PADERBORN UNIVERSITY

Computer Networks (WS23/24)

L2: The Physical Layer

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Materials inspired by David J. Wetherall and Oliver Hahm

Learning objectives

Application

Transport

Network

Link

Physical

We want to send/receive **digital signals**

Communication channels carry **analog signals**

How **signals** are used to **tranfer message bits** over a link

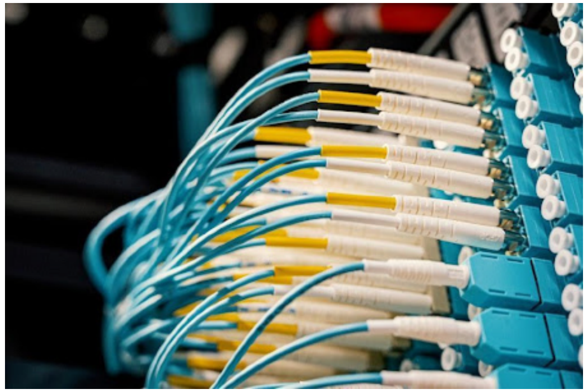
- Properties of media (wires, fiber optics, wireless)
- Signal and its propagation (bandwidth, attenuation, noise)
- Encoding and modulation
- Fundamental limits (Nyquist, Shannon)
- Link modeling

Media

Types of media

Media propagate signals that carry bits of information

Wires

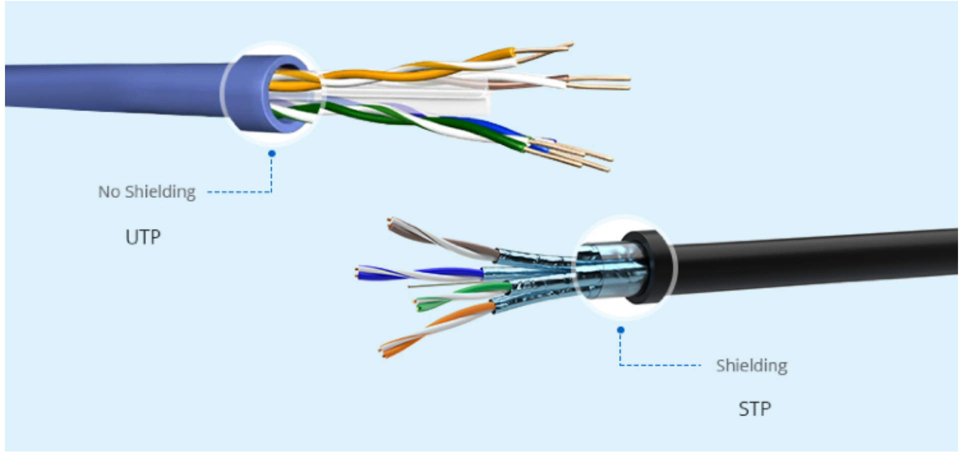


Fiber optic cables

Wireless

Wires - twisted pairs

Commonly used in local area networks (LANs) and telephone lines



Unshielded or shielded twisted pair cable with four **twisted** pairs

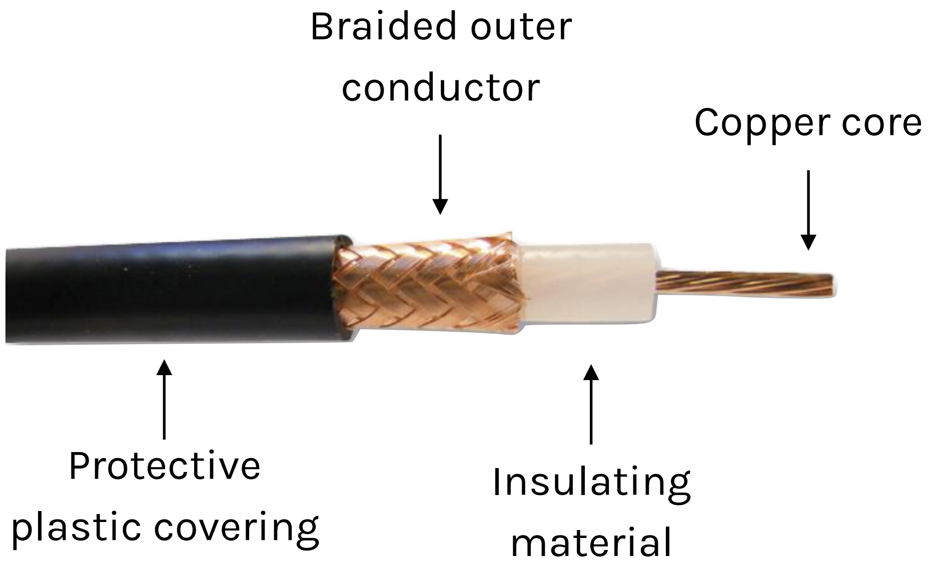
↓

Reduce radiated signal (interference)

https://community.fs.com/article/network-communication-cables-that-power-your-internet.html

Wires - coaxial cable

Commonly used for telephone trunk lines, high-speed networks, cable TV, etc.



Better shielding to eliminate singal interference between parallel cables for **better performance**

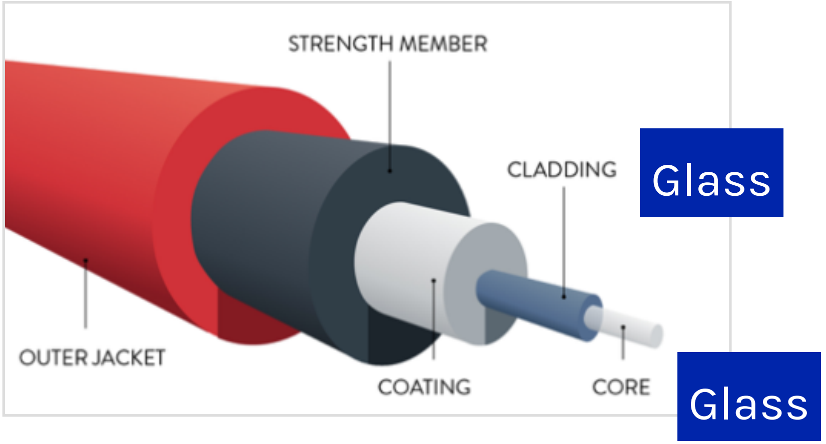
Wires - other kinds

Powerline communication

https://en.wikipedia.org/wiki/Power-line_communication

Fiber (fiber optic cable)

Long, thin, pure strands of glass



One fiber

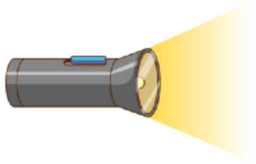
Fiber bundle in a cable

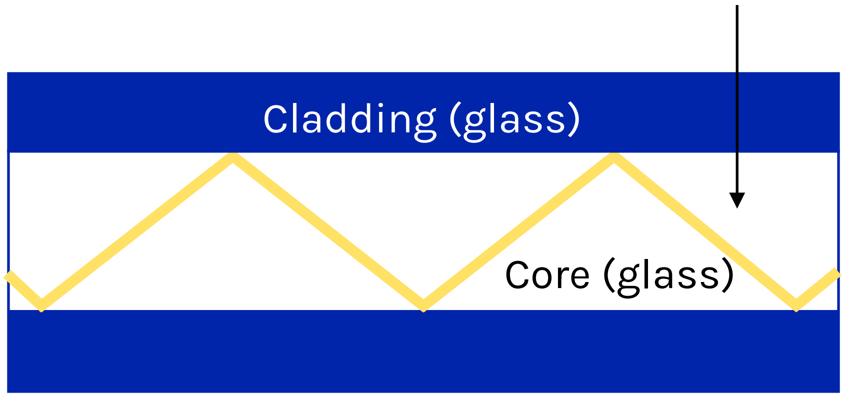
Allow for high-speed transmission over long distance (e.g., underwater, data centers)

https://en.wikipedia.org/wiki/Optical_fiber

Fiber: how it works

Light trapped by **total internal reflection** (from a medium of higher refractive index to a lower one at a sufficiently oblique angle on the interface)





Light source (LED, laser)

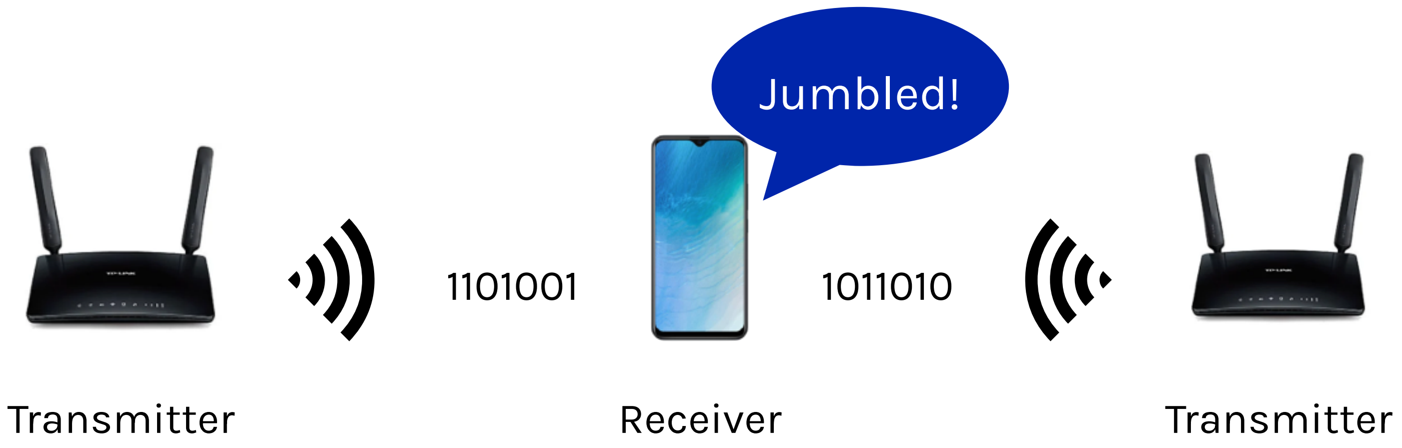
Optical fiber

Photo detector

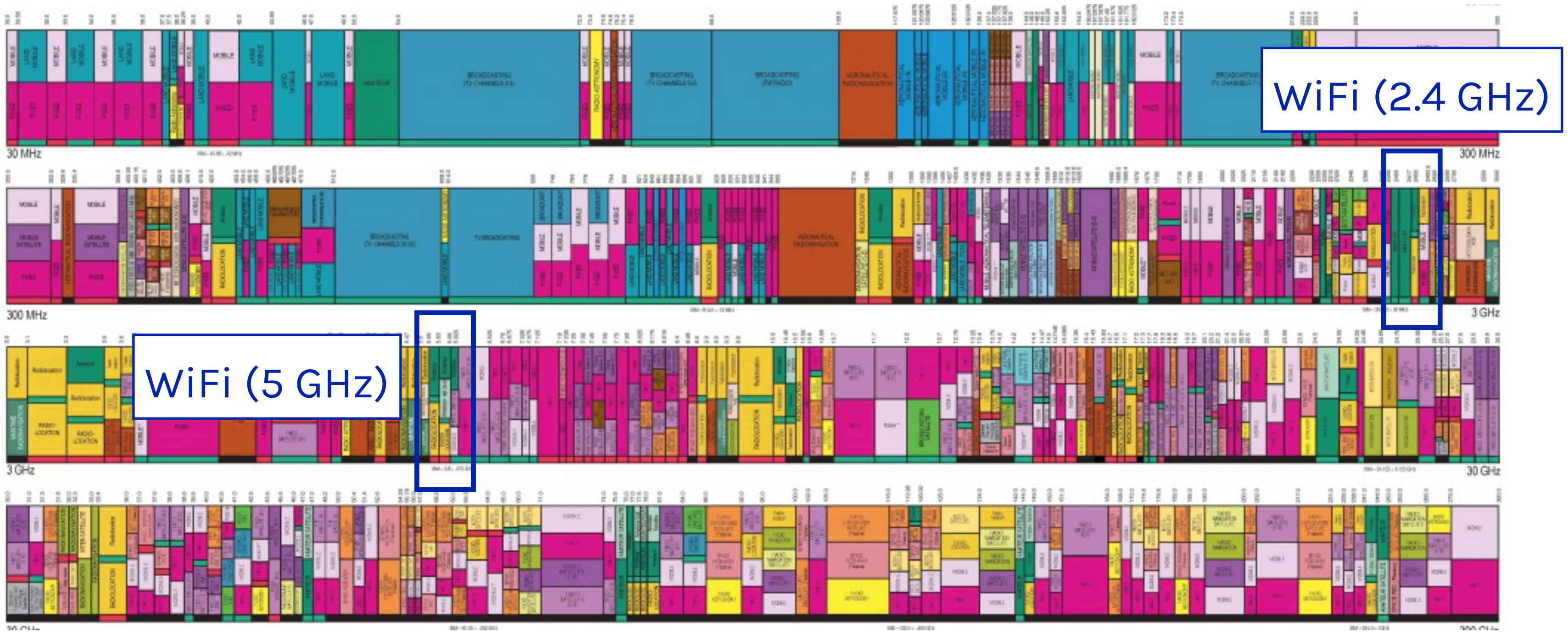
Wireless

Sender radiates signal over a region

- In many directions, unlike a wire, to potentially many receivers
- Nearby signals (in the same frequency) interfere at a receiver; coordination needed



