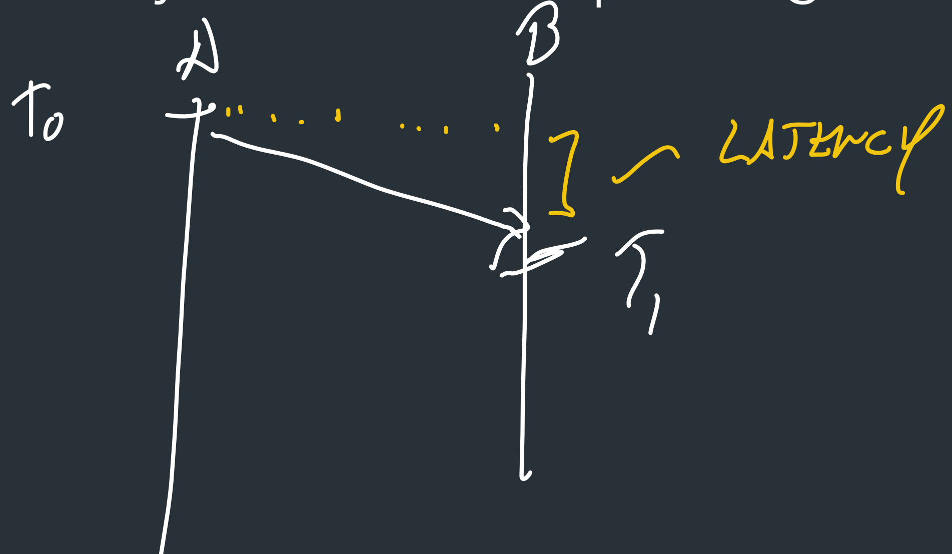


Latency

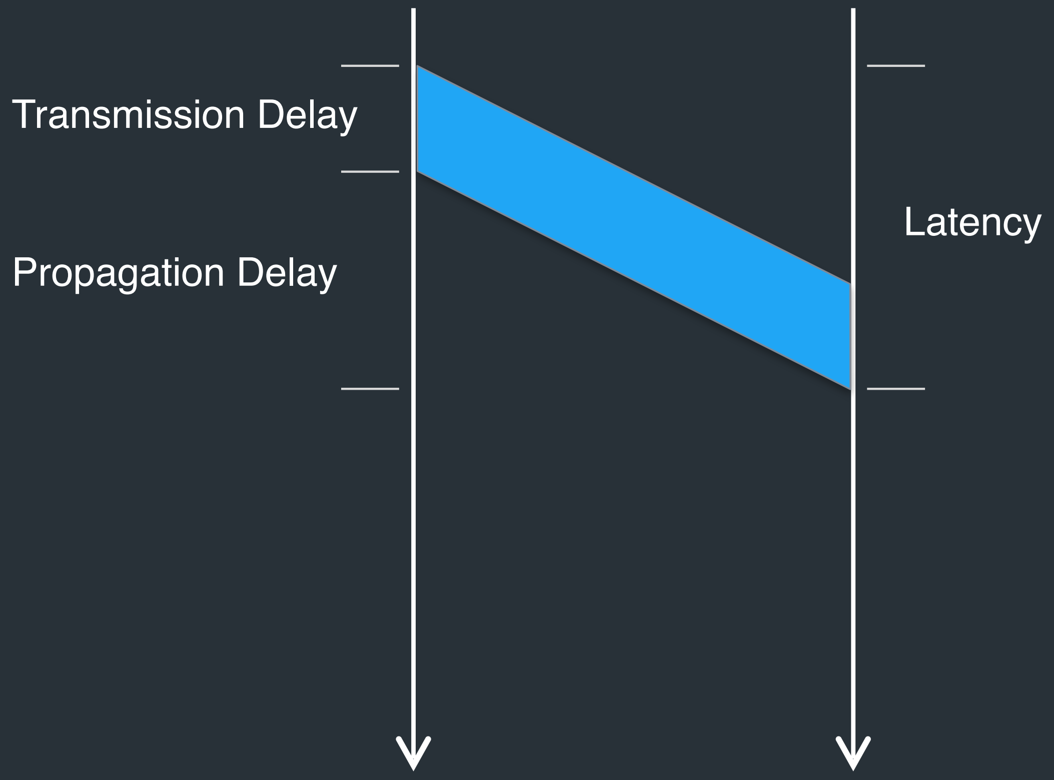
Sending data takes time!

