Lecture 8: The Physical Layer

How do point-to-point links work?

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Chapter 3

Recap

- So far, we have been studying routing, which tells the "network/internet layer" how to route packets by filling its forwarding table
- For the next several lectures, we will come back to the layered architecture of the internet, and work our way slowly upwards starting from the physical layer

Rough approximation of the layers of the internet

Application Layer
Transport Layer
Network Layer (IP)
Link Layer
Physical Layer

This lecture and the next three

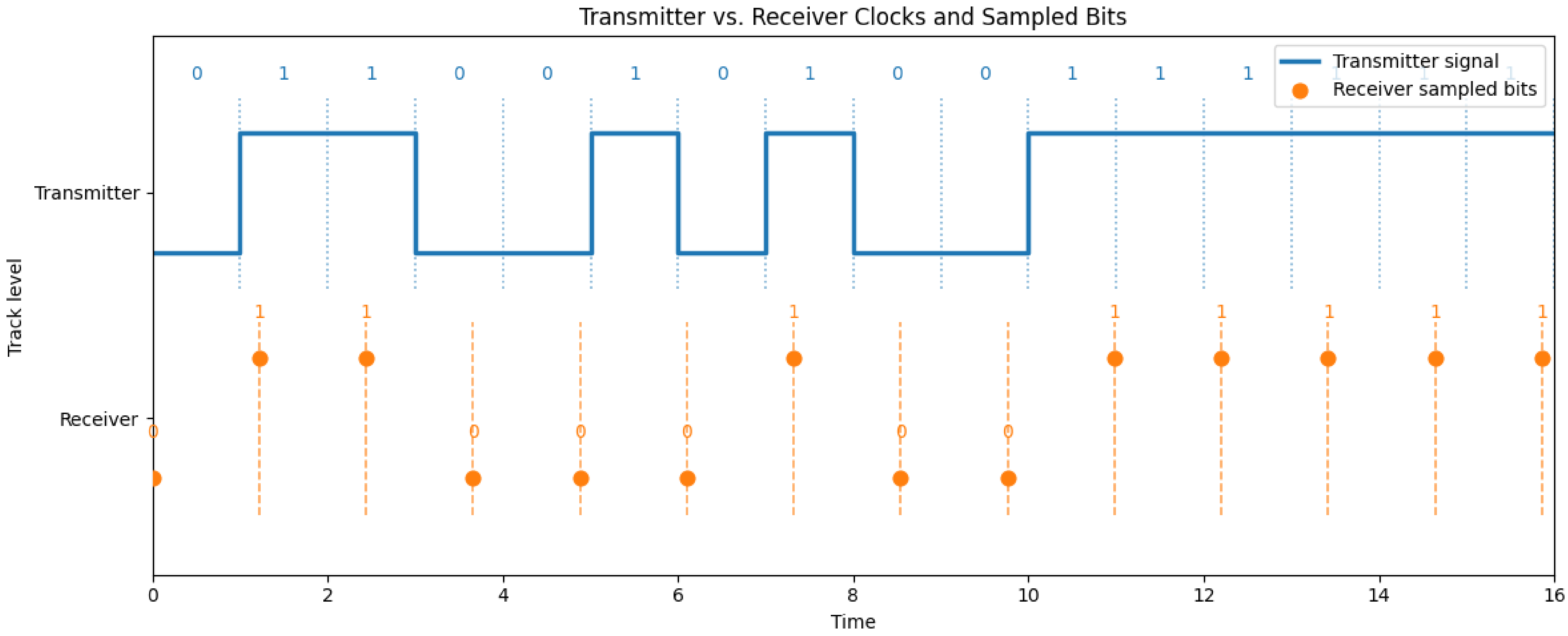
Today’s lecture

Goal: Understand just enough about the physical world that we can make good engineering decisions in the world of bits and bytes

Two topics

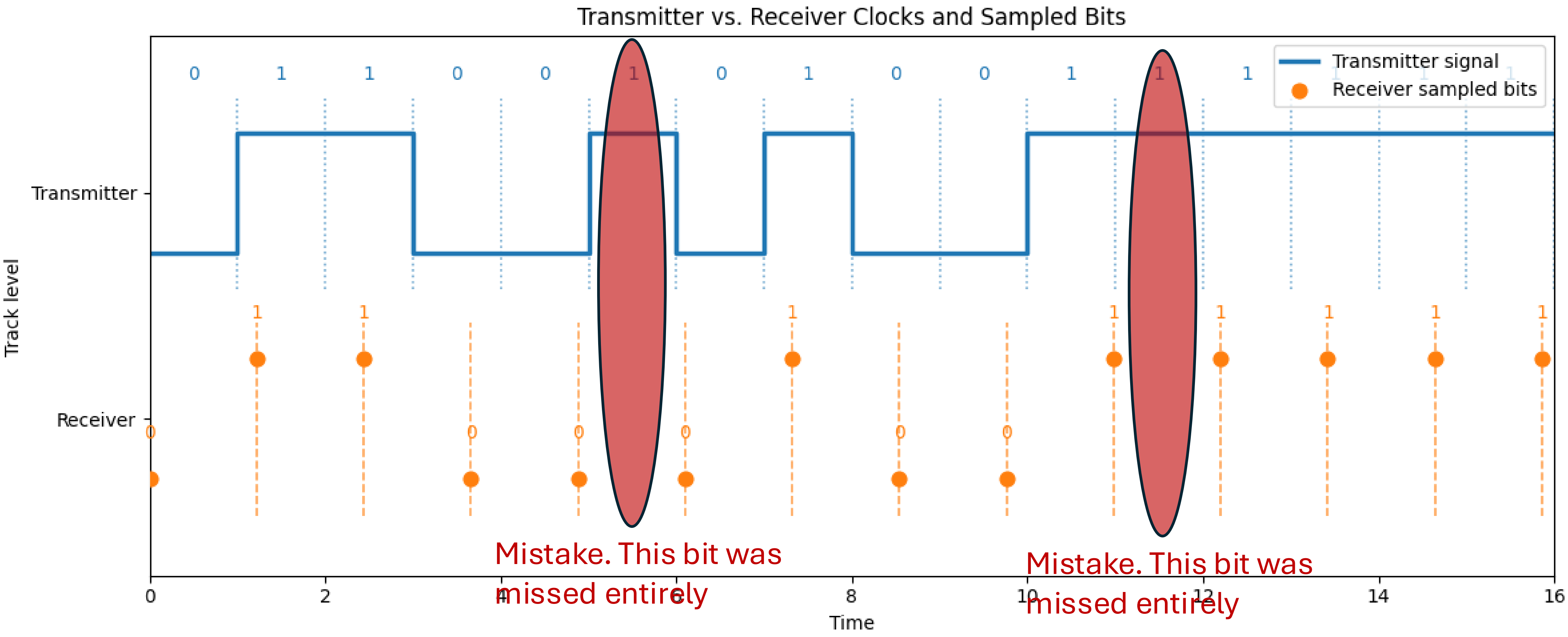
- Clocks
- Frequency sharing: aka Graham Bell’s harmonic telegraph that could send multiple signals on the same wire

