# Computer Networks X_400487

## Lecture 2

## Chapter 2: The Physical Layer

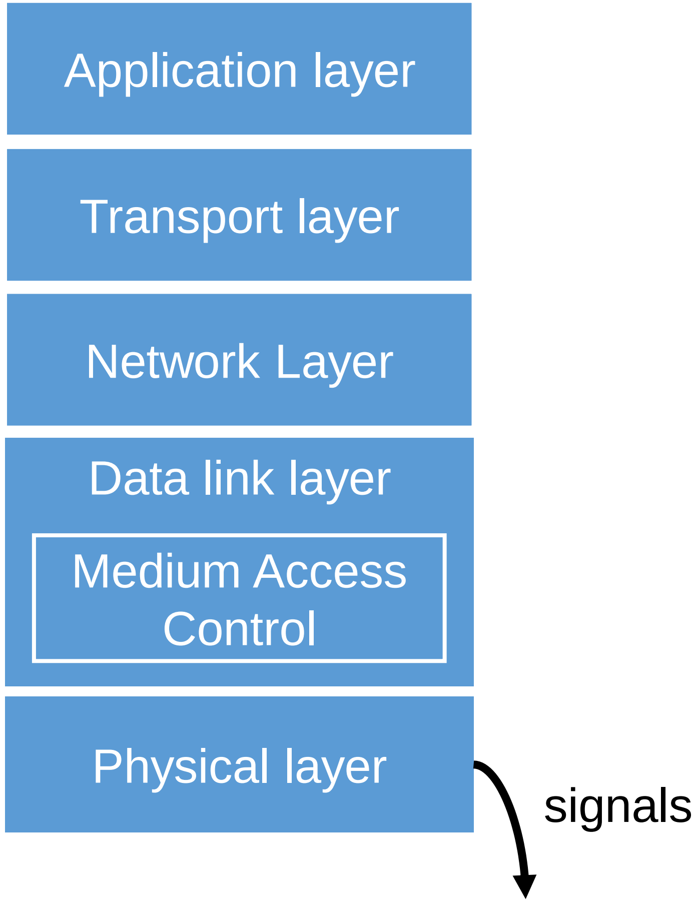
Lecturer: Jesse Donkervliet

# Layered architecture

A (layered) architecture makes the system easier to understand

Real-world networks do not exactly match this architecture

Q: Why do we use it?