Frequency allocation



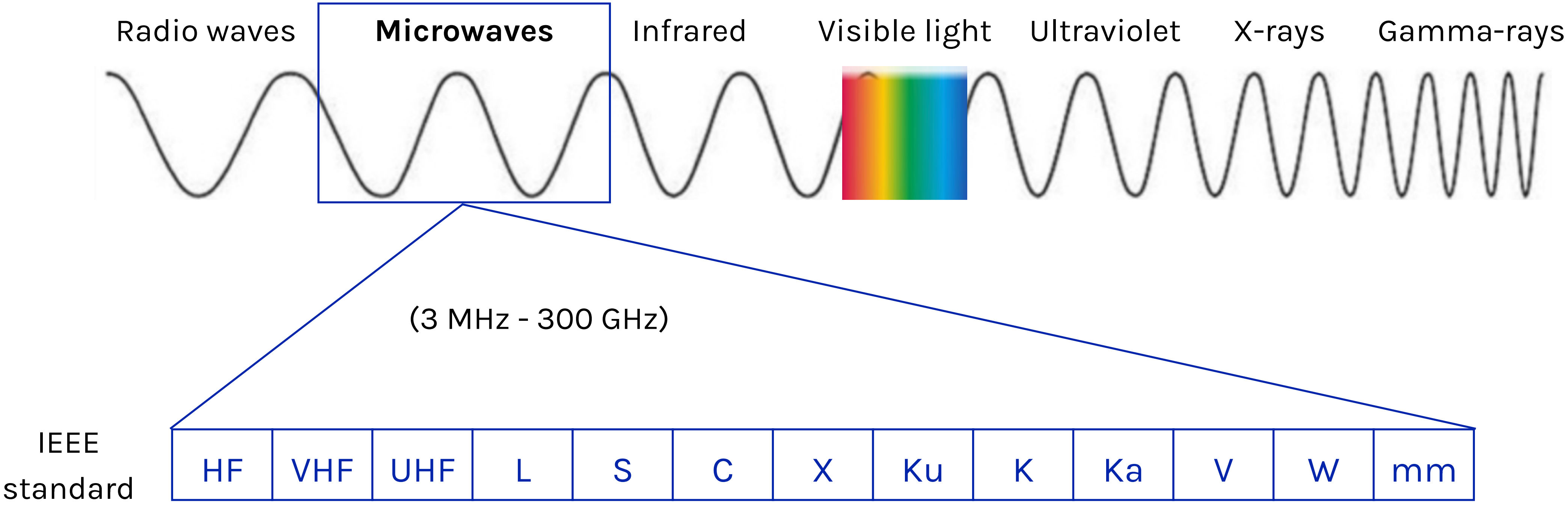
Regulations to manage the frequency spectrum for different purposes
(e.g., TV, radio, aircraft, mobile, WiFi, Bluetooth)

https://en.wikipedia.org/wiki/Frequency_allocation

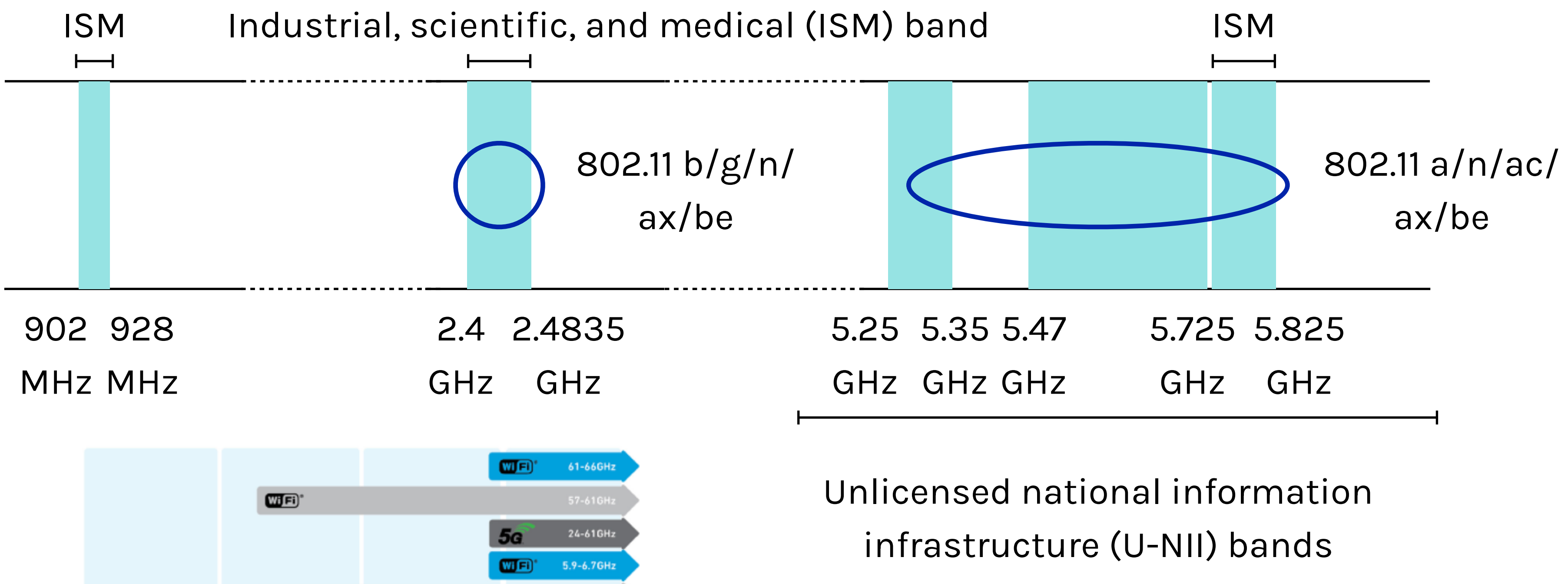
What is the difference between light, radio waves, and gamma rays?

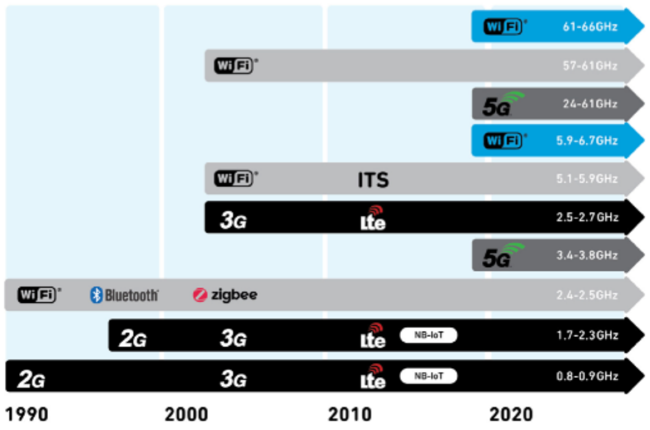
Only one of them makes the Hulk!

Eelectromagnetic radiation frequencies



Wireless frequency bands

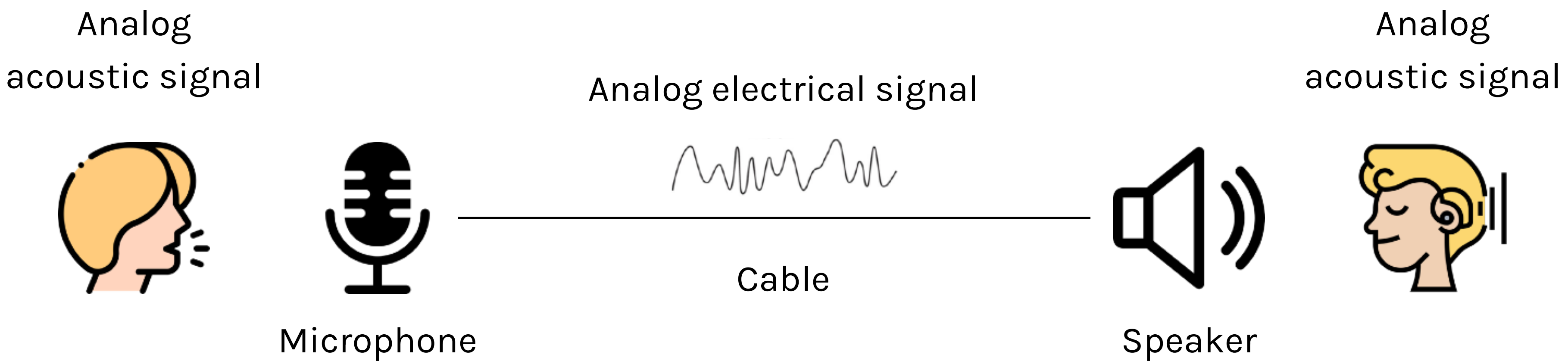




https://www.mouser.com/pdfDocs/qorvo-next-gen-wi-fi-applications-and-solutions-design-guide-mouser-ebook.pdf

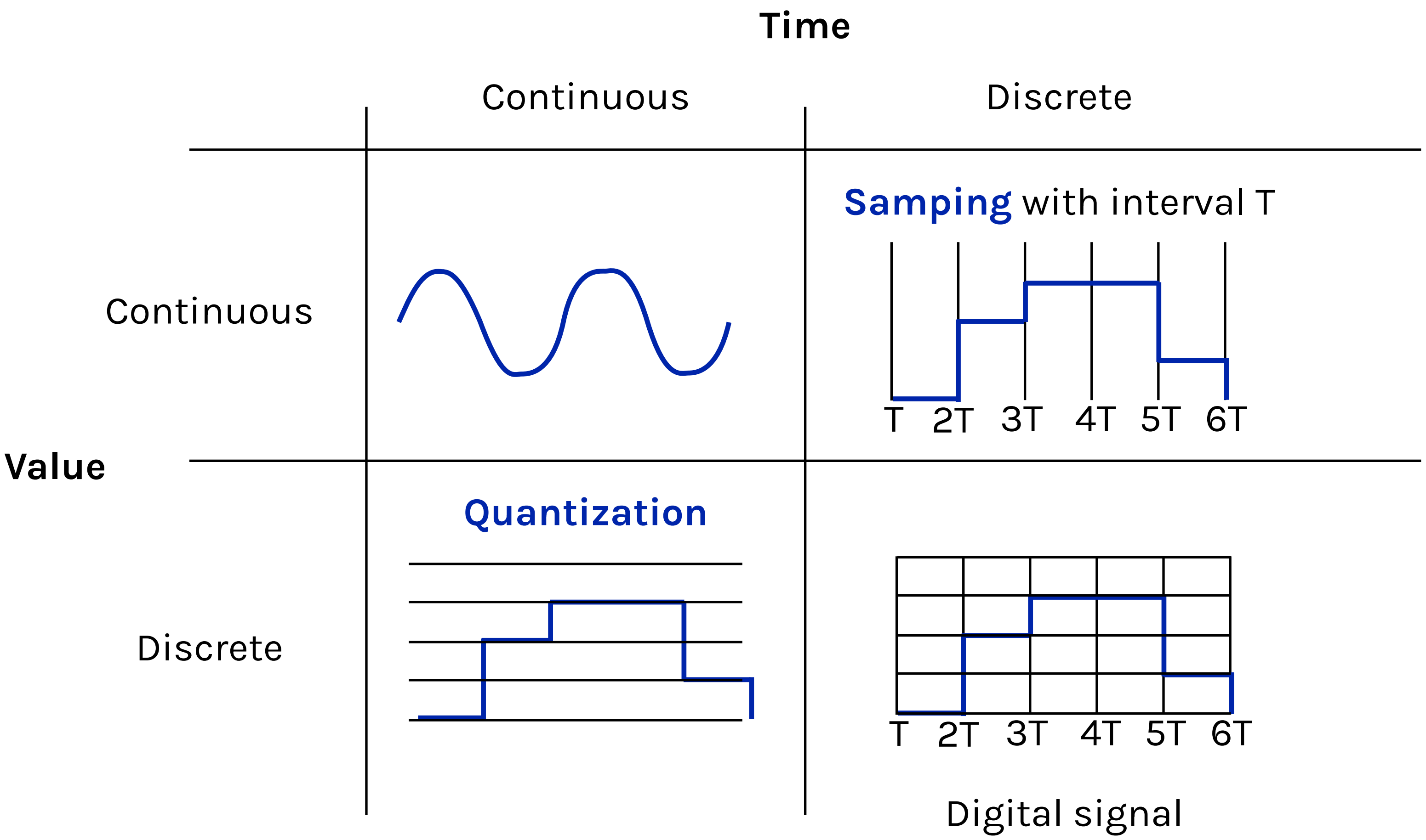
Signal Propagation

The telephone example



Data is converted into a **signal** to be sent over a transmission medium, where a signal is **a chronological sequence of physical values** measured on the medium