Clocks in communication



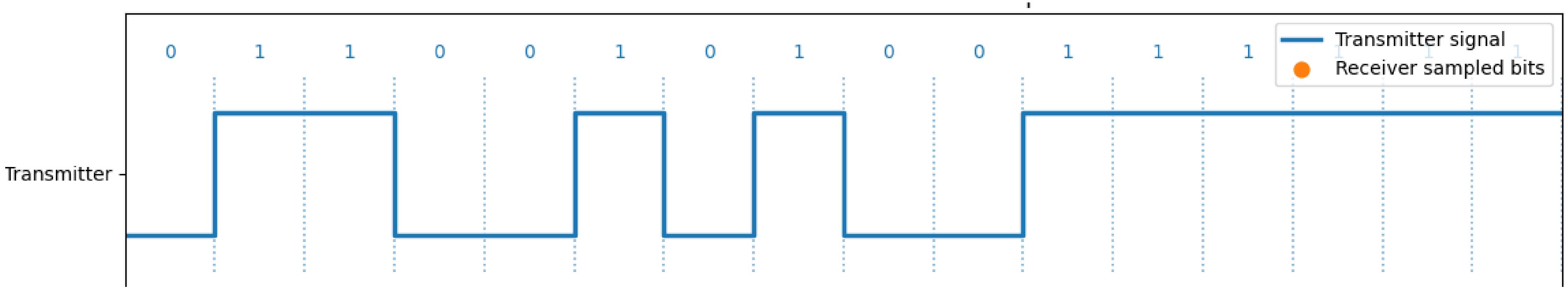
If the transmitter and receiver's clocks are not synchronized, there can be an error in transmission. Here, the receiver's clock is 22% slower than the transmitter's clock

Clocks in communication



If the transmitter and receiver's clocks are not synchronized, there can be an error in transmission

Synchronizing clocks (chapter 2.2)

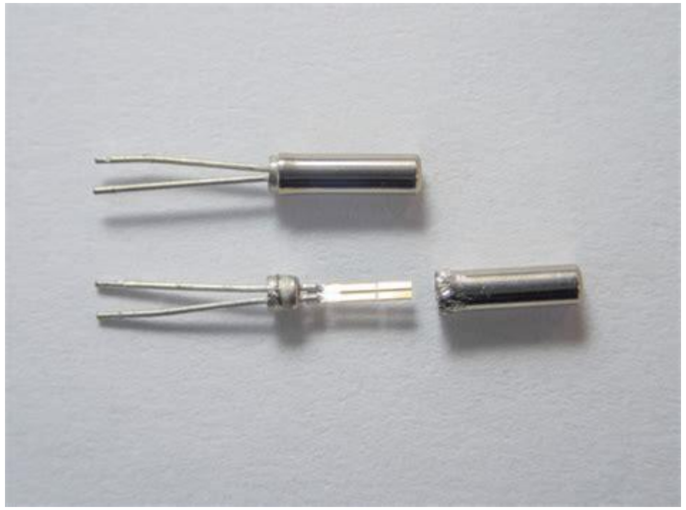


The receiver can observe when the transmitter has their edges, use it to estimate the difference in their frequencies and adjust their clock to match the transmitter's

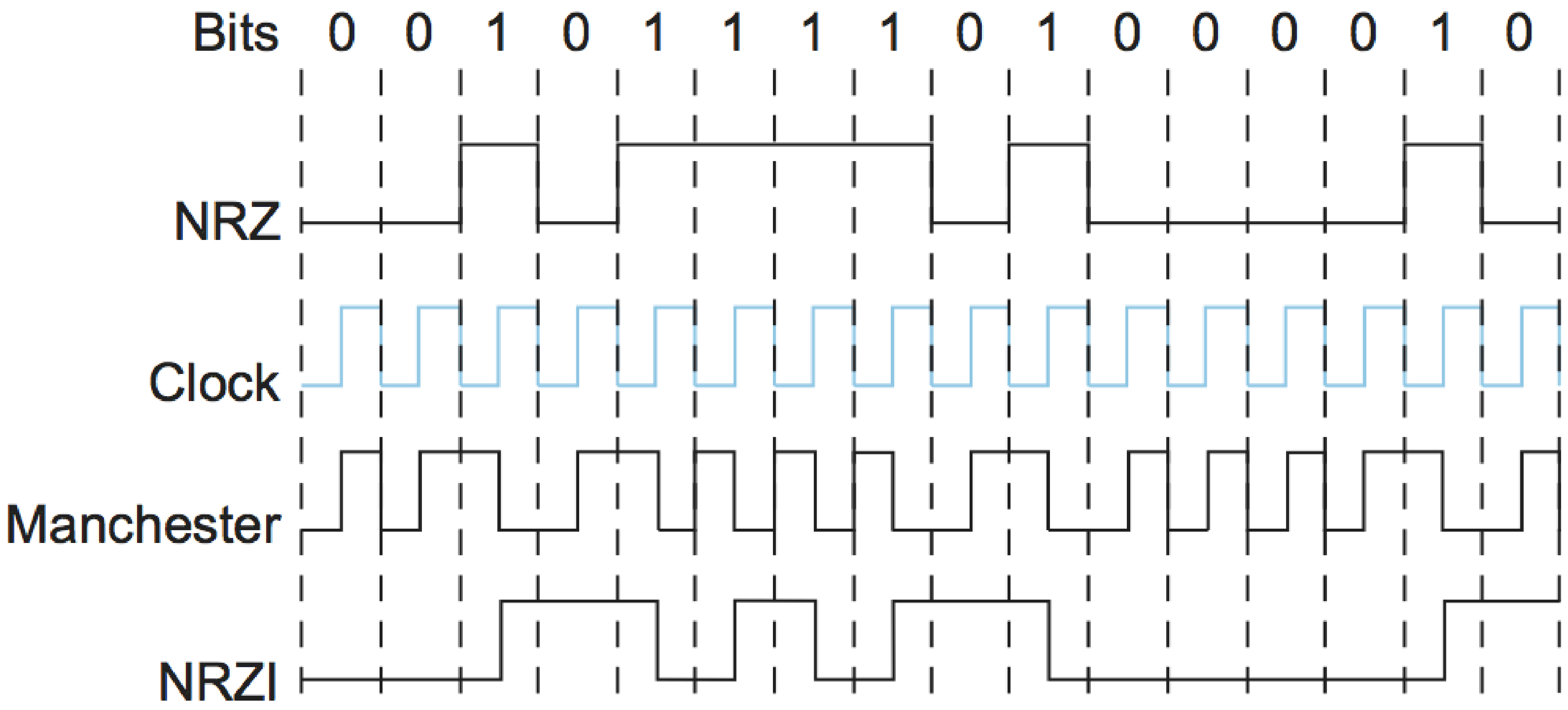
Problem: Clocks can get desynchronized if there is a long sequence of 0s or 1s, in which case there are no edges to synchronize the clocks

Quality of clocks

Quartz crystals are the workhorse of clocks today. Can achieve a frequency accuracy of up to 5 parts per million (ppm). That is, if it is rated to oscillate at frequency f, it will oscillate in the range $f\ (1 \pm 5\ *\ 10^{-6})$



Data encoding strategy: Manchester encoding



NRZ simply means high voltage is 1, low voltage is 0

In Manchester, we look at the transition in the middle of the cycle. Low → high is 0. High → low is 1. Equivalently, it is (NRZ XOR clock)

Solves the clock-sync problem, but the final signal varies twice as fast as the original

Next segment: why that is bad

Baud rate

The rate at which the signal varies (number of flips/second)

For any encoding, increasing the baud rate increases the bandwidth. Should we increase it to infinity?