- Latency: time between sending data and when data arrives (somewhere)

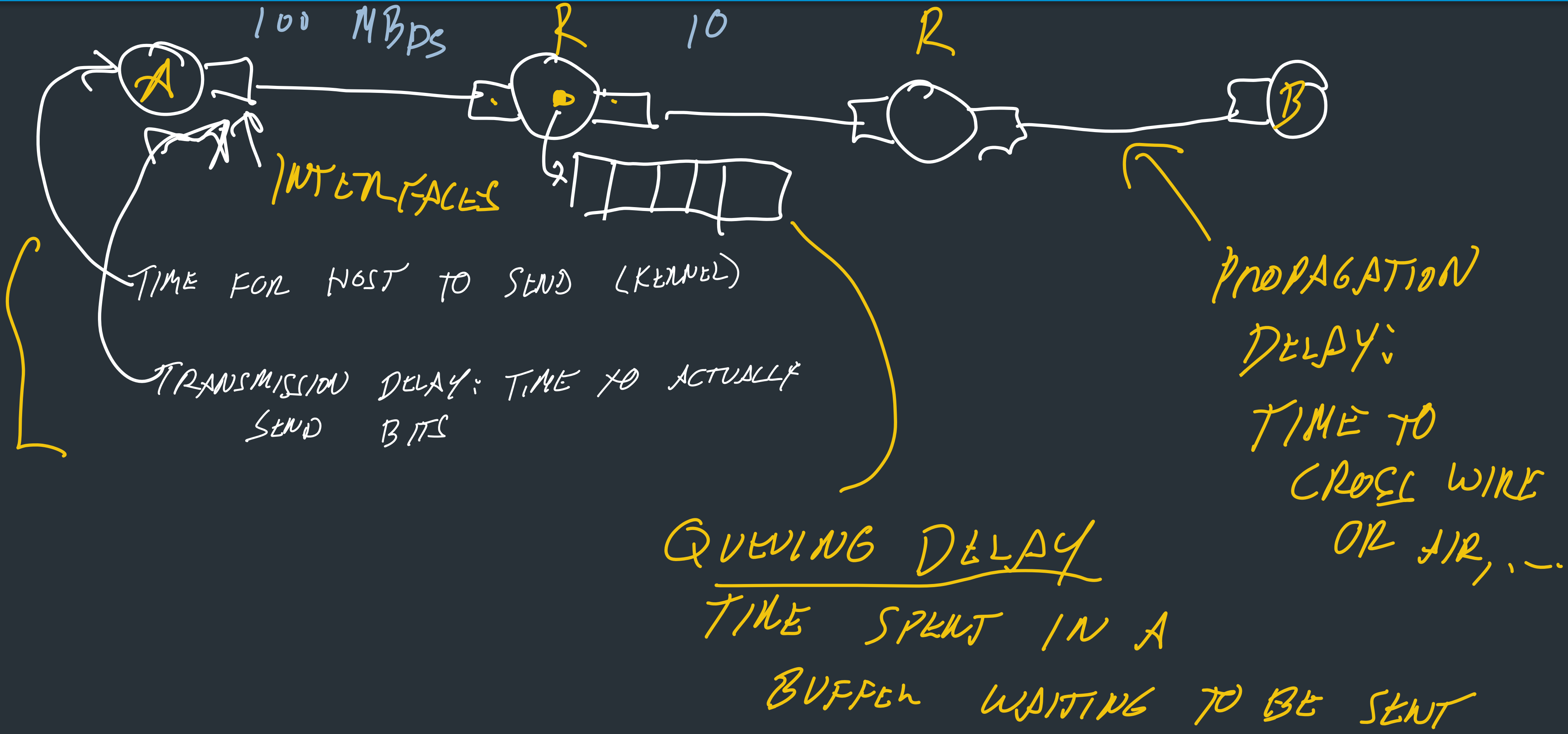
- Multiple components => many definitions, depending on what we're measuring