# Layered architecture

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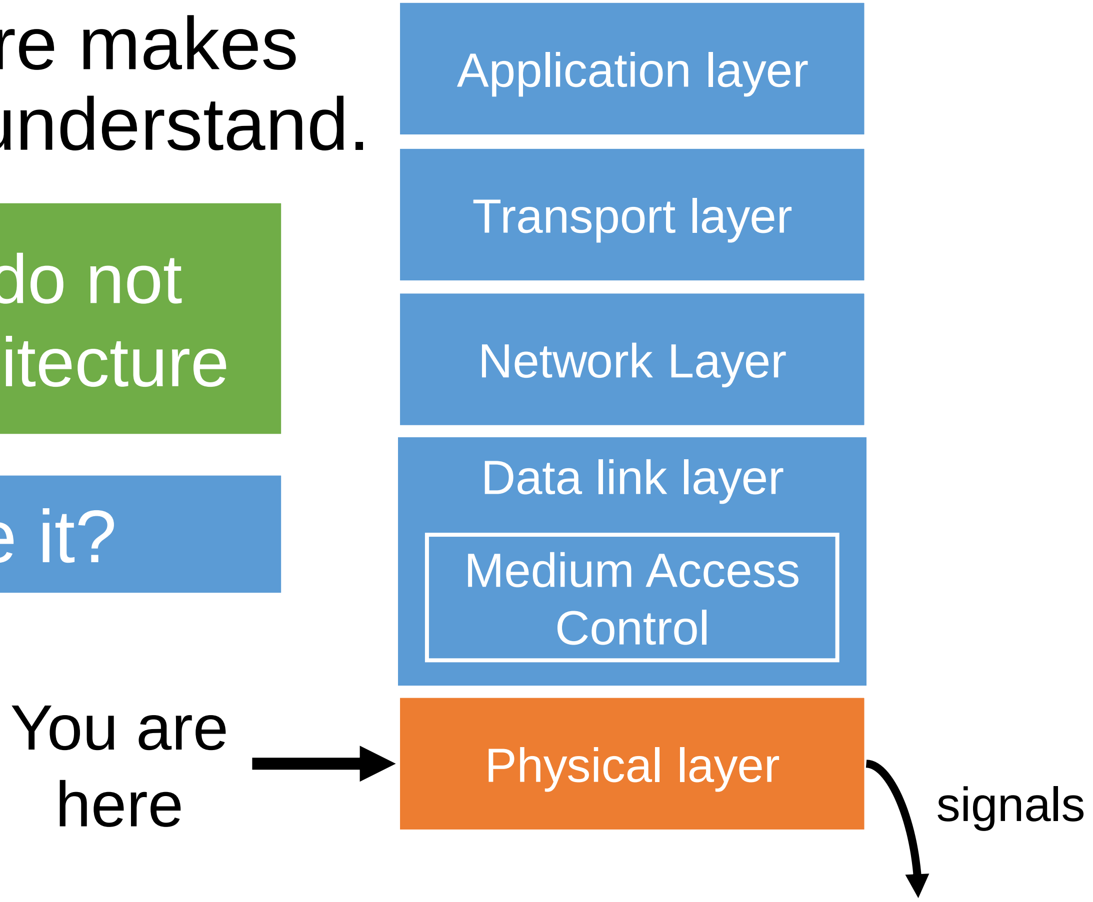
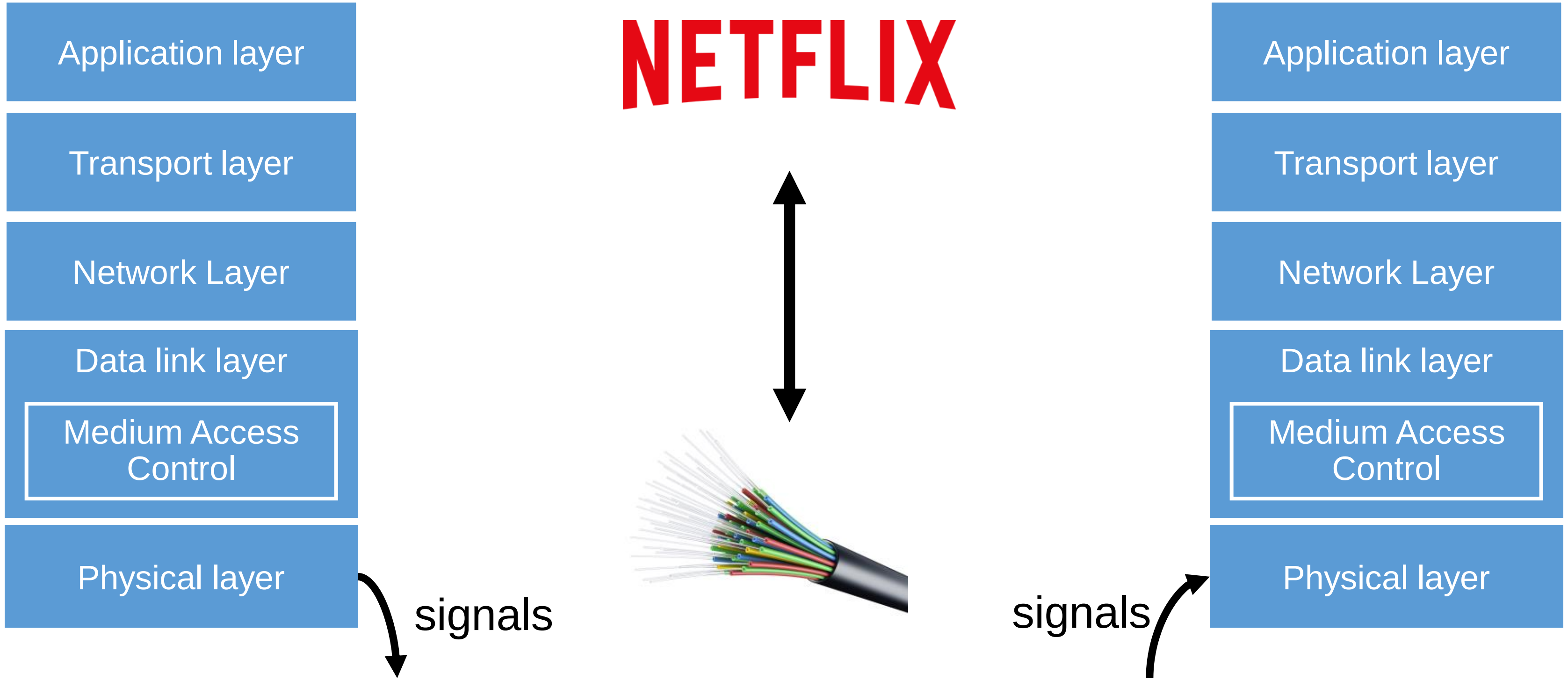
Q: Why do we use it?