Your intuition probably says no. The precise reason is out of scope of this course, but I will explain a little in class

Alternate encoding strategy

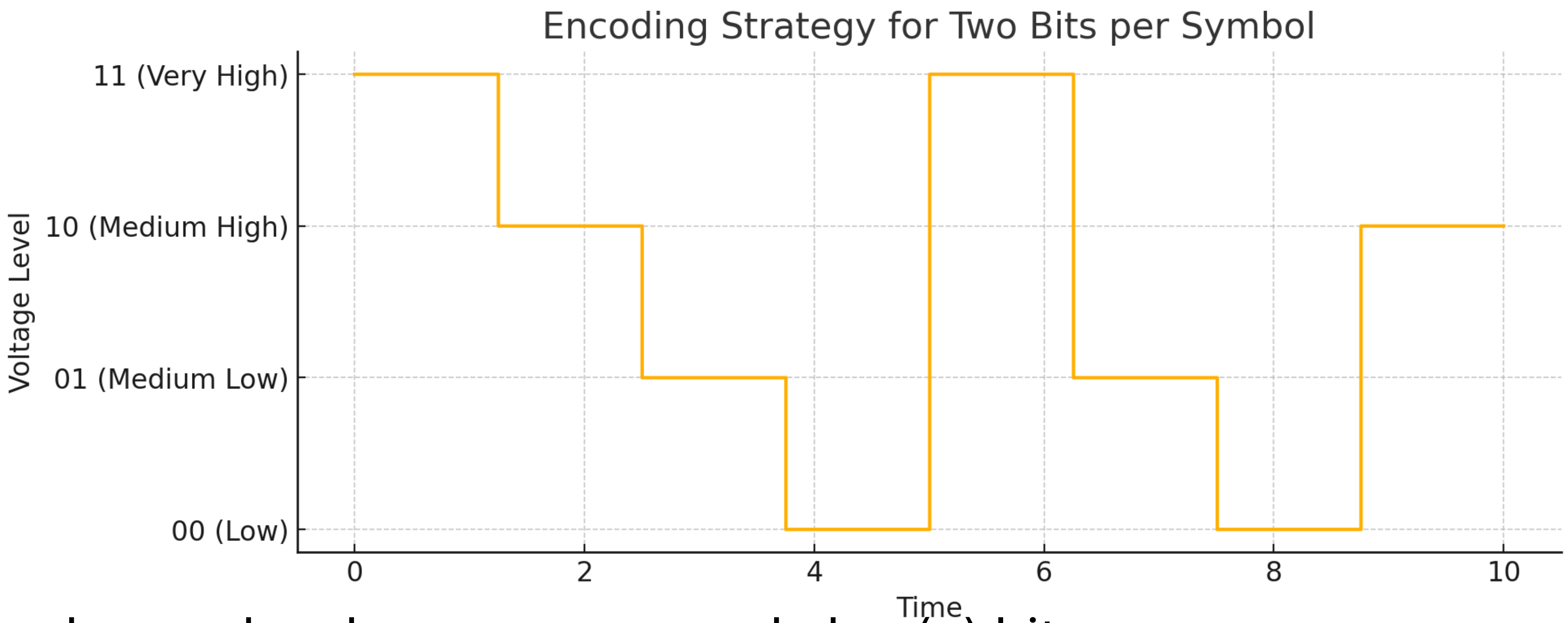
- Encoding strategy is by no means hard. For example, you could do: “if you see 5 consecutive zeros, the next bit *will* be a 1. That one is only for creating an edge. It is not data. Ignore it and look at the bit afterwards”
- This way, bit strings are encoded normally unless there is a string of 5 or more 0s or 1s.
- So “101100000011” becomes “1011000001011”. The red 1 is not a data bit. it is just there to create a transition

- Increases baud rate minimally. There are other tradeoffs because of which people pick different encodings.

Fundamental capacity of a link

(not in book)

Encoding multiple bits per symbol



If you have n levels, you can encode log (n) bits

E.g. if the noise is ¼ the strength of the signal, you can have 4 levels

In general, you can encode log(SNR) bits, where SNR is the signal to noise ratio

Fundamental capacity of a link

Capacity = number of symbols/second * number if bits/symbol

= baud rate * log(SNR)

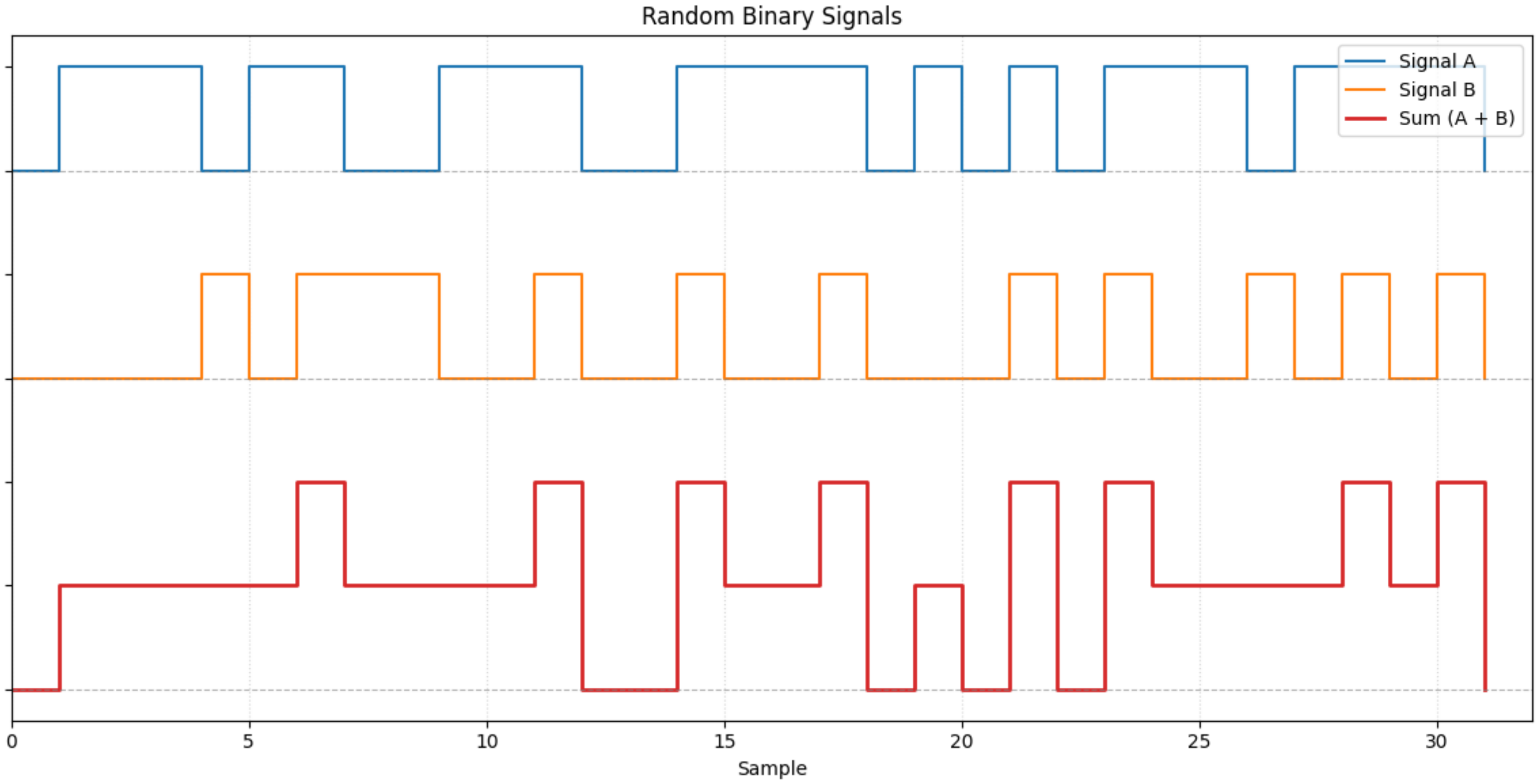
As we shall see, several things limit the baud rate