Sending Frames Across



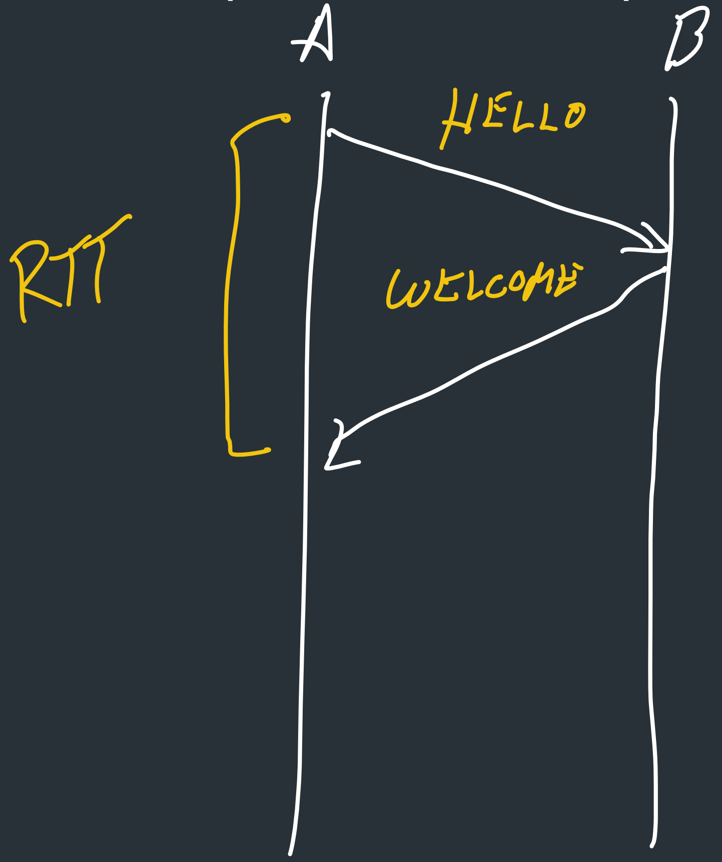
How to think about latency



How to think about latency

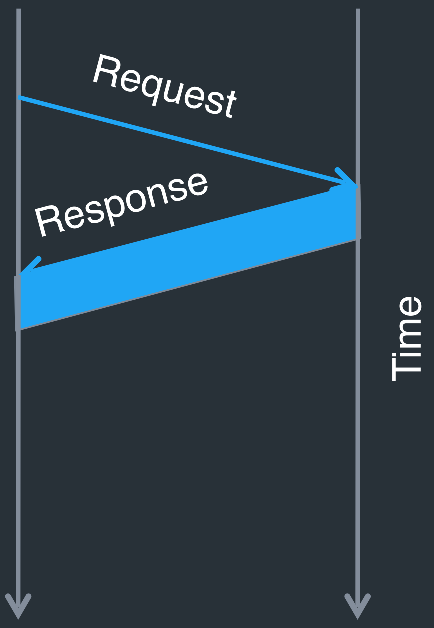
- Processing delay at the node: per message computation
- Queuing delay: time spent waiting in buffers
- Transmission delay: sending out the actual data
  - Size/Bandwidth
- Propagation delay: time for bits to actually go out on the wire
  - Upper bound?
  - Depends on media, ultimate upper bound is speed of light