Signal types



Quantization and sampling

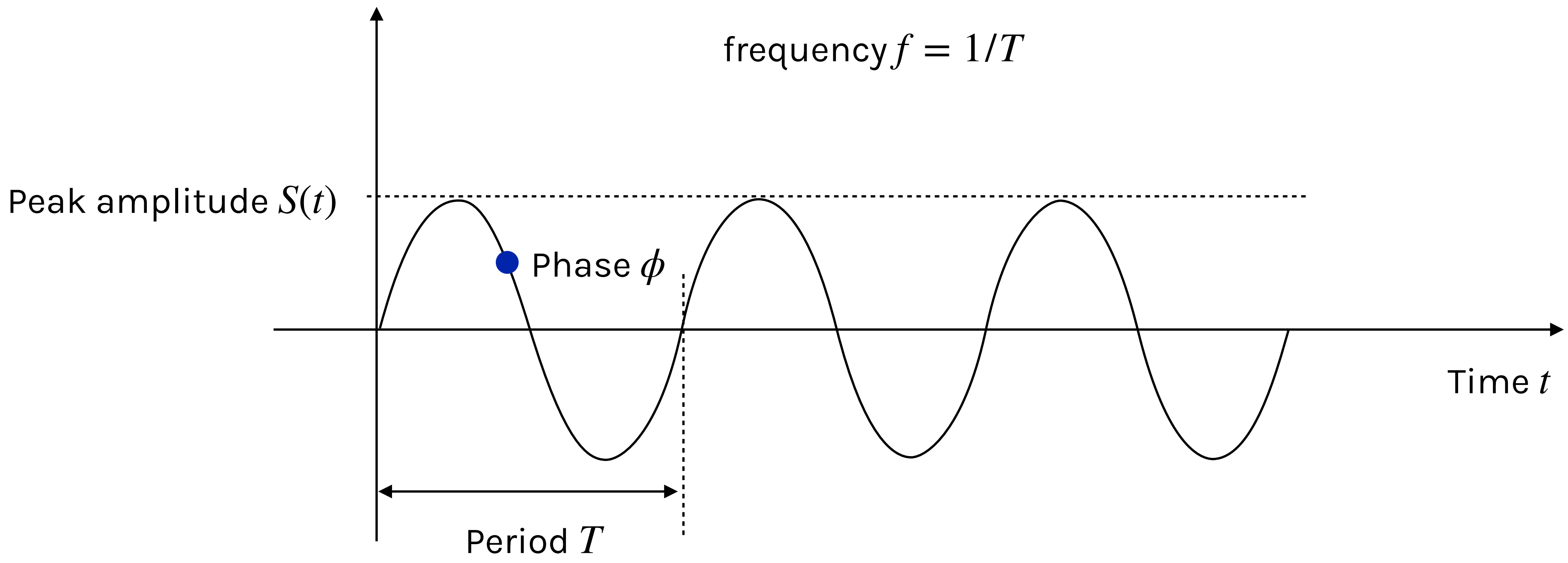
Quantization

- Computer networks deal with **digital data (with discrete values)**
- Physical media are by nature analog (continuous value)
- Conversion from digital to analog values and vice versa

Sampling

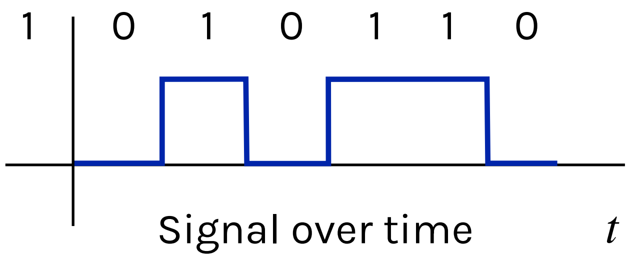
- Computer networks deal with **discrete time**
- Physical media have a continuously varying state (continuous time)
- Periodical measurement of the physical medium is required

Periodic signals

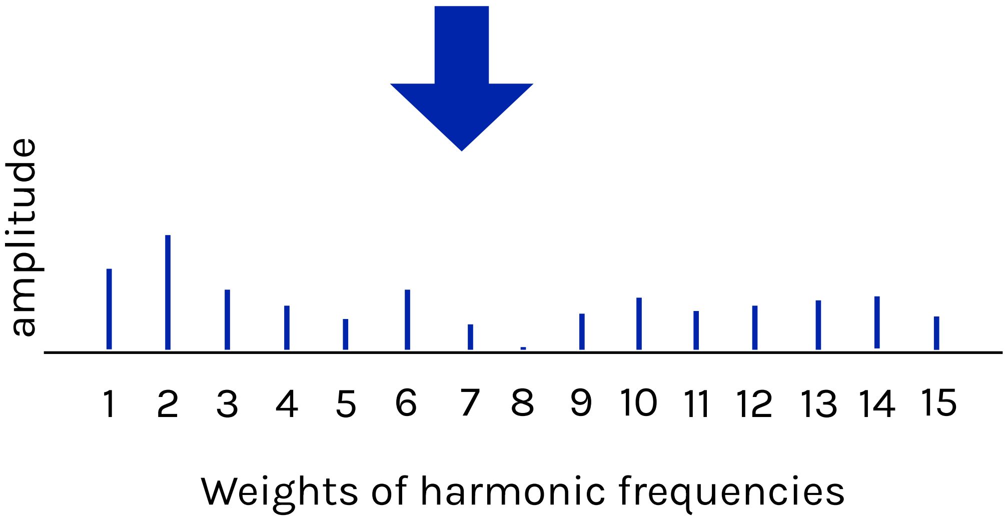


Frequency representation of signals

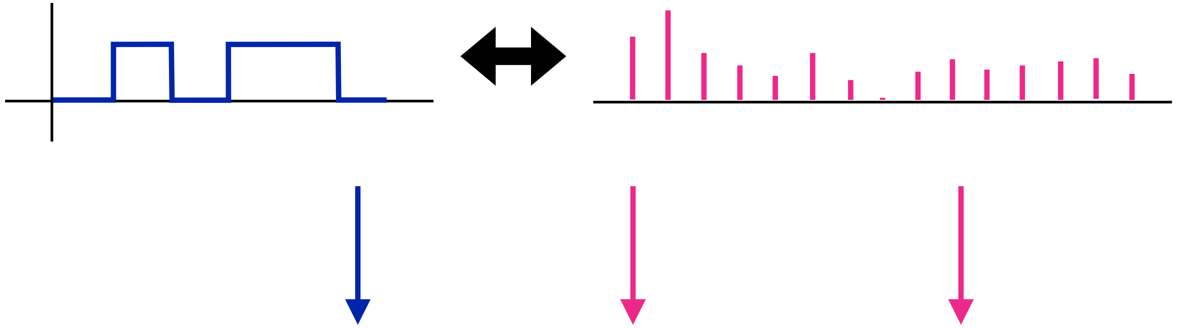
Signal in the
time domain



Signal in the
frequency domain



Fourier analysis



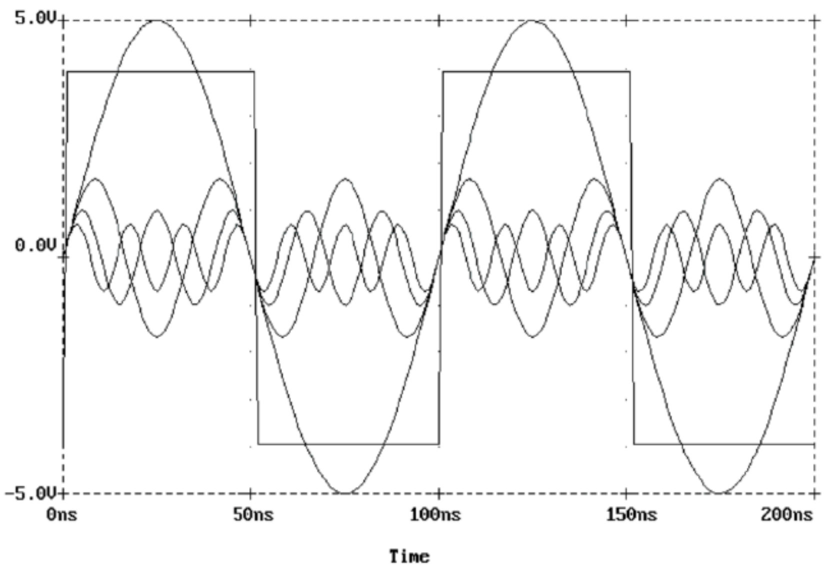
$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi n f t) + \sum_{n=1}^{\infty} b_n cos(2\pi n f t)$$

https://en.wikipedia.org/wiki/Fourier_analysis

Fourier series

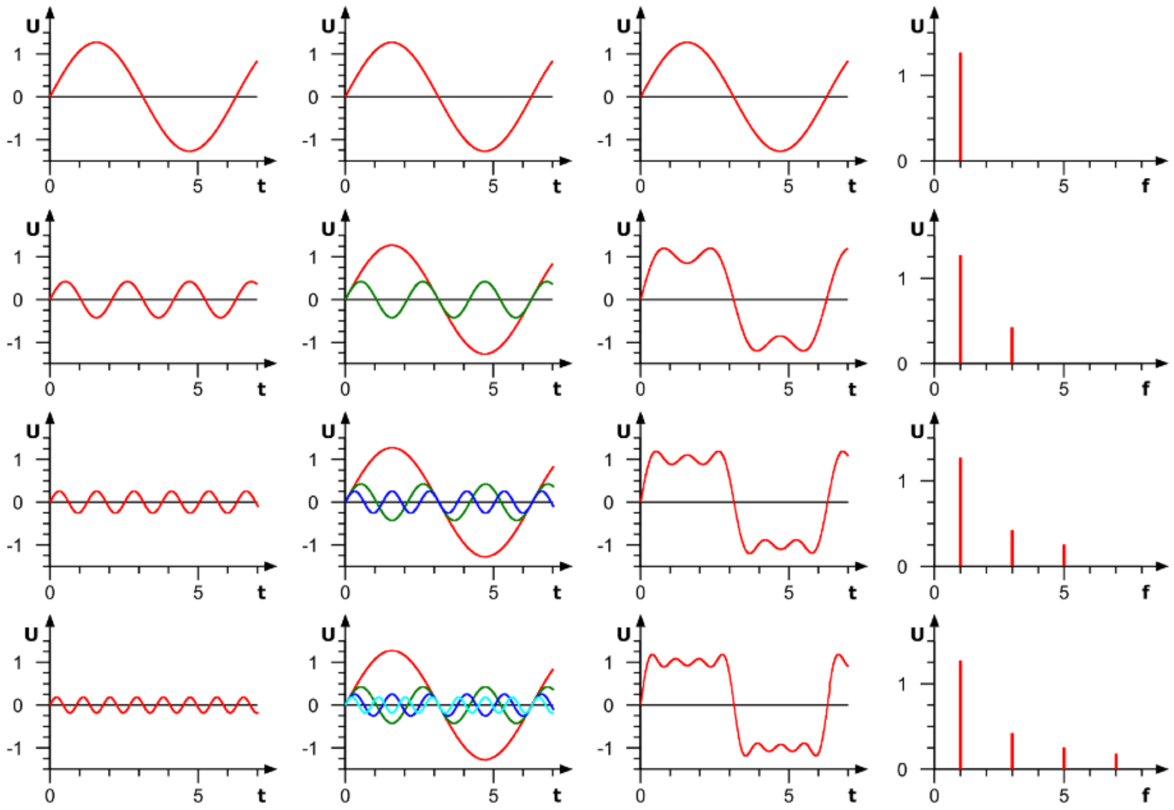
A square-wave signal consists of the sum of a set of oscillating functions

- A square wave signal consists of a **fundamental frequency** and **harmonics**
- Harmonics are integer multiples of the fundamental frequency, often referred to as harmonics of the 3rd, 5th, 7th, etc. order
- The more harmonics are taken into account, the more similar becomes the result with a square wave signal



https://en.wikipedia.org/wiki/Fourier_series

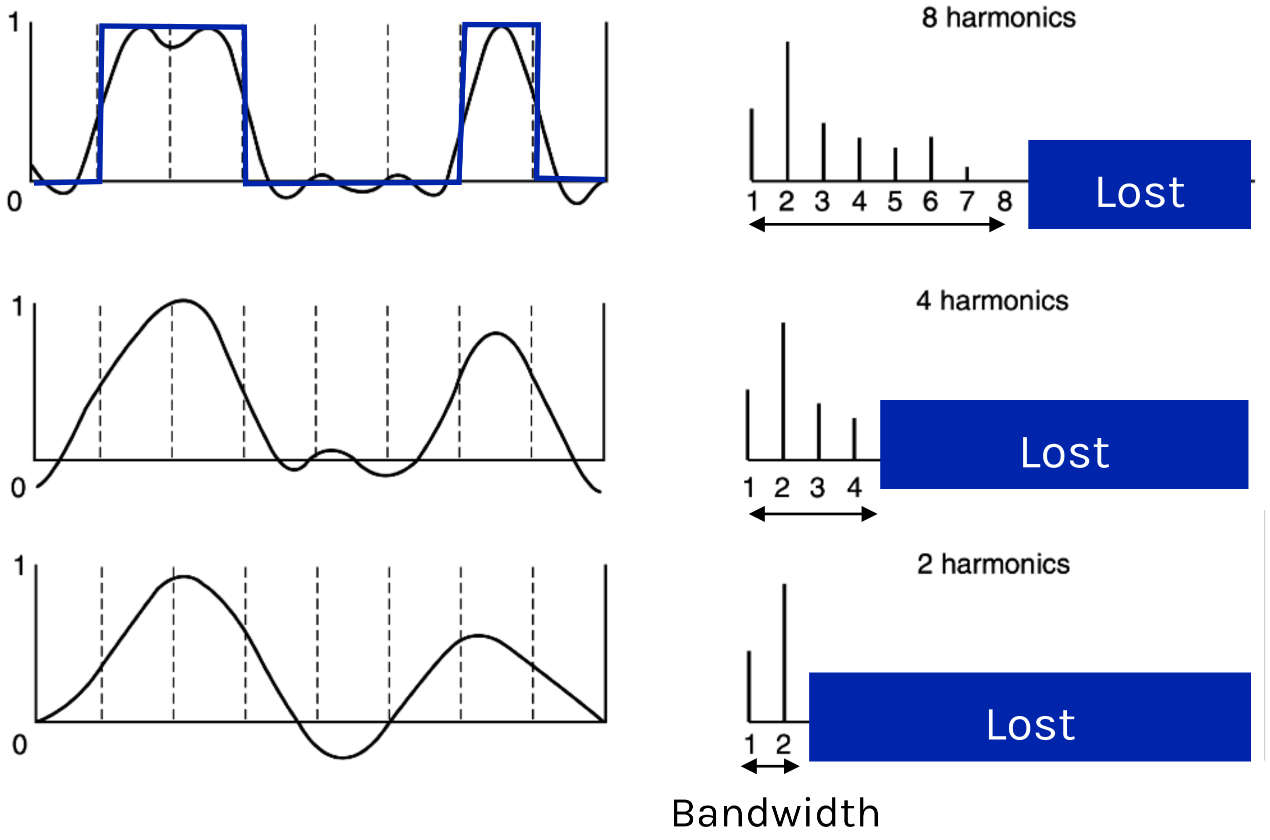
Fourier synthesis of a square-wave signal



https://commons.wikimedia.org/wiki/File:Fourier_synthesis_square_wave_animated.gif

Effect of less bandwidth

Fewer frequencies (i.e., less bandwidth) degrades signal



EE: bandwidth is the width of the frequency band (in Hz)

CS: bandwidth is the maximum data rate of a channel (in bps)

Signals over a wire

What happens to a signal as it passes over a wire?