What limits the baud rate?

What limits the baud rate?

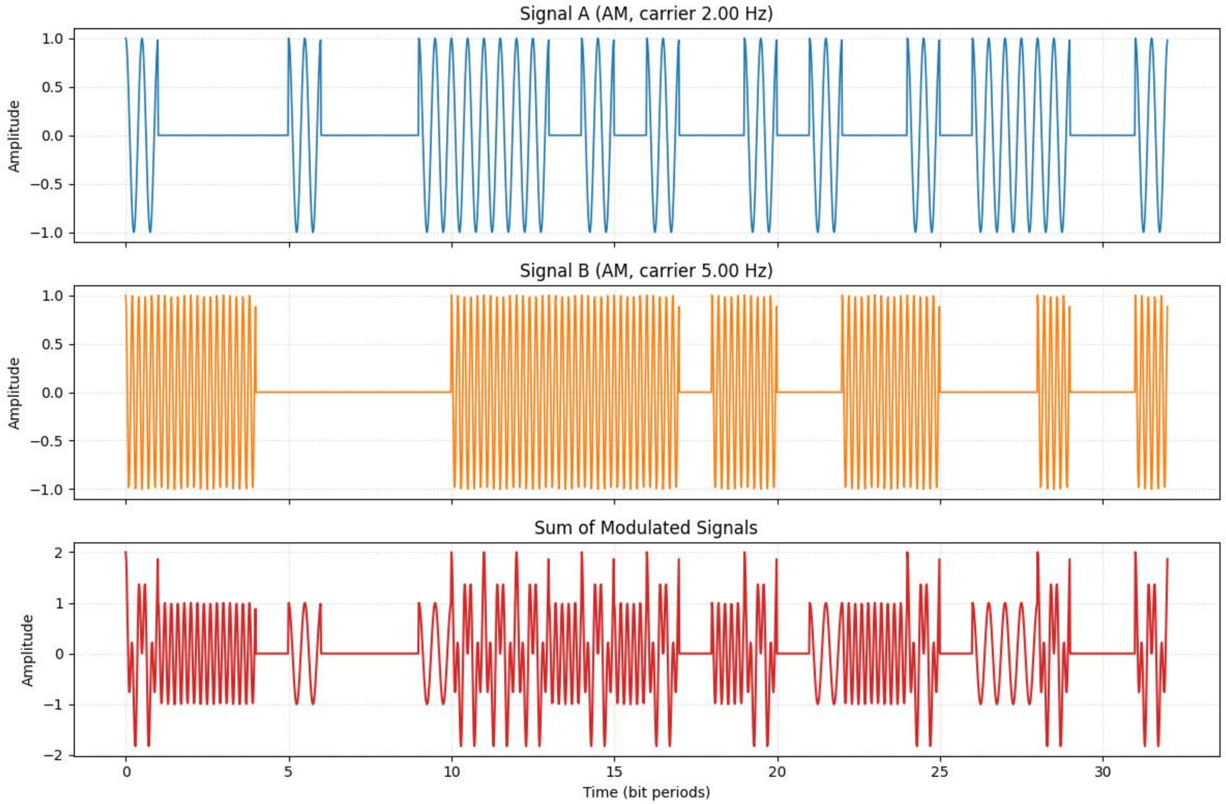
- Transducer limit: How quickly the electronics can switch: usually limited to a few “giga-switches” a second (note, “giga-switch” is not a standard term)
- Physical medium limit: Whether the physical medium can accurately relay signals that vary that quickly
- (Demonstrated on the board) for example, in a multi-modal fiber optic cable, light spreads out in time. This limits baud rate. Every medium has one limit or another.

Sending multiple signals on the same wire



If we just send indiscriminately, the signals get added up in the physical medium. Then it becomes impossible to distinguish which signal is which