Round trip time (RTT): time between request and response



Round trip time (RTT): time between request and response

When we design protocols, can think about performance based on number of RTTs



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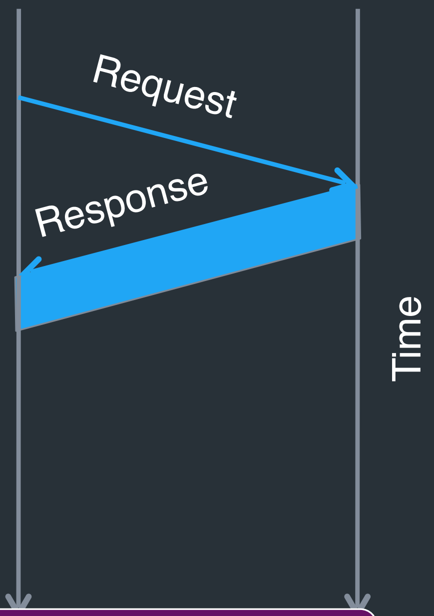
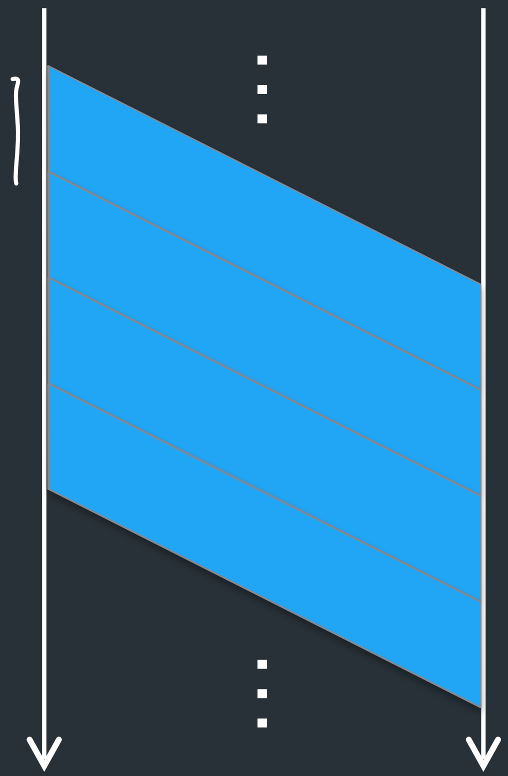


=> Not just about the physical layer!

Sending Frames Across



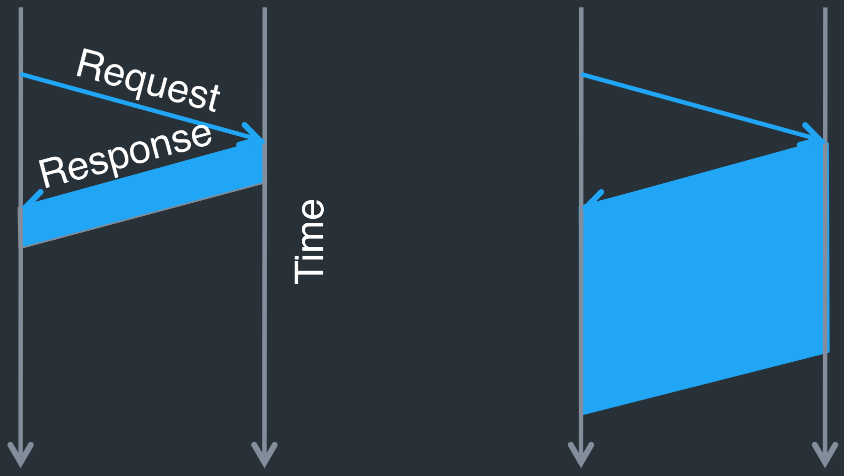
Throughput: bits / s

Error Detection

- Basic idea: use a checksum
  - Compute small check value, like a hash of packet
- Good checksum algorithms
  - Want several properties, e.g., detect any single-bit error
  - Details later

Which matters most, bandwidth or delay?