- The signal is **delayed** (propagation speed $2c/3$)
- The signal is **attenuated** (goes from meters to km)
  - Frequencies above a cutoff are highly attenuated
- Signals are **distorted** (unequal attenuation on different frequencies)
- **Noise** is added to the signal (causes errors)

Signals over a wire

Attenuation: signal weakening

- If the amplitude of a data signal has dropped below a certain value, it can no longer be clearly interpreted
- The attenuation limits the maximum bridgeable distance for all transmission media
- The **higher** the **frequency**, the **higher** is the **attenuation**

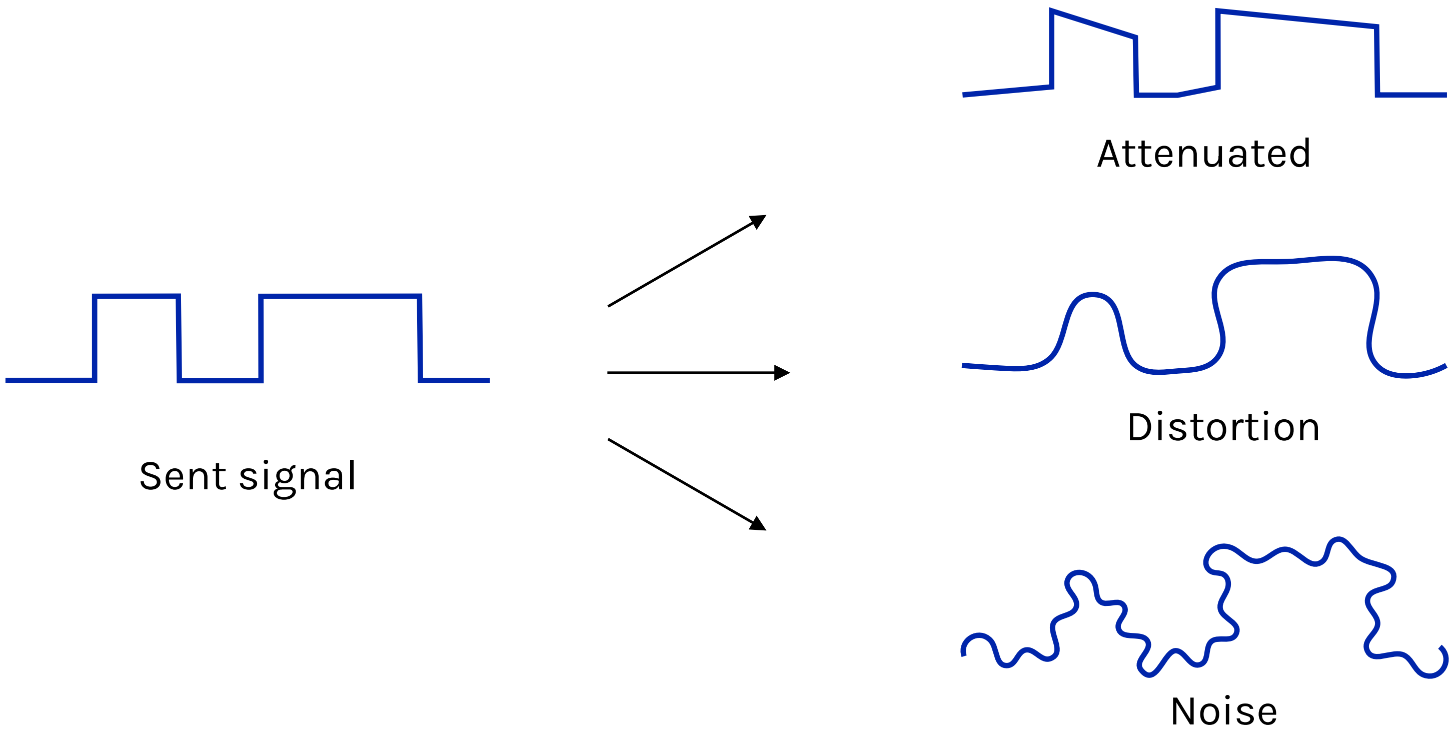
Distortion

- Some of the frequencies suffer more severely from attenuation

Noise

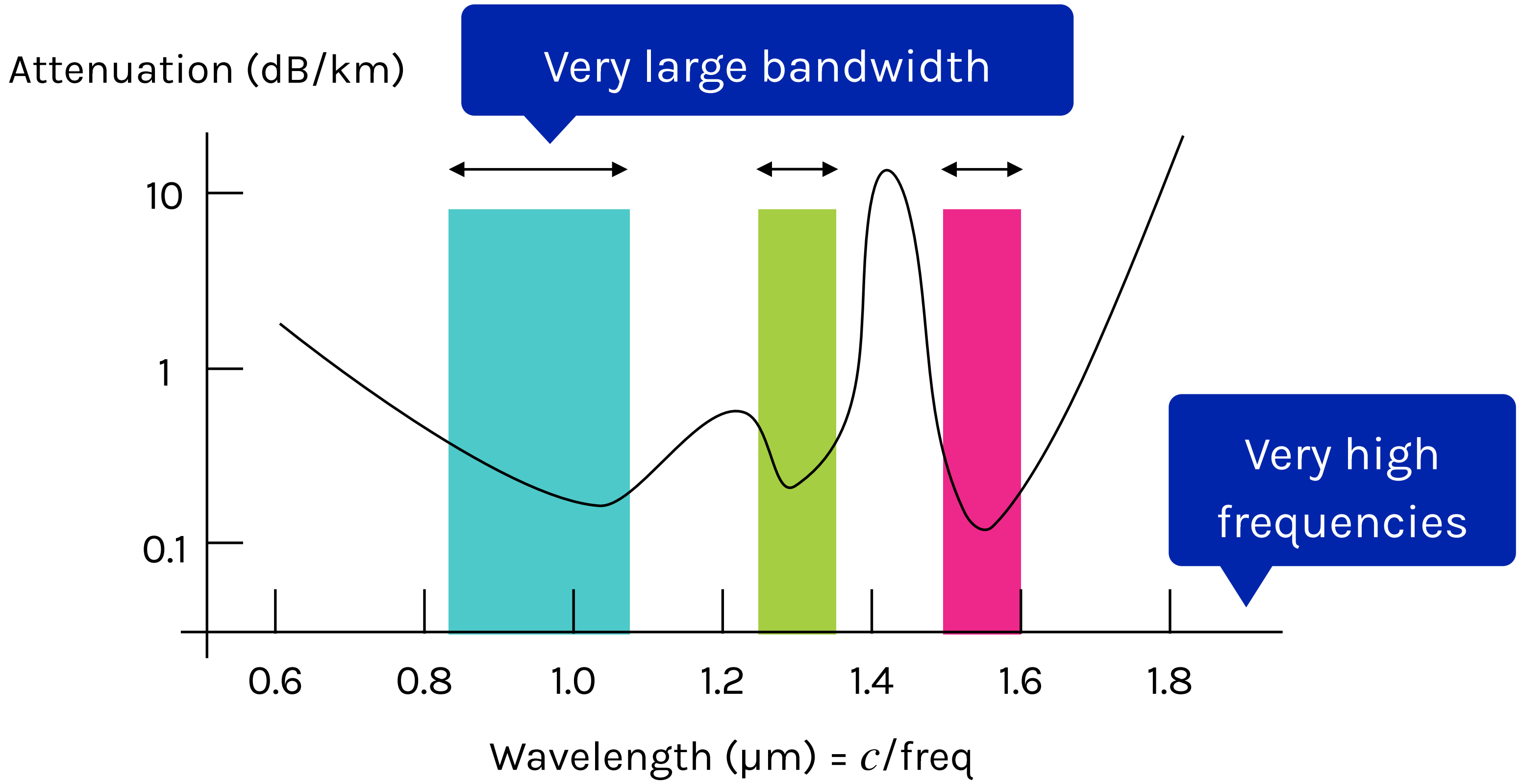
- Thermal noise (also Nyquist noise), crosstalk, inpulse noise, etc.

Signals over a wire

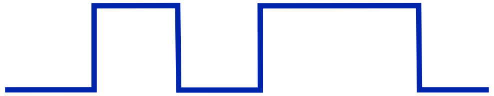


Signals over fiber

Light propagates with very low loss in three very wide frequency bands

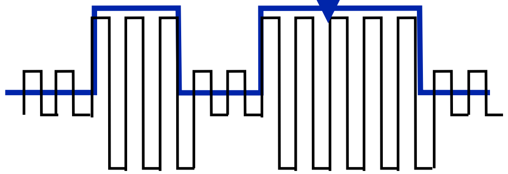


Signals over wireless



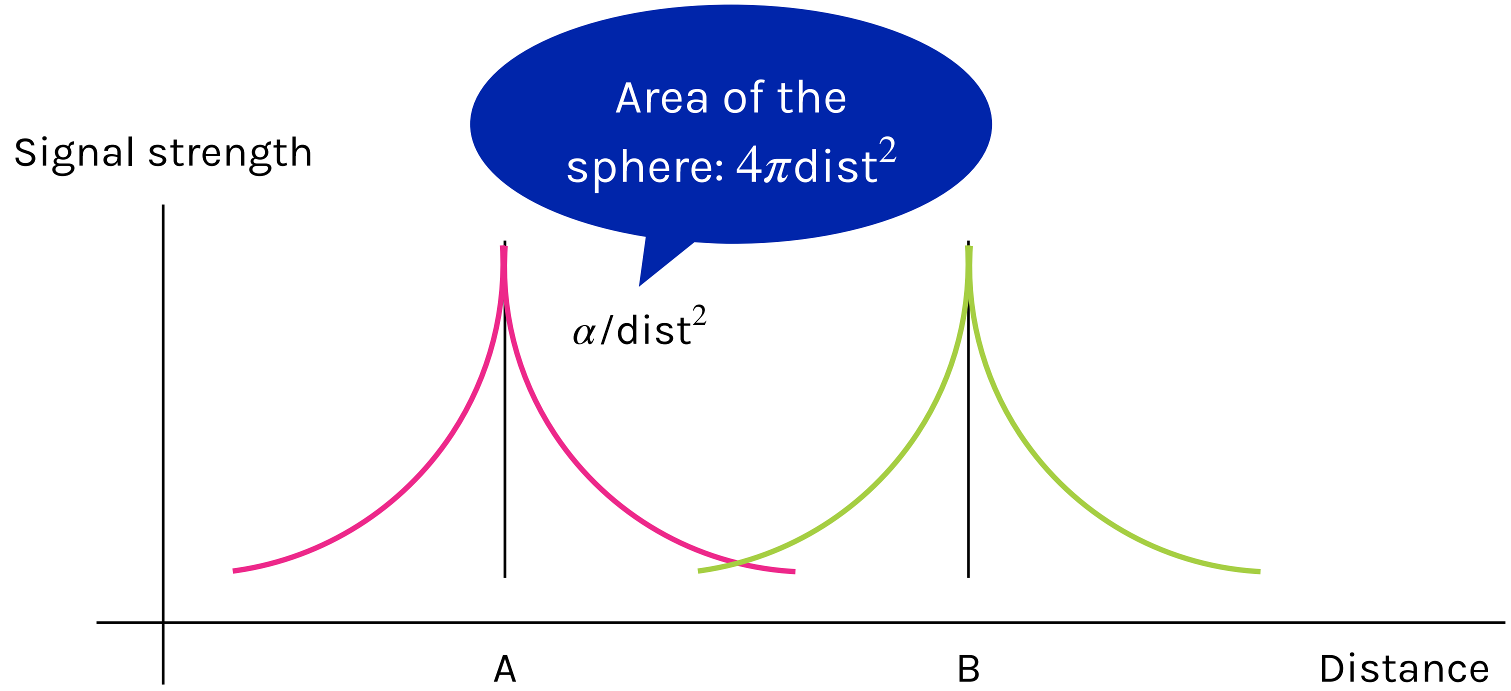
Signal to send
(baseband)