Sending multiple signals on the same wire

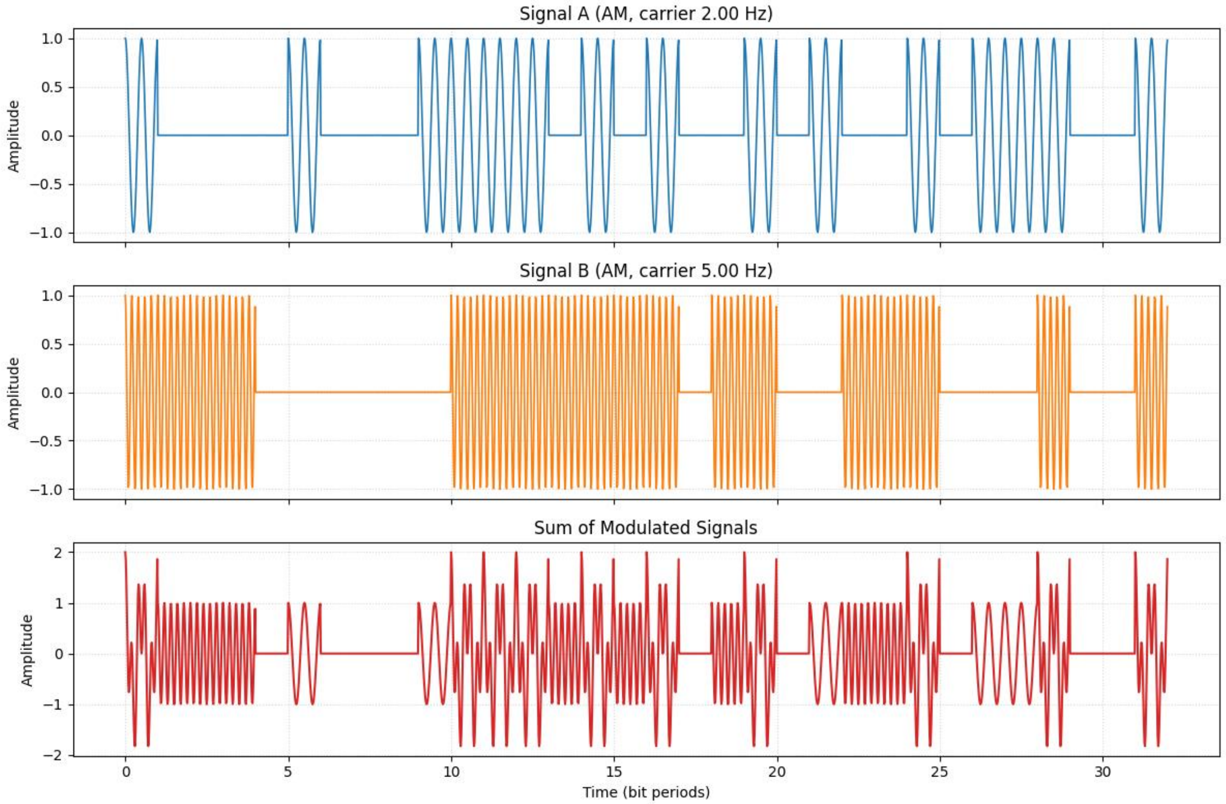


If instead, we multiply the source signals with sinusoids of different frequencies, we can distinguish the two different signals in the resulting sum.

i.e. if m(t) is the binary signal, then send m(t) * sin(f t), where f is the carrier frequency

How do we distinguish signal A and B? We will not discuss that in this course. The field is called signal processing

Sending multiple signals on the same wire



Does this mean we can send infinitely many signals? Just pick a slightly different carrier frequency each time?

Obviously not. Infinite bit rate isn't possible

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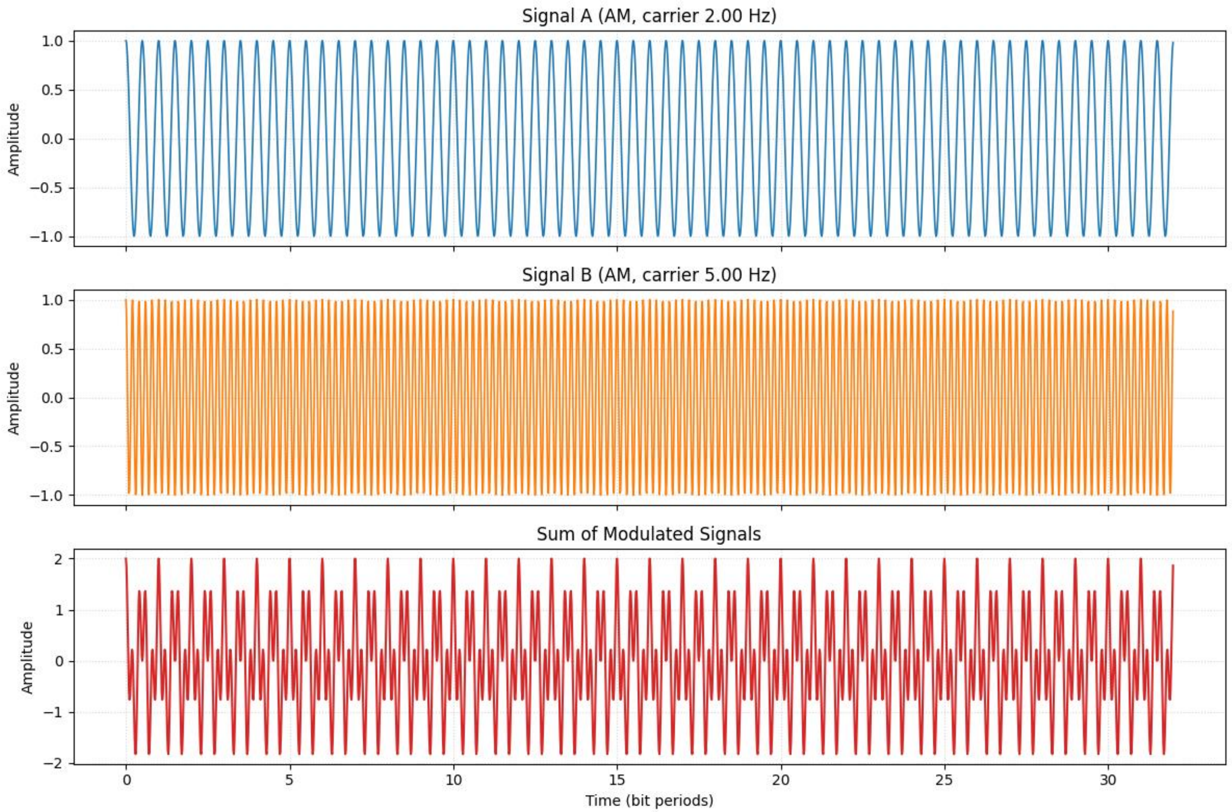
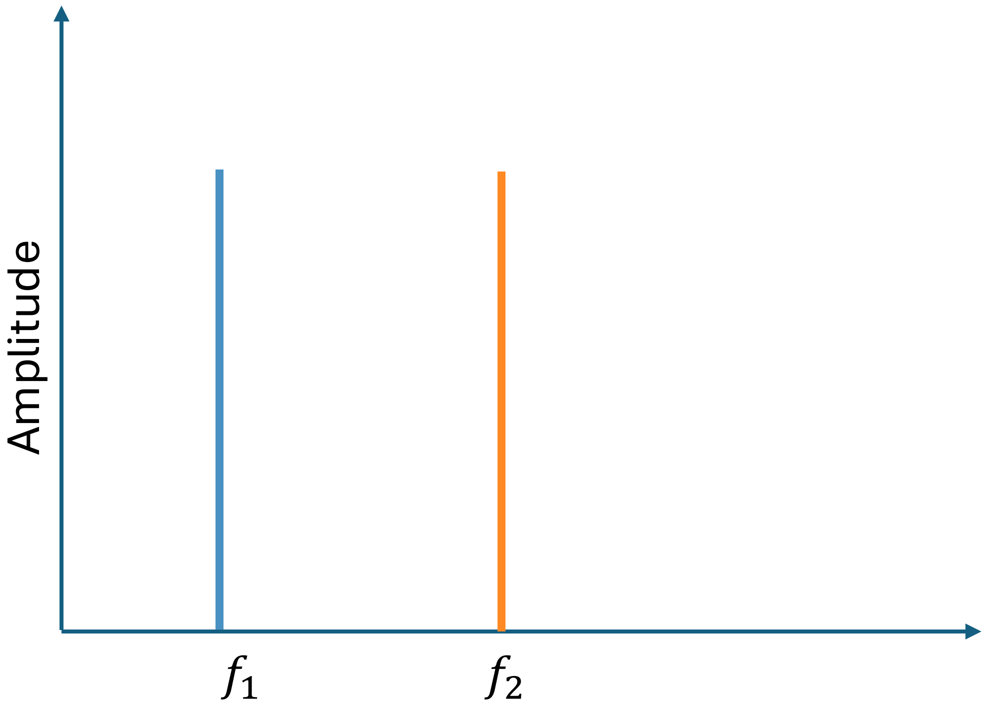
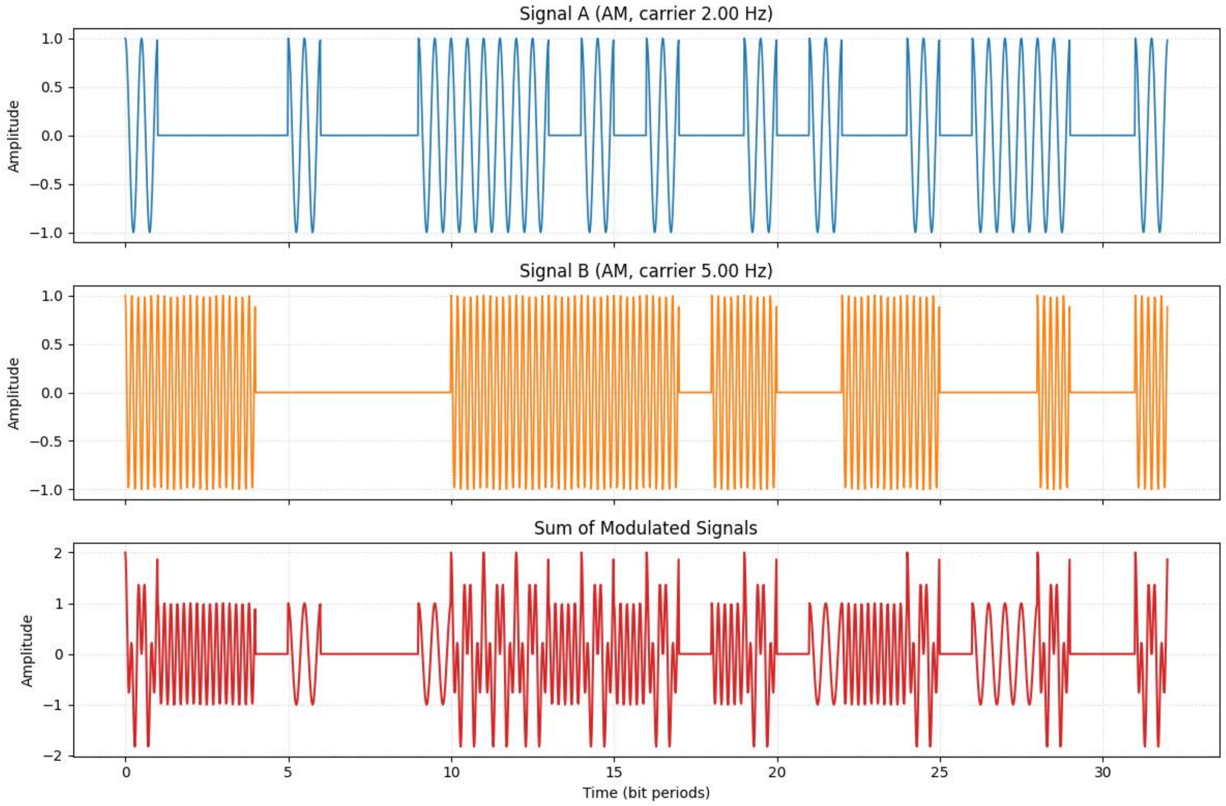