- How much data can we send during one RTT?
- E.g., send request, receive file



For small transfers, latency more important, for bulk, throughput more important

MORE CONTENT

WE DIDN'T COVER

FEEL FREE TO READ AHEAD!

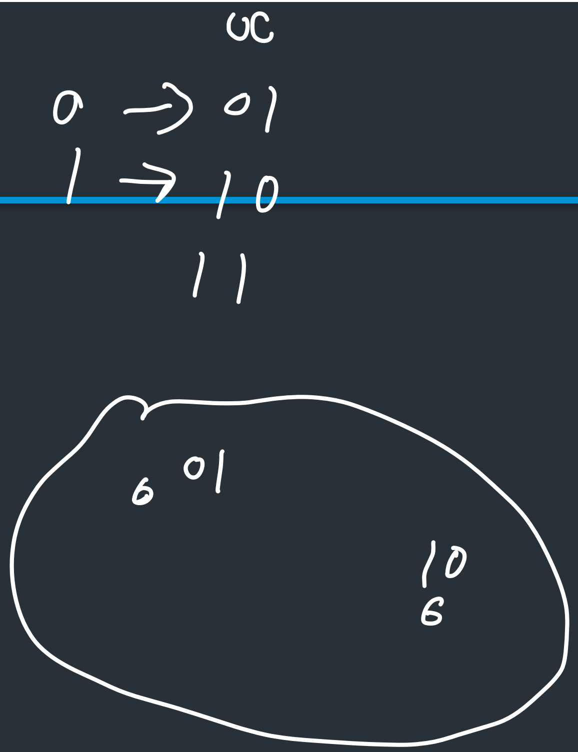
Performance Metrics

- **Throughput:** Number of bits received/unit of time
  - e.g. 100 Mbps
- **Goodput**: Useful bits received per unit of time
- **Latency**: How long for message to cross network
- **Jitter**: Variation in latency

Error Detection and Correction

Error Detection

- Idea: have some codes be invalid
  - Must add bits to catch errors in packet



Error Detection

- Idea: have some codes be invalid
  - Must add bits to catch errors in packet
- Sometimes can also correct errors
  - If enough redundancy
  - Might have to retransmit
- Used in multiple layers

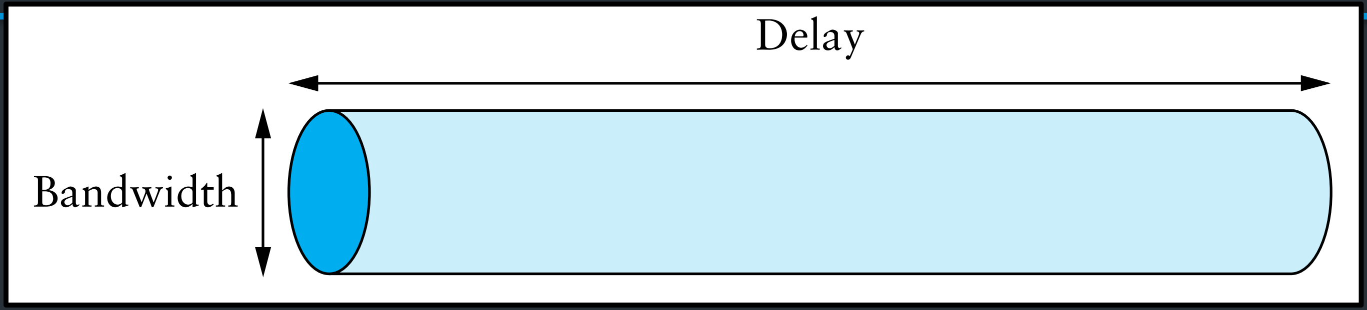
On reliable delivery

- Many link layer protocols don't account for reliable delivery!
  - Eg. Wifi does, Ethernet does not

- Usually, reliable delivery guaranteed by other protocol layers if needed, such as TCP

- Why might we NOT want reliable delivery at the link layer?