E.g., change the amplitude of the carrier signal



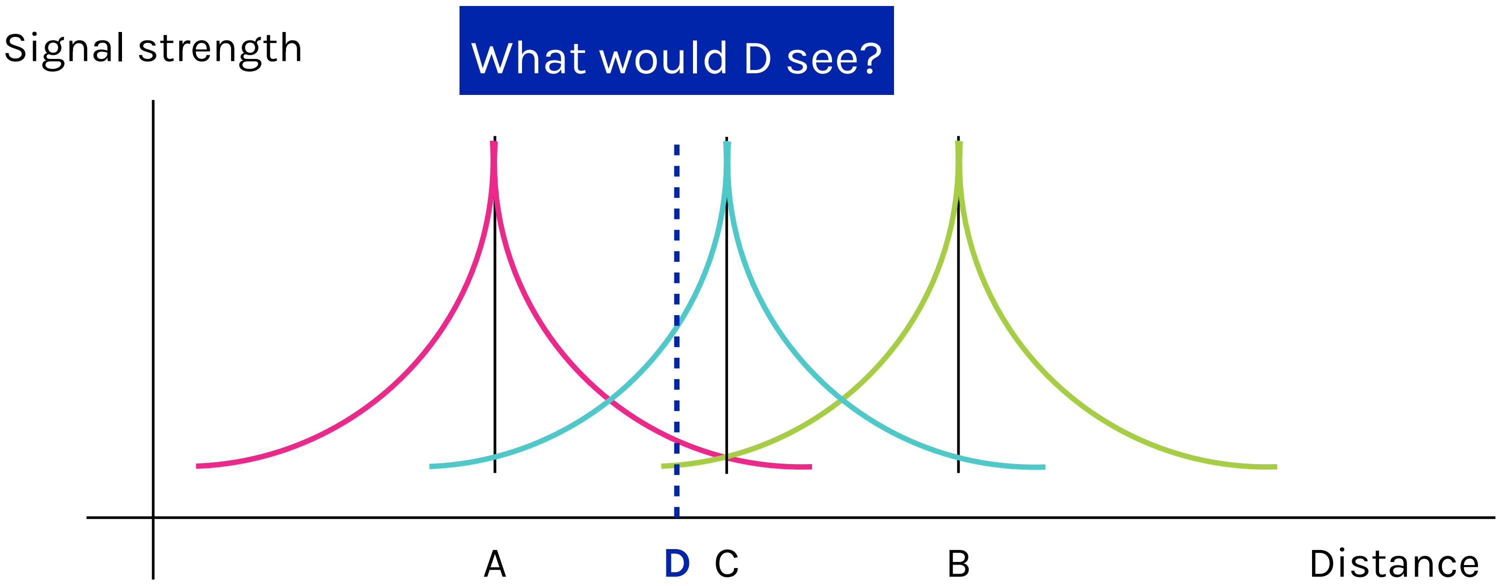
Signals are transmitted over a carrier frequency higher than the baseband
(passband)

Signals over wireless: attenuation



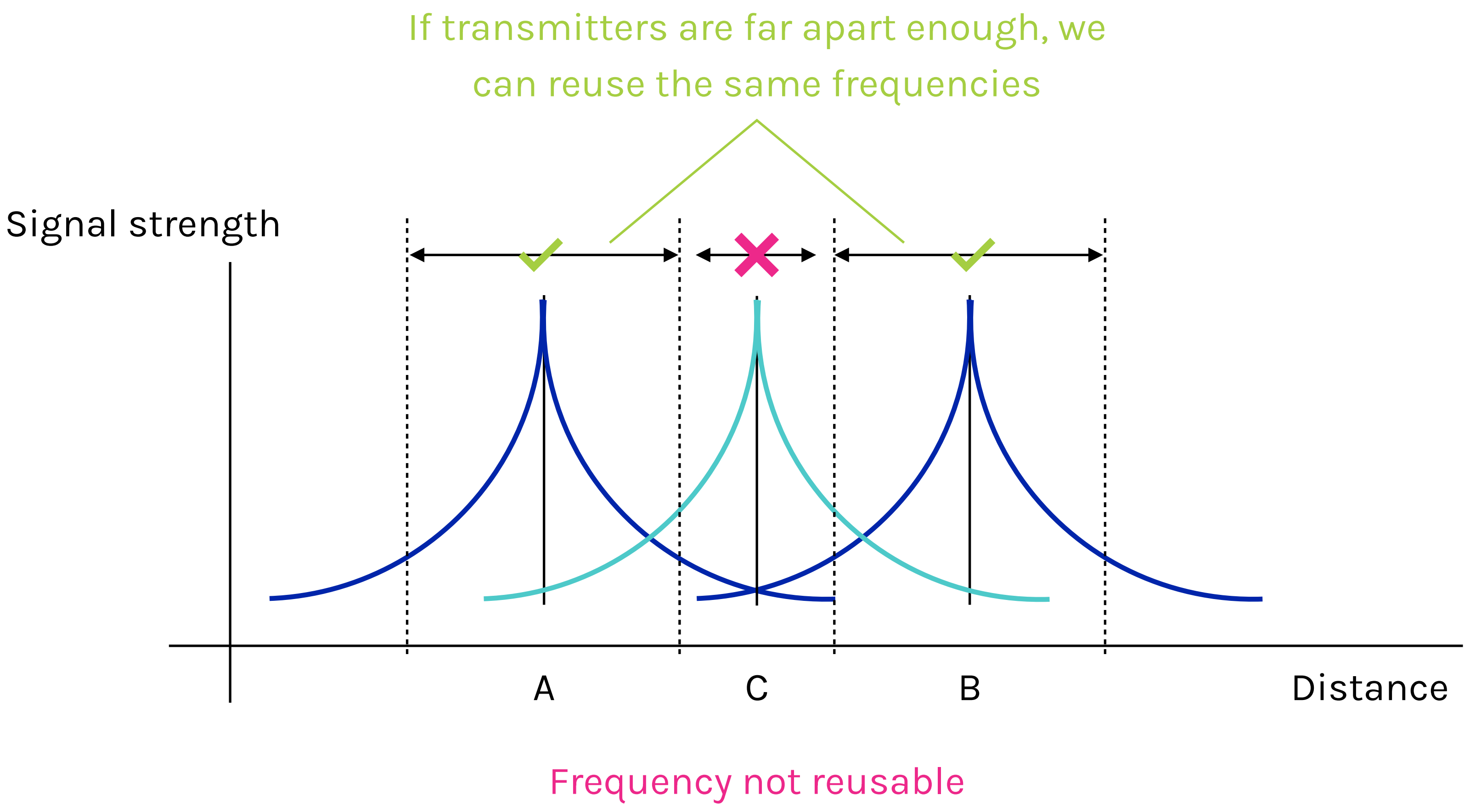
The signal travels at the speed of light, spread out and attenuate faster than $1/\text{dist}^2$

Signals over wireless: interference



D will see a strong signal C plus weak signals from A and B, leading to jumbled signals hard to separate

Signals over wireless: spatial reuse



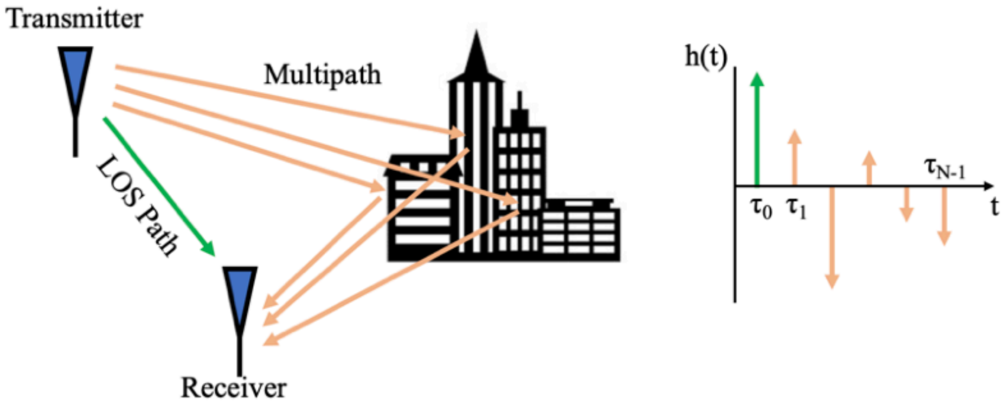
Signals over wireless: others

Various other effects

- Wireless propagation is complex, depends on the environment

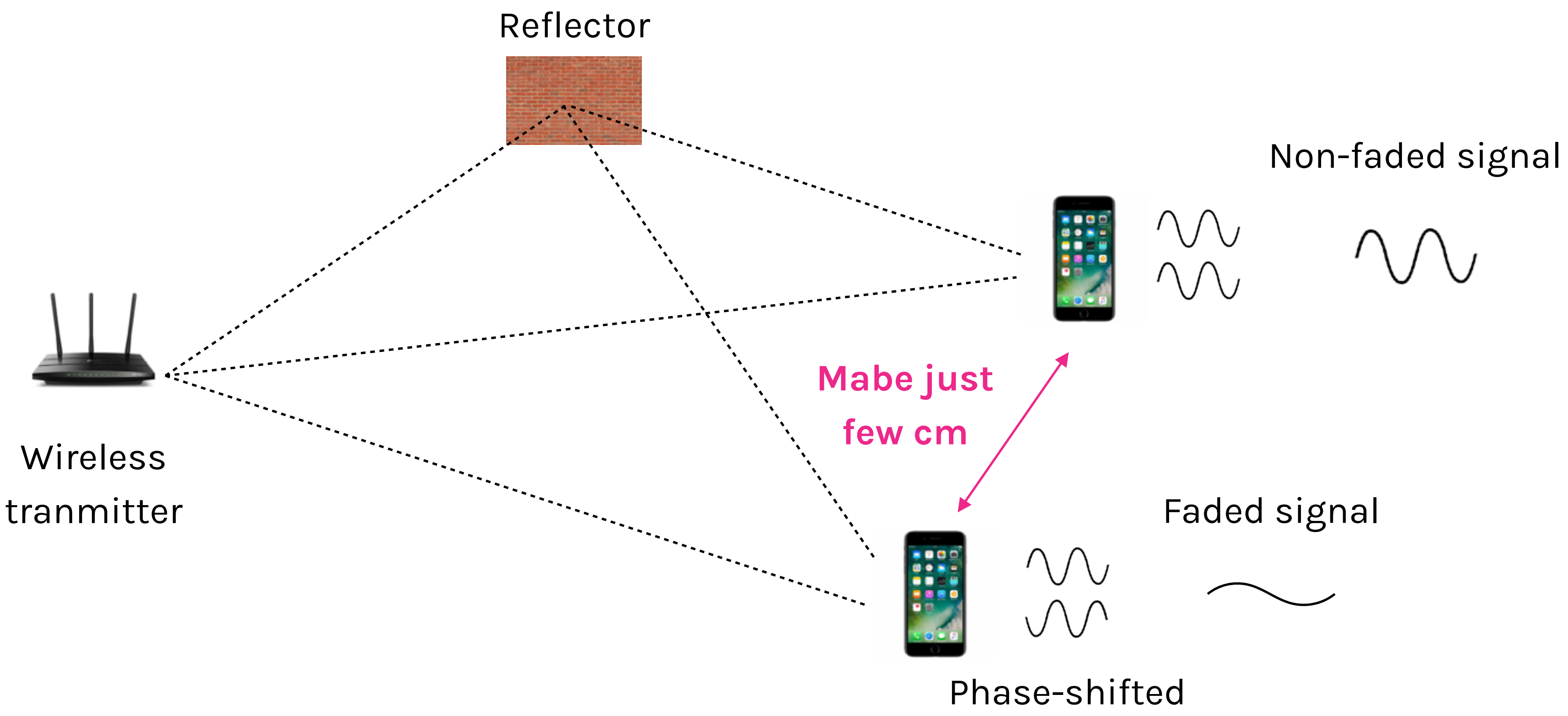
Some key effects are highly frequency dependent

- For example, multipath at microwave frequencies (for wireless communication)



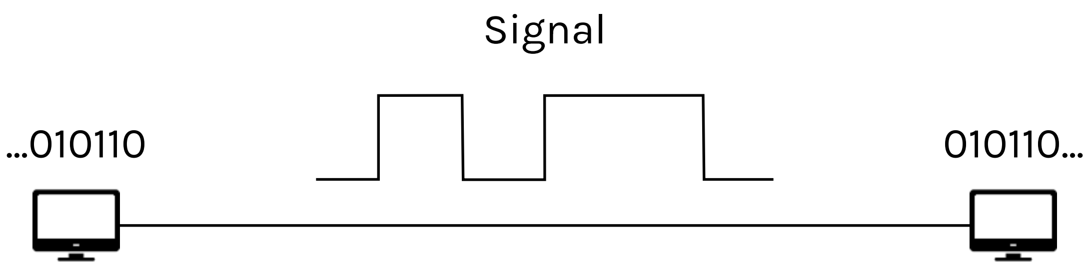
Wireless multipath fading

Sophisticated methods such as OFDM (Orthogonal Frequency Division Multiplexing)



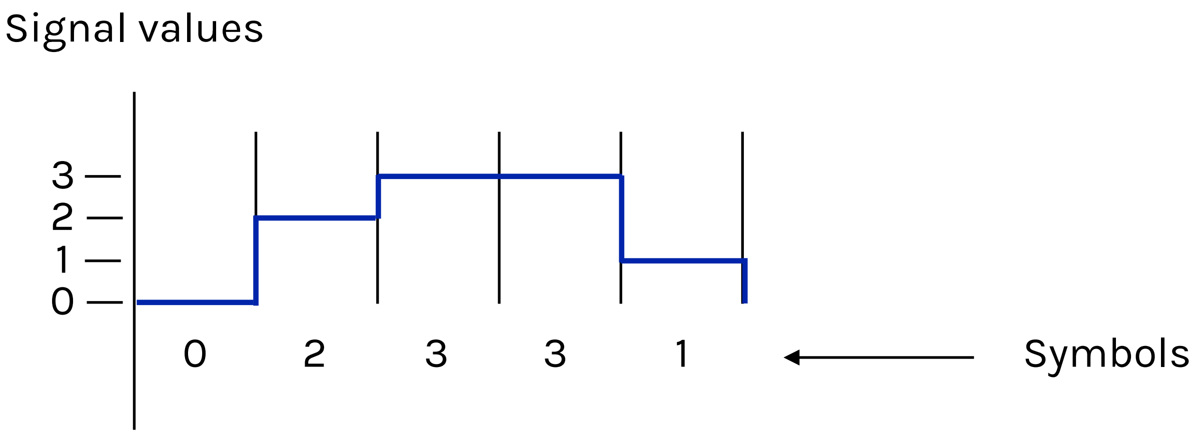
Encoding and Modulation

Encoding overview



How do we use **signals** to represent **bits**?