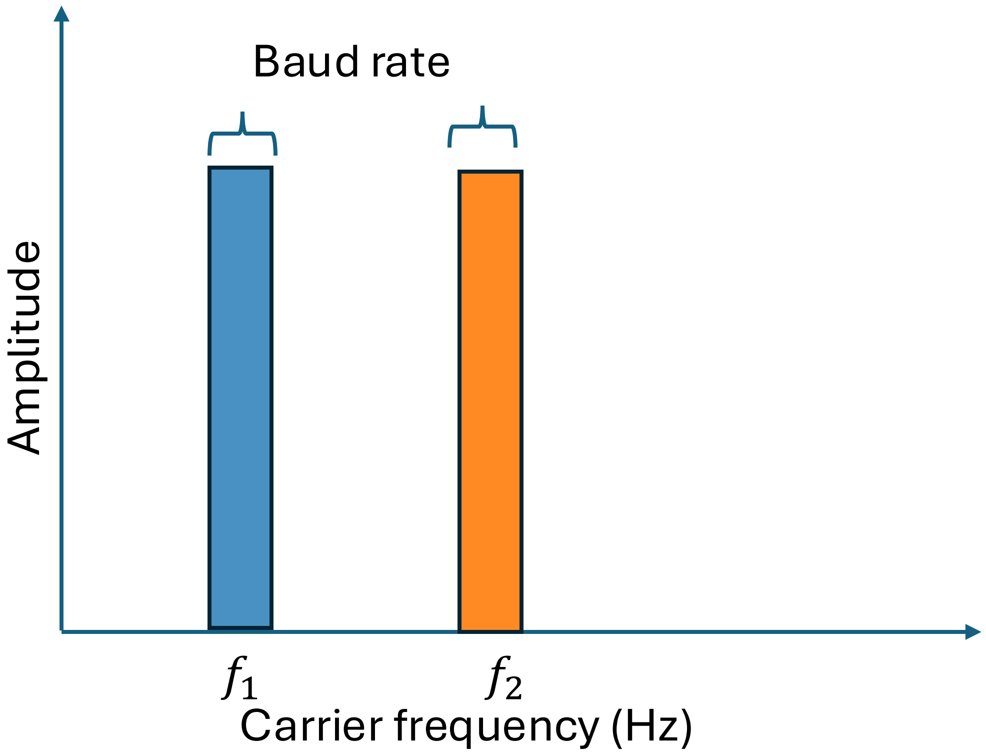


We send pure carrier frequencies: $\sin(f_1 t) + \sin(f_2 t)$ (shown on the left)

We represent this on the right as two “delta functions” (i.e. vertical lines) at those frequencies. This is called the frequency-domain representation