Maximizing Throughput



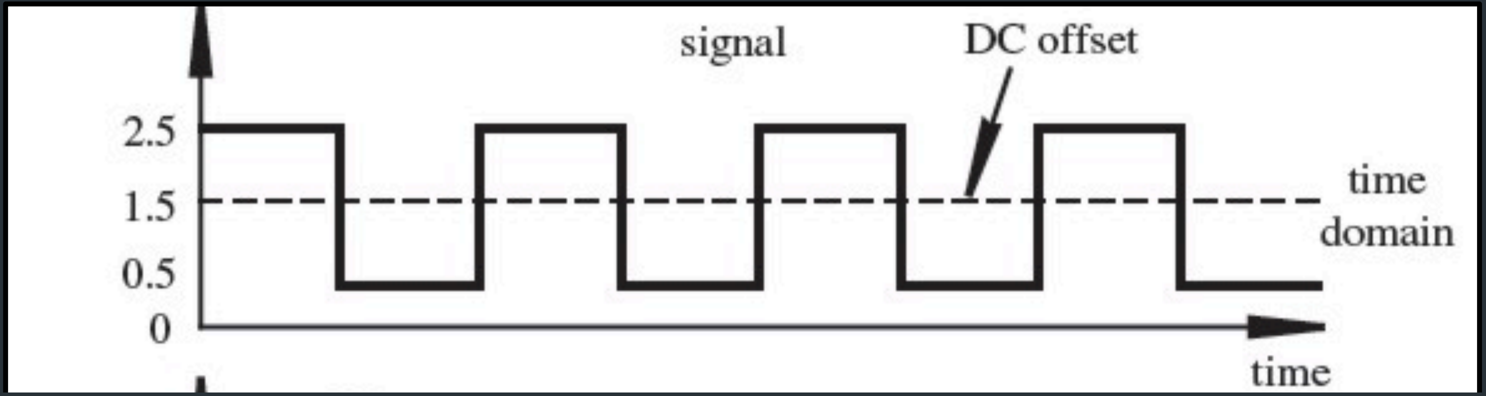
- Can view network as a pipe
  - For full utilization want bytes in flight ≥ bandwidth × delay
  - But don't want to overload the network (future lectures)

Summary: Reliable delivery

- Want exactly once
  - At least once: acks + timeouts + retransmissions
  - At most once: sequence numbers
- Want efficiency
  - Sliding window