Symbol



The number of discrete values of a signal are denoted as

- 2: binary
- 3: ternary
- **4: quaternary**
- 8: octonary
- 10: denary

Symbol rate vs. bit rate

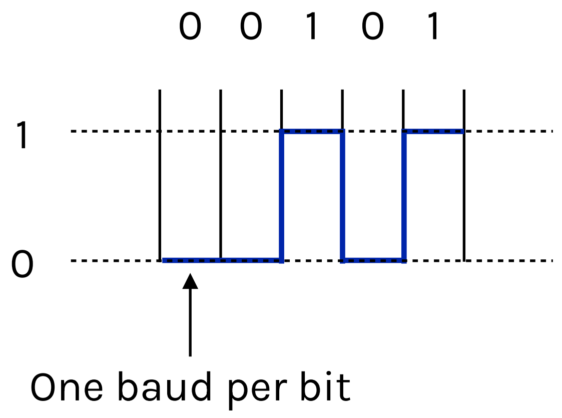
Symbol rate

- Number of transferred symbols per time unit, specified as **baud**

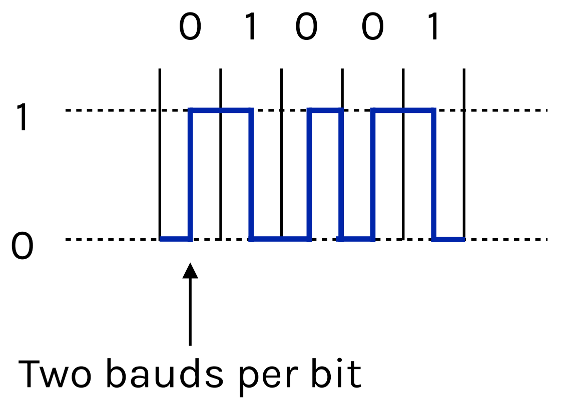
Bit rate

- Number of transferred bits per time unit, specified as **bit/s** or **bps**

The ratio between the bit rate and symbol rate depends on the encoding scheme



Encoding scheme #1



Encoding scheme #2

Encoding requirements

Robustness

- Tolerate as much distortion as possible

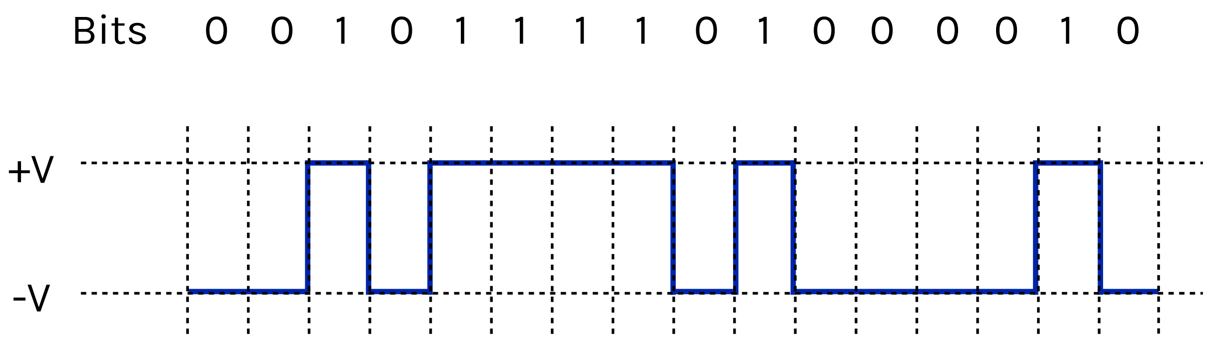
Efficiency

- Achieve the highest possible data transmission rate (e.g., binary code vs. ternary code)

Synchronization: allowing the receiver to keep in sync

- Transmission of an explicit clock signal
- Synchronize on certain points, e.g., start of character
- Self-synchronizing signal

Non-Return to Zero (NRZ)

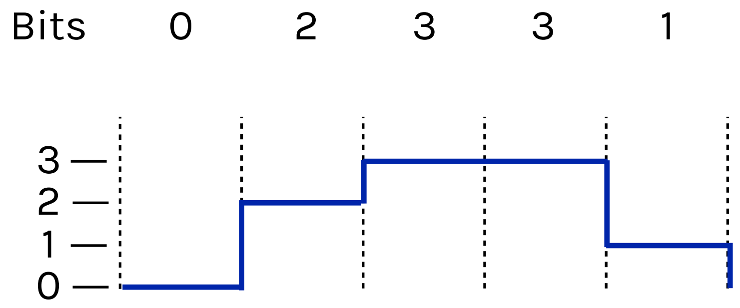


0: low voltage (-V), 1: high voltage (+V)

Other encoding schemes

We can use more levels

- Using 4 levels we can represent 2 bits per symbol



Practical schemes are driven by engineering considerations

- Issues: baseline wander, clock recovery

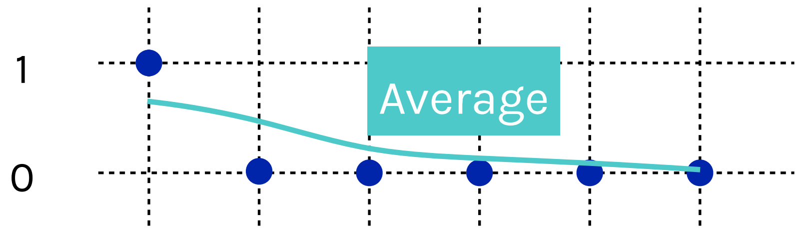
Baseline wander

Key issue: shift of the average signal level

Receiver distinguishes the physical signal levels by using the average signal level of a certain number of received signals

- Signals **below** the average signal level are interpreted as logical 0
- Signals **above** the average signal level are interpreted as logical 1

When transmitting long sequences of 0s or 1s, the average signal level may shift too much, making it difficult to detect a change of the physical signal

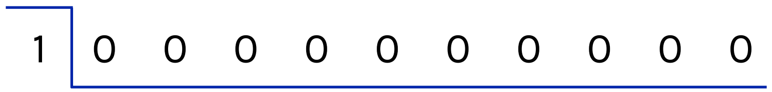


Solution: using signal levels equally often

Clock recovery

Recover the clock from the transmission

- Accurate clocks are expensive
- Using a separate line to transmit just the clock is impractical

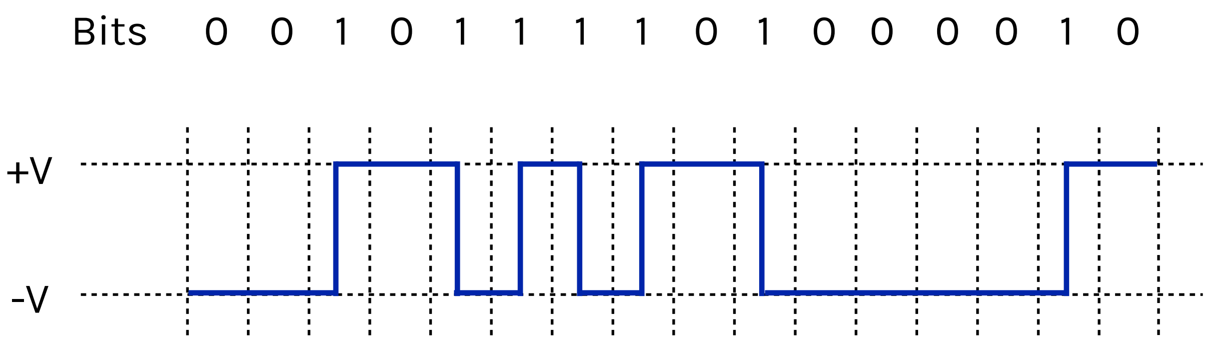


How many 0s was that?

Use signal transitions to recover the clock

- Implicit clock synchronization
- Receiver needs frequent signal transitions

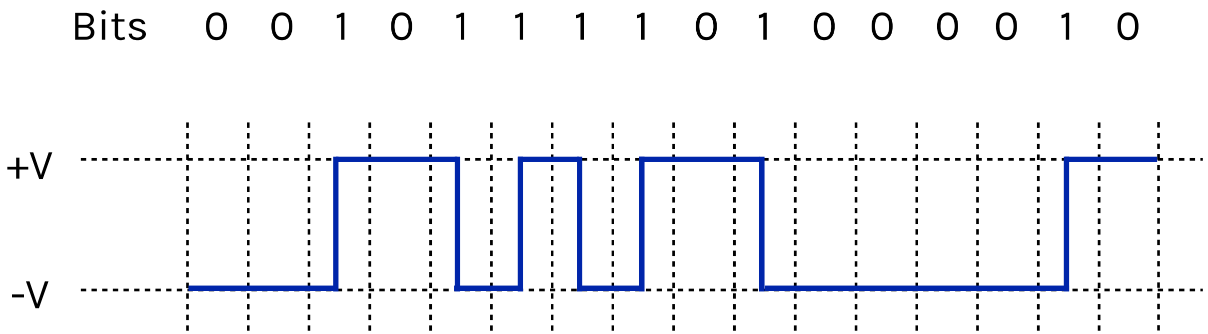
Non-Return-to-Zero, Inverted (NRZI)



0: no signal level changes, 1: signal level flips

Do baseline wander and clock recovery problems exist?

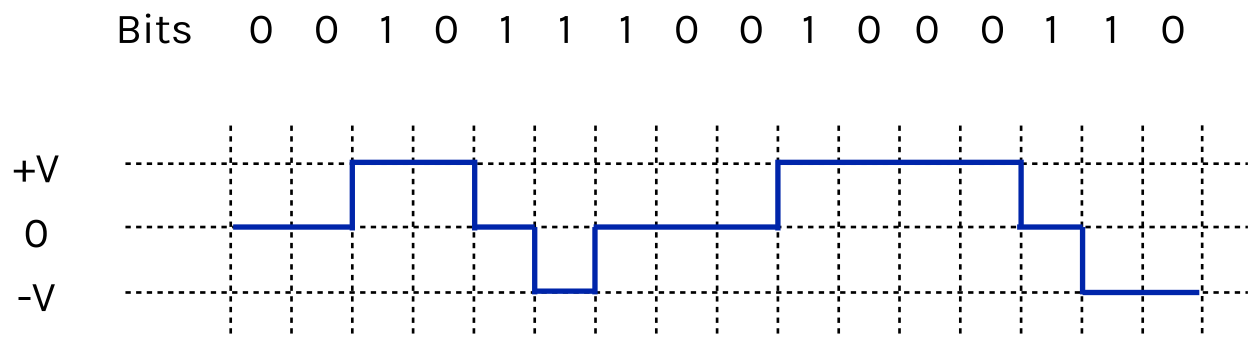
Non-Return-to-Zero, Inverted (NRZI)



0: no signal level changes, 1: signal level flips

Baseline wander can occur and clock recovery problem exists for sequences of 0s

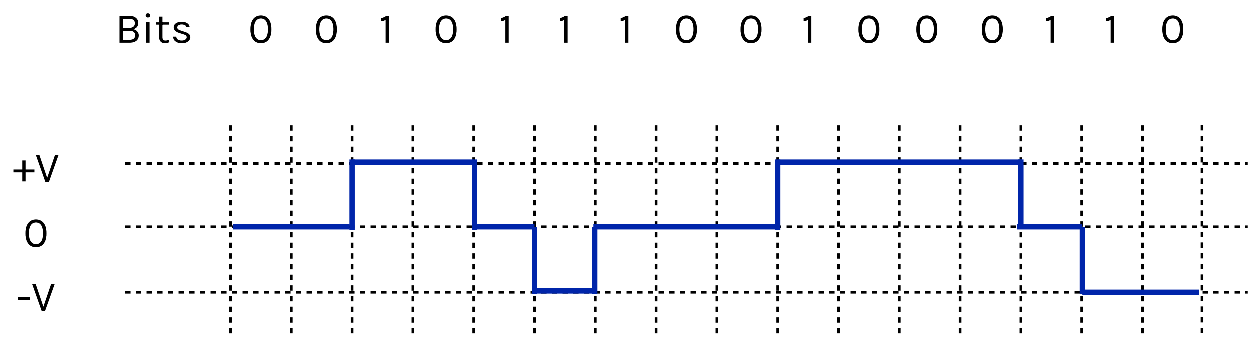
Multilevel transmission encoding (MLT-3)



0: no signal level changes, 1: alternating encoded according to sequence [+1, 0, -1, 0]

Do baseline wander and clock recovery problems exist?