Sending multiple signals on the same wire



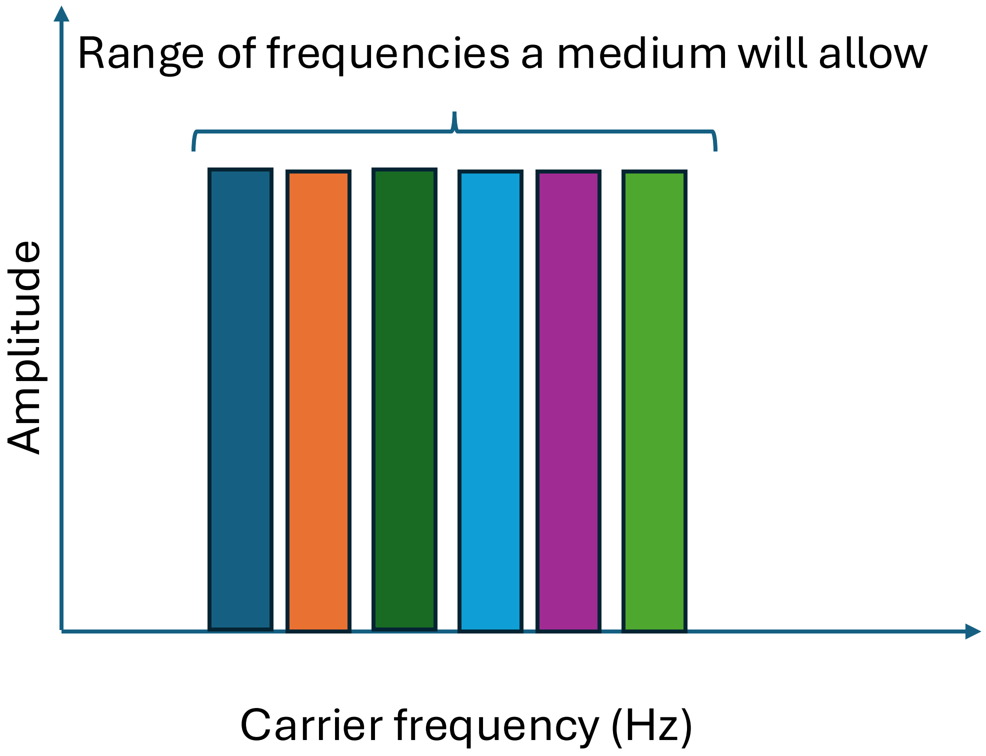


Once you modulate the carrier signal with the message, the two peaks on the representation on the right become broader. Their width is proportional to the baud rate (also measured in Hz).

Interference is guaranteed to not occur as long as the rectangles in the frequency domain representation do not overlap. This is another limit on the baud rate

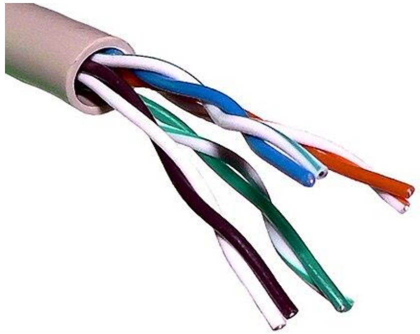
Types of physical links

- Wired
  - Copper wires
    - Twisted pair
    - Coaxial cables
  - Optical fibers
    - Uni/multi-modal
- Wireless
  - WiFi
  - Cellular
  - Satellite
    - Low earth orbit (LEO)
    - Geostationary orbit (GEO)

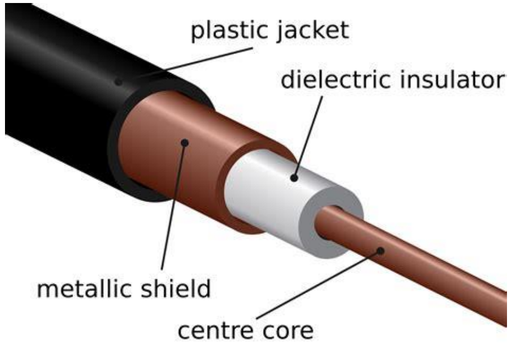


Each type of link has a range of frequencies in which it will operate. You can assign “bands” within that range to different transmitters

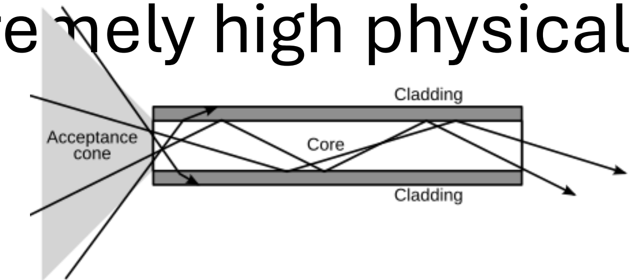
Wired physical layer media

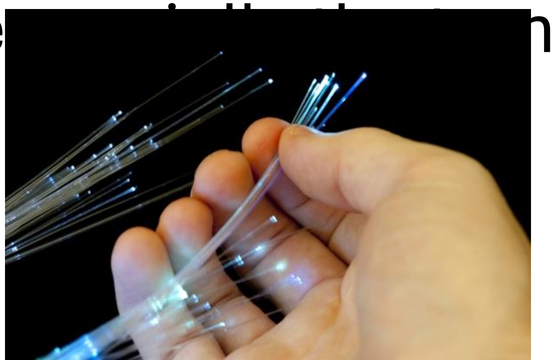


- Twisted pair – inexpensive, lower capacity (e.g. USB)
- Coaxial cable – more expensive, higher capacity
  - Why not any old wire? – out of scope, but we will discuss in class



- Optical fiber – even more expensive, e[illegible]nsducers, extremely high physical bandwidth





Wireless links sharing the air

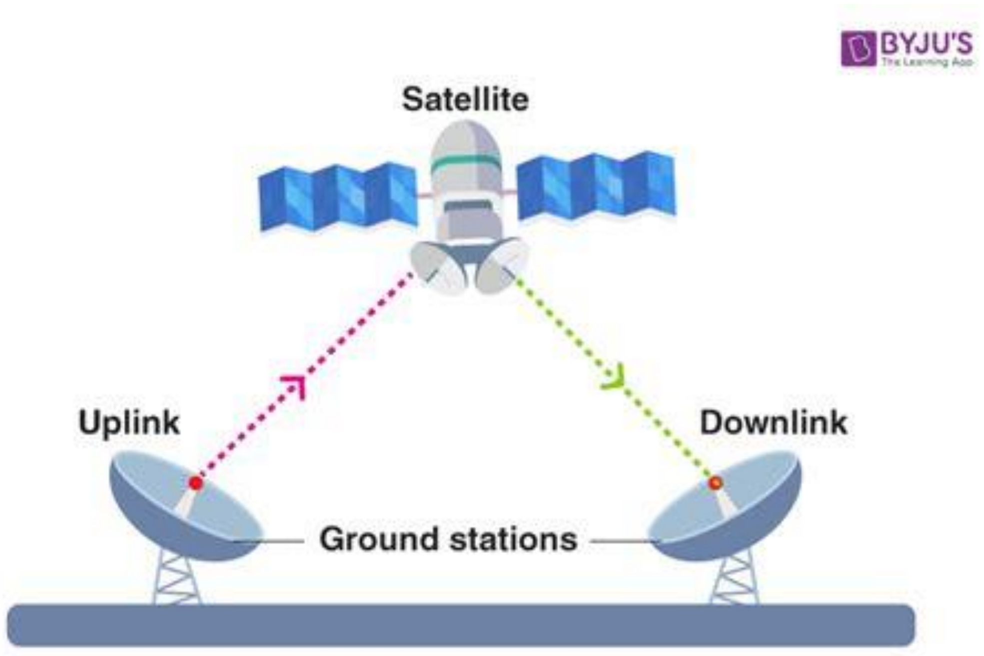
Wireless links such as WiFi and cellular networks need to share the same medium. Thus, if one pair of devices are transmitting, another pair that are close enough to be able to “hear” them, cannot transmit simultaneously