Extra content

Components of a Square Wave



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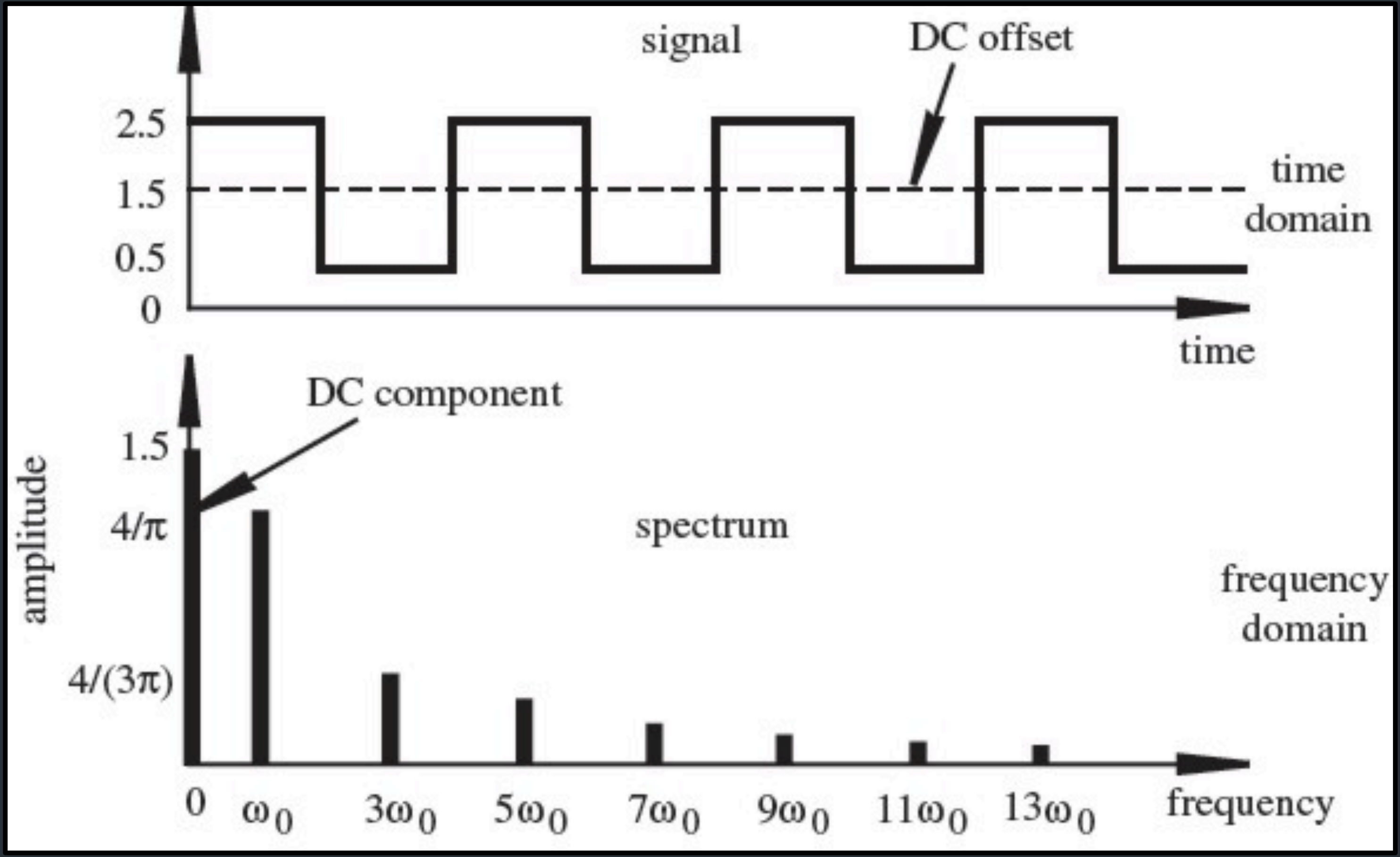
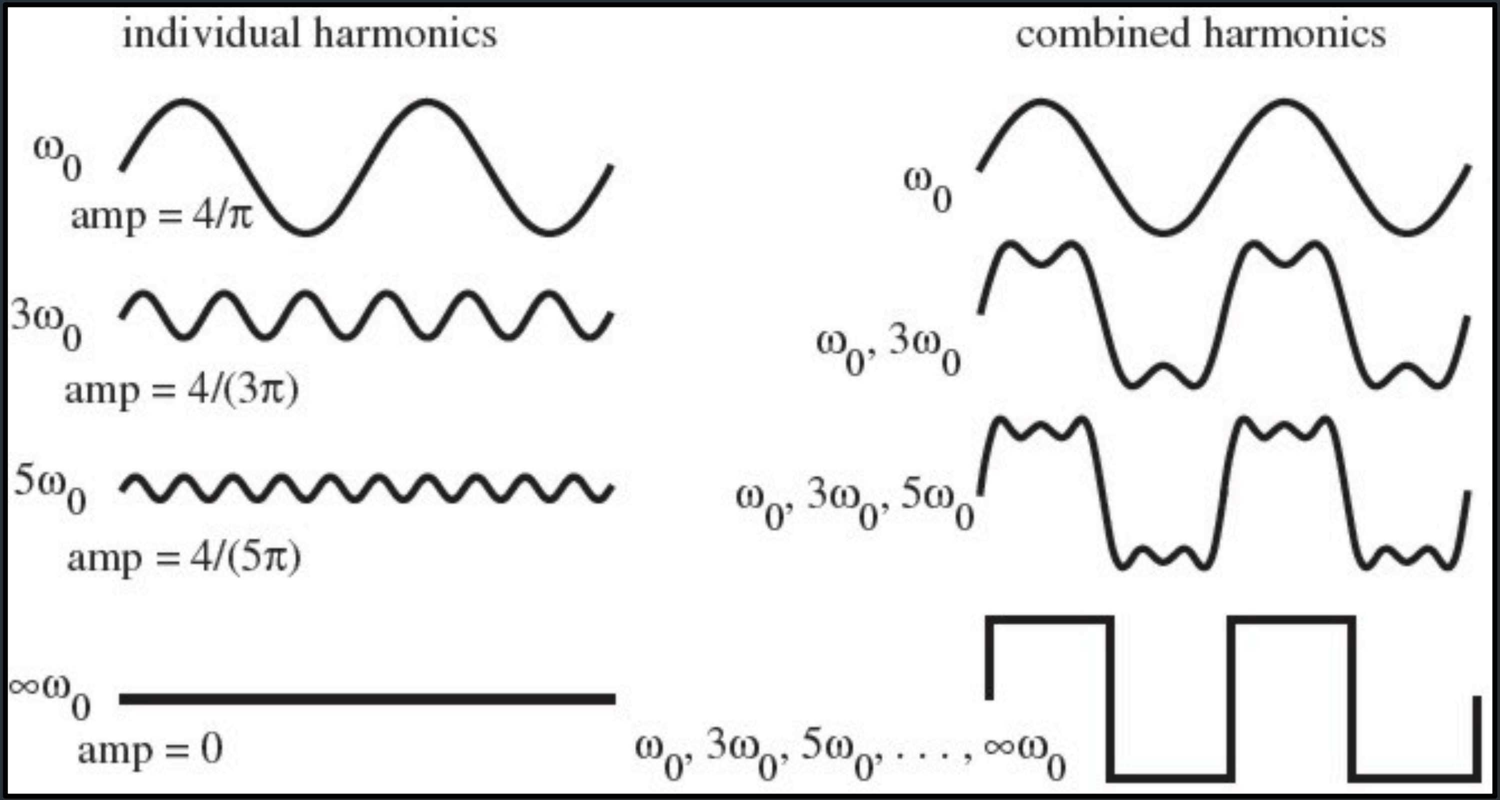