Multilevel transmission encoding (MLT-3)

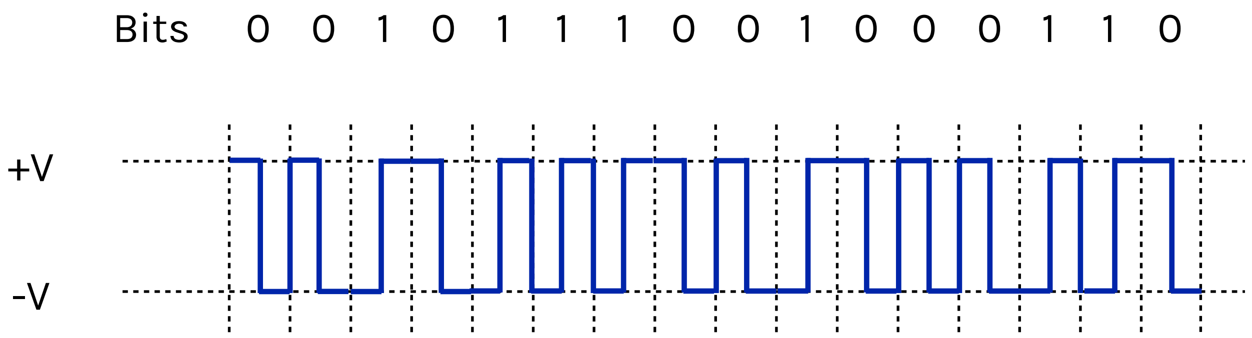


0: no signal level changes, 1: alternating encoded according to sequence [+1, 0, -1, 0]

Baseline wander can occur for sequences of +1 or -1 and clock recovery problem exists with series of 0s

Manchester code

As per IEEE 802.3



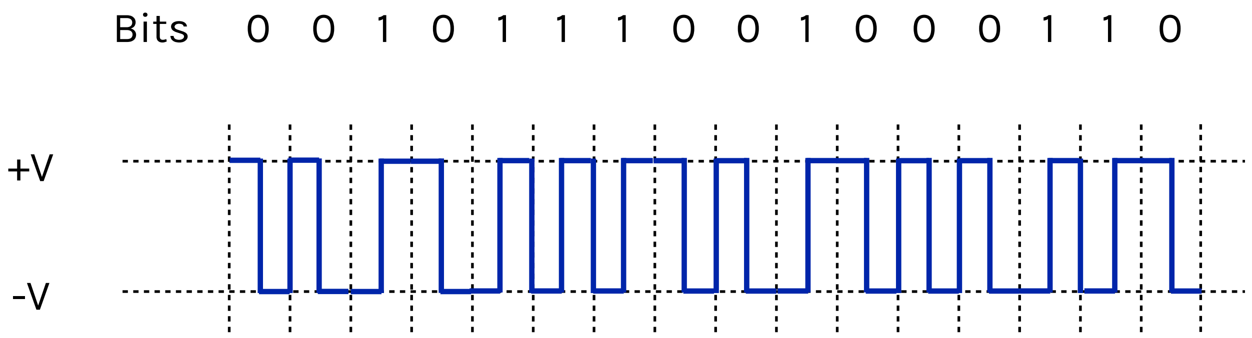
0: falling edge (from high to low), 1: rising edge (from low to high)

Do baseline wander and clock recovery problems exist?

https://en.wikipedia.org/wiki/Manchester_code

Manchester code

As per IEEE 802.3



0: falling edge (from high to low), 1: rising edge (from low to high)

Baseline wander cannot occur and clock recovery is no problem

Low efficiency: bit rate is half the baud rate due to the frequent signal level changes

https://en.wikipedia.org/wiki/Manchester_code

4B/5B code

Map every 4 data bits into 5 code bits without long runs of zeros

- At most 3 zeros in a row → clock recovery is possible
- Combined with NRZI → baseline wander cannot occur

```
0000  ───────▶  11110
0001  ───────▶  01001
 ...             ...
1110  ───────▶  11100
1111  ───────▶  11101
```

The complete encoding table can be easily found online

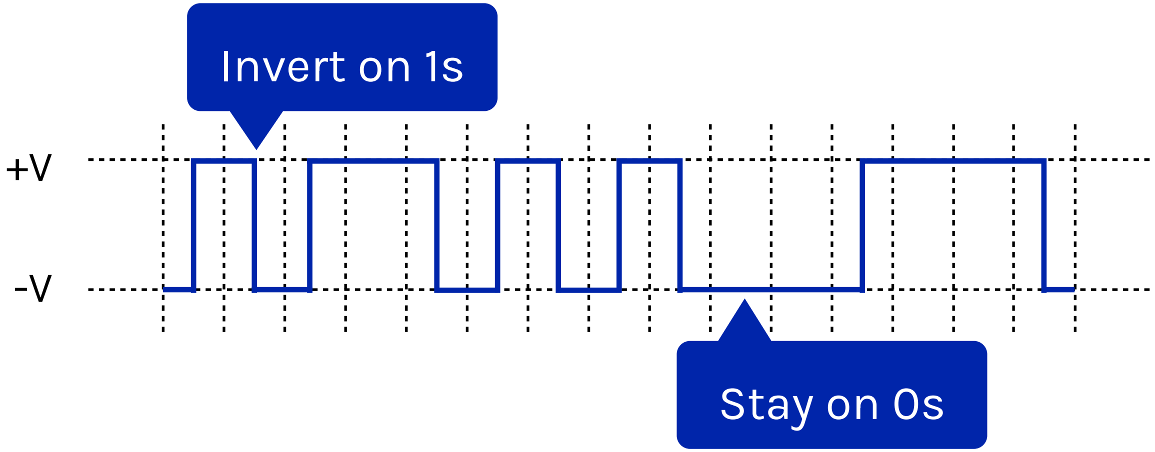
https://en.wikipedia.org/wiki/4B5B

4B/5B with NRZI example

Message bits 1 1 1 1 0 0 0 0 0 0 0 1

11101 11110 01001

Coded bits 1 1 1 0 1 1 1 1 1 0 0 1 0 0 1



Modulation

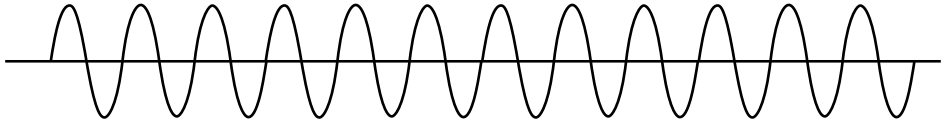
What we have seen is baseband modulation for wires

- Signal is sent directly on a wire

These signals do not propagate well on fibers / wireless media

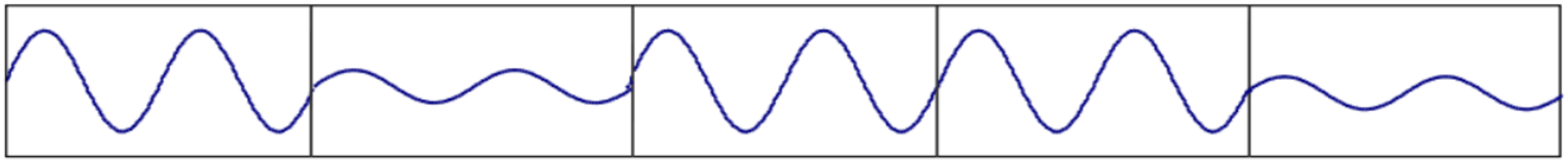
- Need to send at higher frequencies

Passband carries a signal by modulating a carrier signal at a higher frequency



A signal oscillating at a desired frequency that can be modulated by changing **amplitude**, **frequency**, or **phase**

Amplitude shift keying (ASK)



Characteristics:

- Easy to realize
- Does not need much bandwidth (single frequency)
- Not robust against distortion
- Often used in optical networks (low-noise environment)

Frequency shift keying (FSK)

Characteristics:

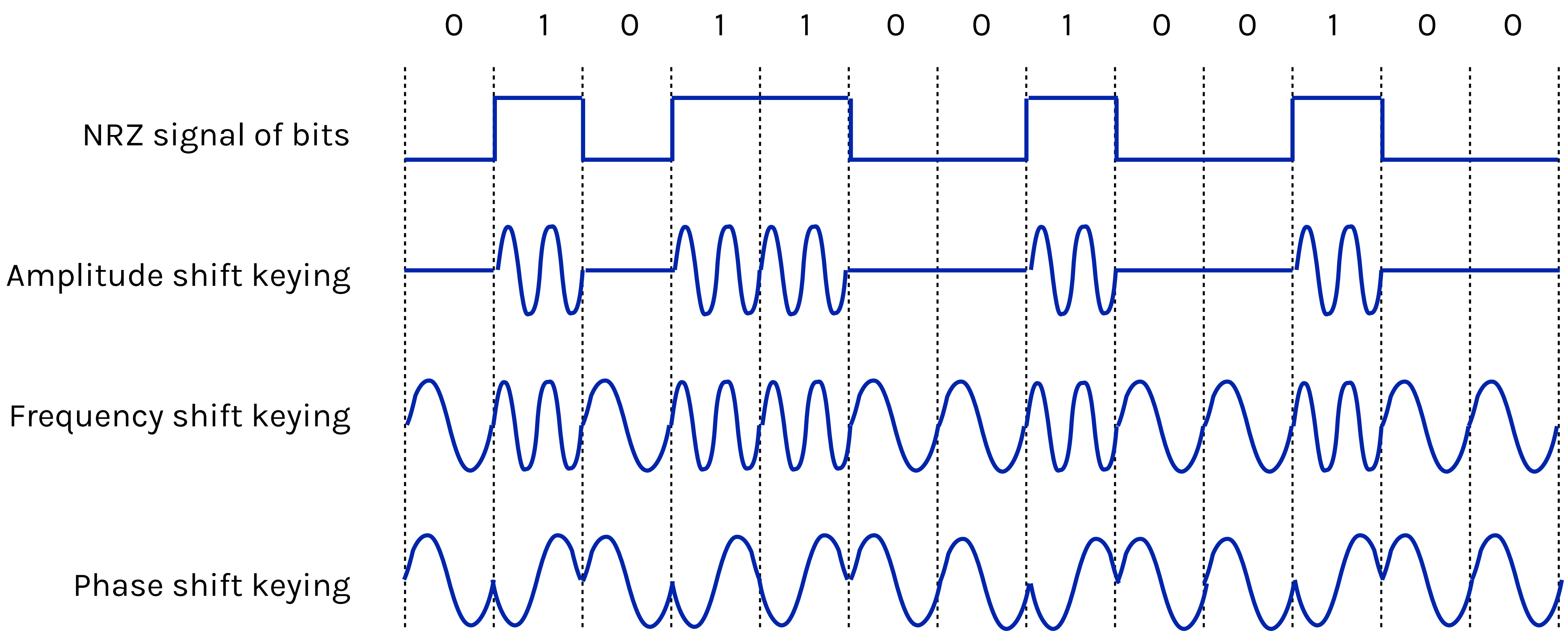
- Waste of frequencies
- Needs a lot of bandwidth
- Intial principle used in data transmission on phone lines

Phase shift keying (PSK)

Characteristics:

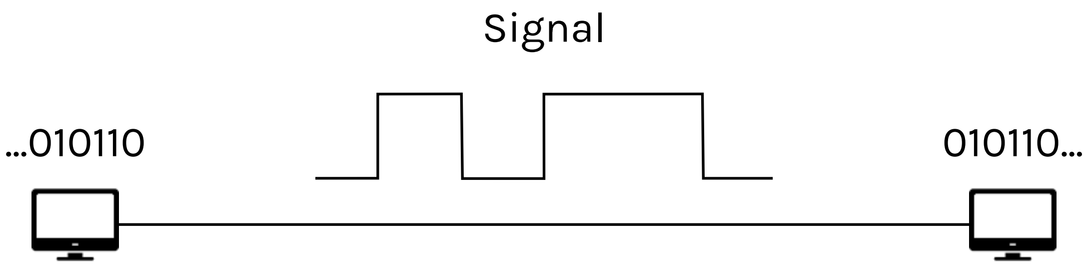
- Does not need much bandwidth (single frequency)
- Robust against distortion
- Complex demodulation process
- Best generic solution

Modulation schemes overview



Fundamental Limits

Fundamental limits overview



How rapidly can we send information over a link?