In practice, people allocate different “frequency bands” to different devices. Physics tells us that the frequencies will not mix. Thus they can transmit simultaneously

Sharing policy

- WiFi and Bluetooth
  - There is a portion of the spectrum that is allocated to WiFi
  - While the laws and exact frequencies vary by country, roughly speaking, any device can transmit at 2.4-2.5 GHz and 5-6 GHz.
  - These are called the **ISM** bands. As long as the transmission power is limited, any device may use them. Incidentally, this is why most microwave ovens use 2.4GHz
- Cellular Networks
  - Governments allocate rights to different companies. They say that "company X can transmit at frequency Y in zone Z"
  - These are usually allocated through auction
  - Most of the spectrum in the US is allocated for the military (80% I think)

Satellite communication



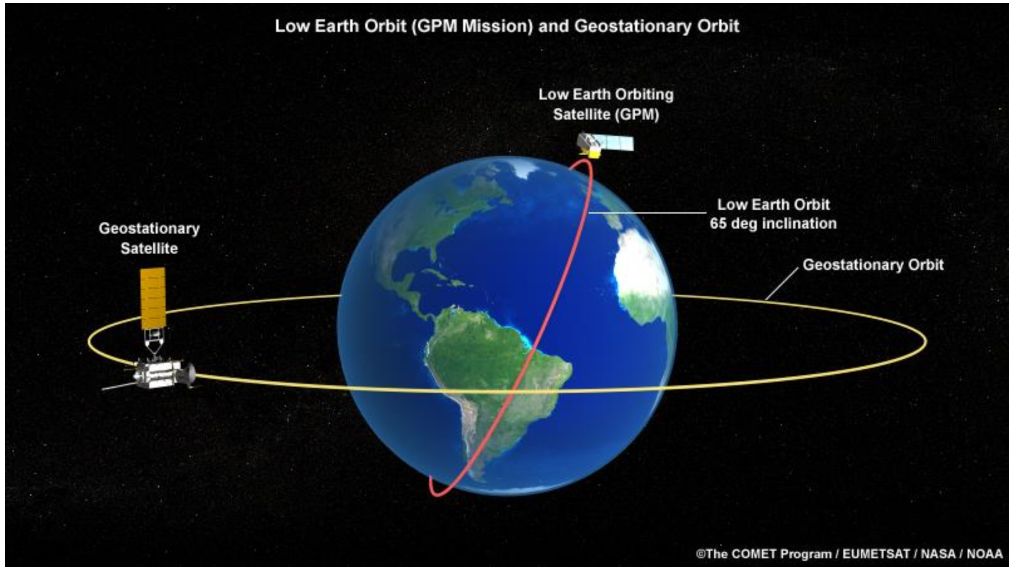
Conceptually straightforward.

Two main types:

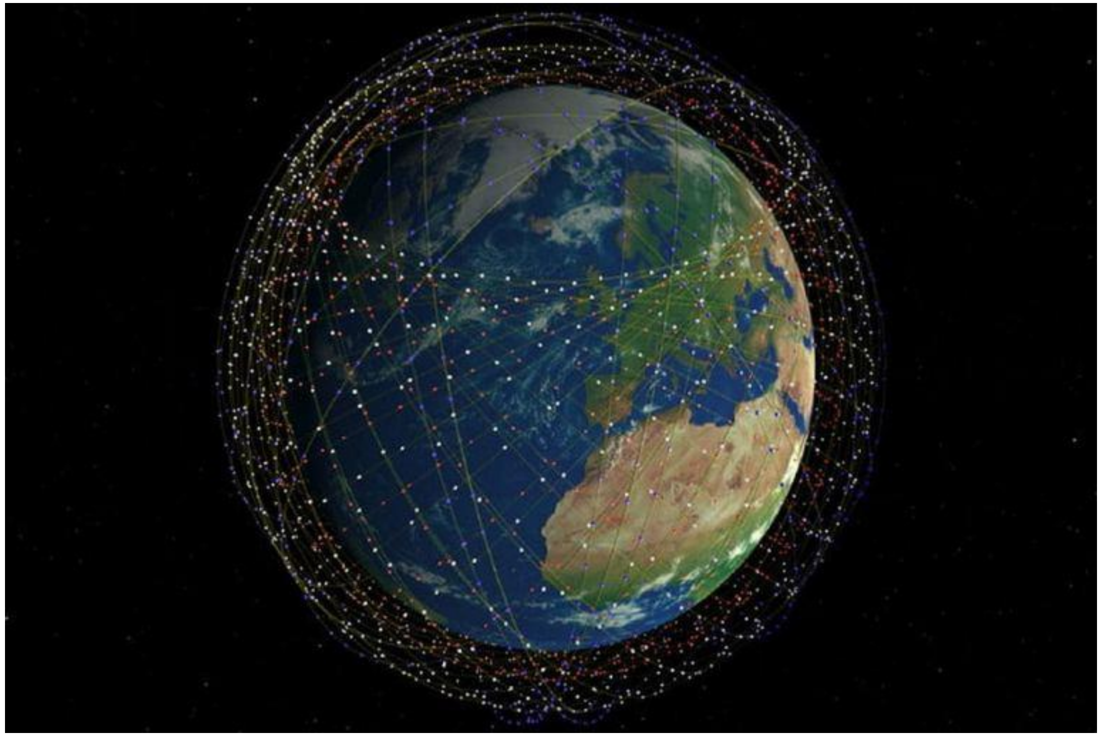
- geostationary satellites (old school)
- Low-earth orbit satellites (new school)

Satellite communication

- Geostationary orbit
  - Each satellite has a lot of range
  - Which means that the same bandwidth is shared across a large swath of the earth
  - Latency is much higher
- Low-earth orbit (LEO)
  - New trend, especially with lowering launch costs
  - Lower latency



LEO Satellites: new technology



Covers the entire planet with a low latency network that is also lower capacity compared to fiber network, primarily because of earth-to-space communication bottleneck
Needs more satellites to cover the planet, but also means more capacity than GEO

Instapoll

SpaceX is a space launch company that has deployed a large number of low earth orbit (LEO) satellites to offer internet services to a large portion of the earth. It has approached several governments to ask for the right to transmit at certain frequencies. What technical considerations should the governments make?

Should they just grant SpaceX the right to transmit at any frequency they like?