Graphs from Dr. David Alciatore, Colorado State University

Approximation of a Square Wave



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Can we do better?

Can we do better?

- Suppose channel passes 1KHz to 2KHz
  - 1 bit per sample: alternate between 1KHz and 2KHz
  - 2 bits per sample: send one of 1, 1.33, 1.66, or 2KHz
  - Or send at different amplitudes: A/4, A/2, 3A/4, A
  - n bits: choose among 2^n frequencies!

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What is the capacity if you can distinguish M levels?

Hartley’s Law

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$$C = 2B \log_2(M) \text{ bits/s}$$

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Great. By increasing M, we can have as large a capacity as we want!

Or can we?

The channel is noisy!

Putting it all together

- Noise limits M!

$$2B \log_2(M) \le B \log_2(1 + S/N)$$

$$M \le \sqrt{1+S/N}$$

Example: Telephone Line has 3KHz BW, 30dB SNR

- S/N = 10ˆ(30 dB/10) = 1000
- $C = 3KHz \log_2(1 + 1000) \approx 30Kbps$
- M < sqrt(1001) ≈ 31 levels

Putting it all together

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Signal-to-noise ratio (SNR)
is typically measured in Decibels (dB)
$dB = 10\log_{10}(S/N)$

Manchester Encoding

- Map 0 → 01; 1 → 10
  - Transmission rate now 1 bit per two clock cycles
- Solves clock recovery & baseline wander
- … but halves transmission rate!