Nyquist limit
(~1924)

Shannon capacity
(1948)

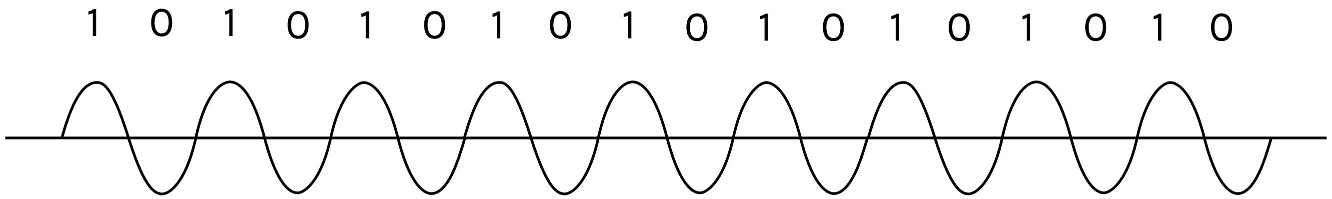
Key channel properties

Bandwidth (B) limits
the rate of transmission

Signal (S) and **noise (N)** limit how many
signal levels we can distinguish

Nyquist limit

The maximum symbol rate is 2B



Thus, if there are V signal levels, ingoring noise, the maximum bit rate is

$$R = 2B \log_2 V \text{ bits/sec}$$

Claud Shannon (1016-2001)

Father of information theory

- "A Mathematical Theory of Communication", 1948

Fundamental contributions to digital computers, security, and communications

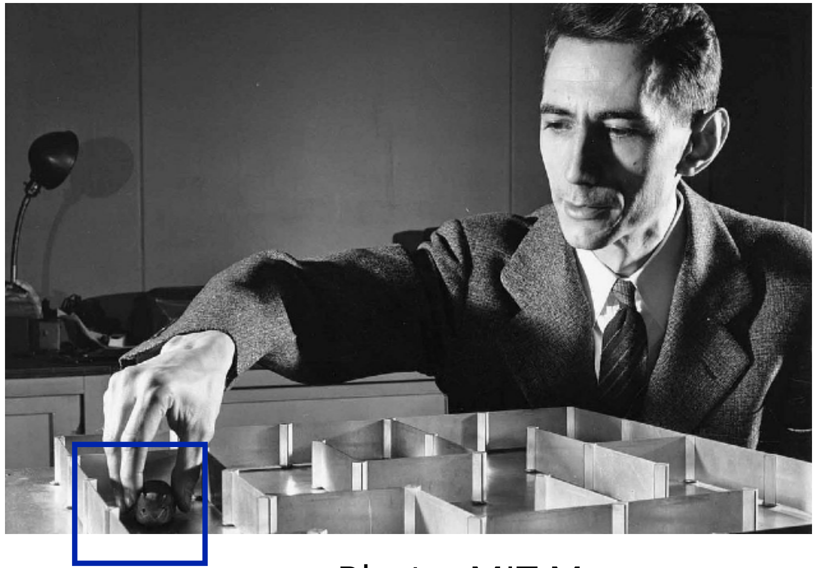


Photo: MIT Museum

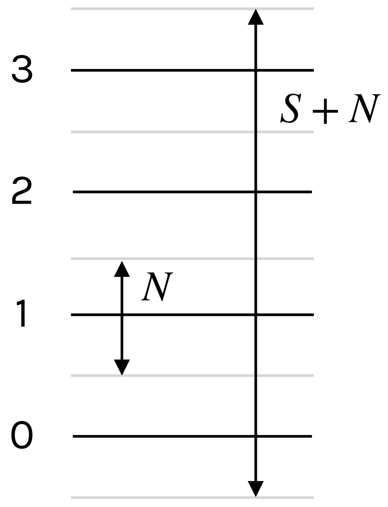
Electromechanical mouse that "solves" mazes!

https://www.hnf.de/ausstellungen/rueckblick/codes-und-clowns/claude-shannon.html

Shannon limit

How many levels we can distinguish depends on S/N

- Or so called SNR, the Signal-to-Noise Ratio
- Note that noise is random, hence some errors



SNR given on a log-scale in deciBels:

$$\text{SNR}_{\text{dB}} = 10 \log_{10}(S/N)$$

The Capacity (C)—the maximum information carrying rate of the channel—is given by

$$C = B \log_2(1 + S/N) \text{ bits/sec}$$

Shannon limit takeaways

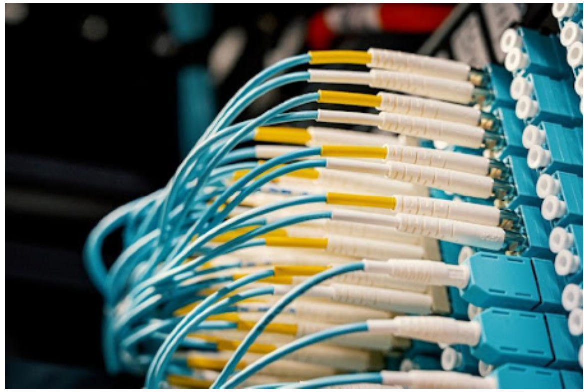
$$C = B \log_2(1 + S/N) \text{ bits/sec}$$

- There is some rate at which we can transmit data **without loss** over a random channel
- Assuming noise is fixed, increasing the signal power yields **diminishing returns**
- Assuming SNR is fixed, increasing bandwidth increases capacity **linearly**

Wired/wireless perspective

Wires

Fiber



Wireless

Engineer link to have requisite SNR and B
→ adapt SNR for data rate

SNR varies significantly
→ adapt data rate for SNR

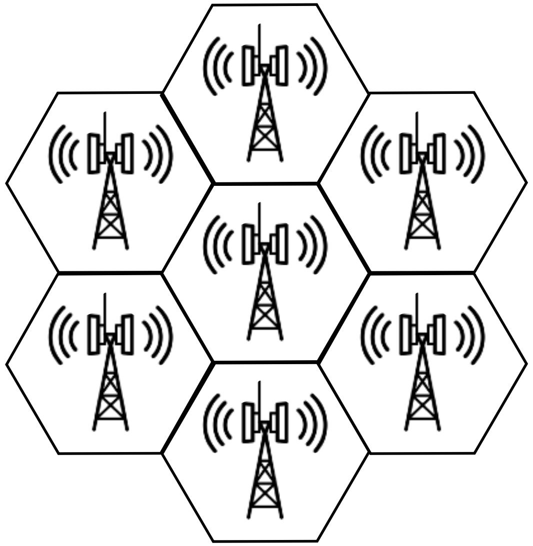
5G: there is no magic

To increase the data rate, we need either more spectrum or more power

- More spectrum means more bandwidth, higher frequency
- More power means higher SNR

Both are limited by physics… How can we work around it?

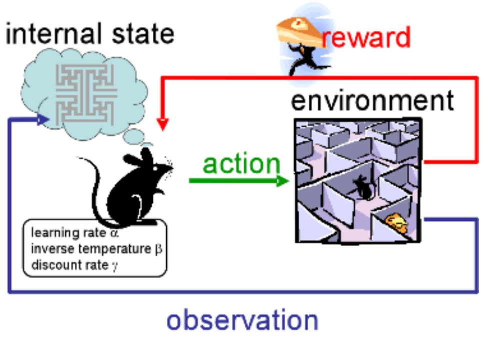
Remember "spatial reuse"



Make the cells smaller, so we can have more of them!

Layer management in 5G

How to select the different channels that are available to each end device?



Reinforcement learning
(research project available)

A Simple Link Model

Link model

Oftentimes, we do not really care about the nitty-gritty details of signals

- We do care about some properties of the link

An abstraction of a physical channel

- Rate (or bandwidth, capacity, speed) in bits/sec
- Delay in seconds, related to link length
- Other important properties: broadcast, error rate

Delay D, rate R

Message latency

Latency is the delay to send a message over a link

- Transmission delay: time to put M-bit message "on the wire"

$$T_{\text{t}} = M \text{ (bits) / } R \text{ (bits/sec)} = M/R \text{ secs}$$

- Propagation delay: time for bits to propagate across the wire

$$T_p = \text{length / speed of signal} = D$$

- Combining the two terms we have $L = T_t + T_p = M/R + D$

Latency example

"Dial-up" with a telephone modem

- $D = 5$ ms, $R = 56$ kbps, $M = 1250$ bytes
- $L = (1250 \times 8)/(56 \times 10^3)$ sec $+ 5$ ms $= 184$ ms

Broadband cross-country link

- $D = 50$ ms, $R = 10$ Mbps, $M = 1250$ bytes
- $L = (1250 \times 8)/(10 \times 10^6)$ sec $+ 50$ ms $= 51$ ms

A slow rate or a long link means high latency: usually one component dominates

Bandwidth-delay product (BDP)

Messages take space on the wire

The amount of data in-flight is the bandwidth-delay product (BDP): $R \times D$

- Measured in bits, or in messages
- Small for LANs, big for "long fat" pipes

Bandwidth-delay product example

Fiber at home, cross-country

- $R = 40$ Mpbs, $D = 10$ ms

- $\text{BDP} = 40 \times 10^6 \times 10 \times 10^{-3}$ bits
  $= 400$ Kbits
  $= 50$ KB

That is quite a lot of data in the network!

Summary

Different media

- Wires, fiber, wireless

Signal propagation

- Signal analysis and propagation

Encoding and modulation

- Encoing schemes
- Baseline wander & clock recovery
- Modulation schemes

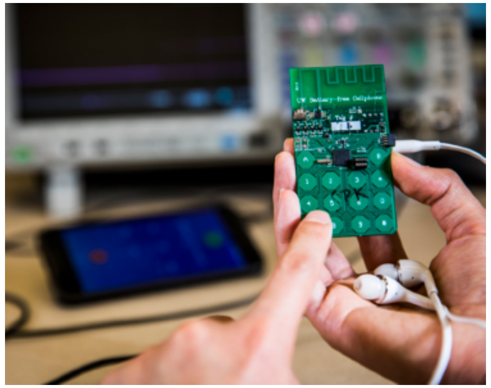
Fundamental limits

- Naquist limit
- Shannon capacity

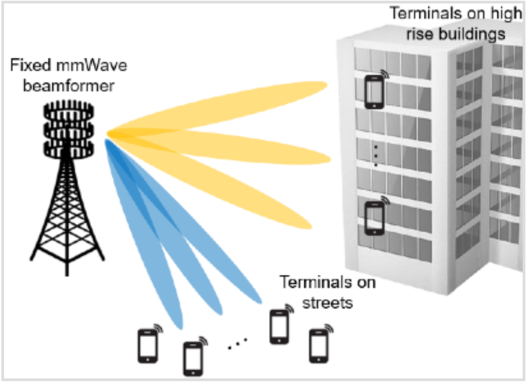
Link model

- Bandwidth and latency
- Bandwidth-delay product

New innotations in the physical layer

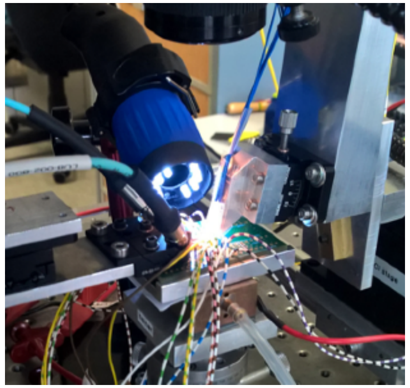


Battery-free cellphone



mmWave beamforming

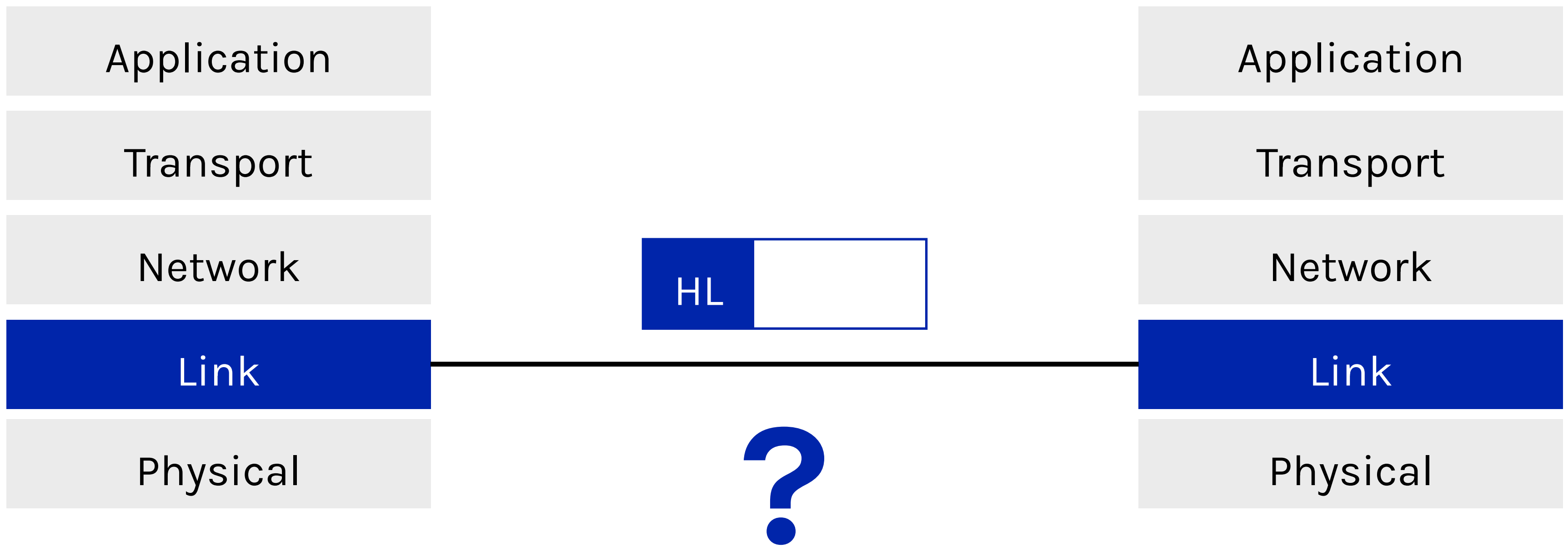
LiFi



World record @ UPB

https://batteryfreephone.cs.washington.edu/
https://www.5gmmwave.com/5g-mmwave/beamforming-in-5g-mmwave-radios/
https://lifi.co/
https://www.uni-paderborn.de/en/news-item/86758

Next time: data link layer



Further reading material

Andrew S. Tanenbaum, David J. Wetherall. Computer Networks (5th edition).

- Section 2: The Physical Layer

Larry Peterson, Bruce Davie. Computer Networks: A Systems Approach.

- Section 2.2: Encoding