# From a service to a signal, and back again



# How can we transport data?

Q: Can you think of mediums used for computer networks?

Well-known mediums:

1. Copper cables
2. Optical fibers
3. Radio waves

A medium allows you to transport data from one place to another

Other possible of mediums:

1. Postal service ("snail mail")
2. A truck full of SSD drives
3. Trained pigeons with USB drives attached to their feet
4. …

# Digital Modulation

**Q: How to communicate bit strings (e.g., 101011101) between computer systems?**

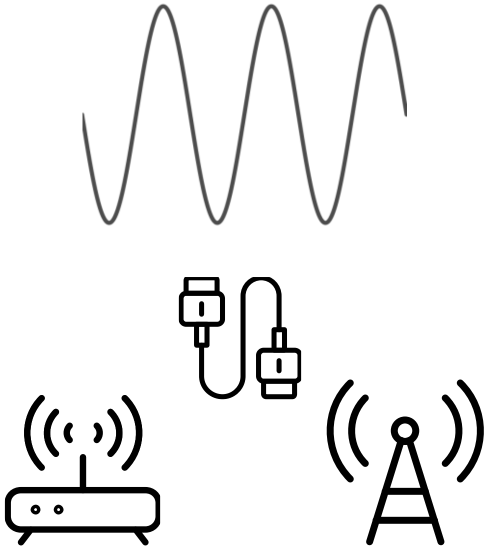
Bits and Bytes

11010101

Modulation

Put information onto a carrier signal

Waves and Signals



Demodulation

Extract information from a carrier signal

Bits and Bytes

11010101

# Different channel, different properties

Q: Which properties are important for *video on-demand*?

**Bit rate**
Number of bits per second. Depends on protocol, channel bandwidth, and other factors.

**Delay**
How long does it take a bit to get to the end?

**Storage Capacity**
How many bits can the channel hold at once?
Capacity = Bit rate × Delay

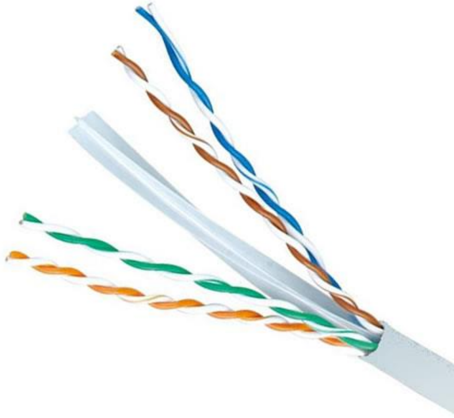
**Error Rate (Noise, Attenuation)**
What is the probability of a bit flipping?

Non-functional properties can enable new technologies!

# Physical Layer Lecture

1. **Physical Properties of Different Mediums**
2. Communication Speed Limits
3. Digital Modulation
4. Multiplexing

# Twisted pair



Commonly used for:

1. Telephone networks.
2. Wired LANs.

**Q: Why are the wires twisted?**

Q: What about the latency and error rate?

Example: Category 6 (“CAT 6”) cables.
Some support 500 MHz bandwidth.

High bandwidth allows higher data rates

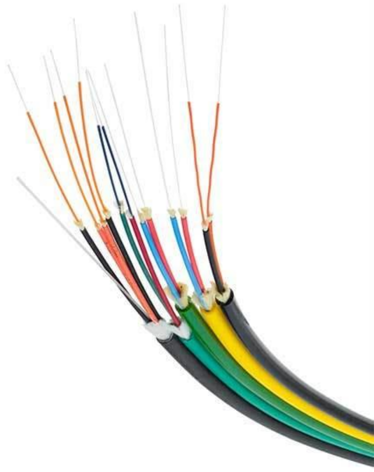
# Coaxial (“coax”) cable

Commonly used for:

1. Telephone networks
2. Cable television
3. Wired Metropolitan Area Networks (MANs).

Bandwidth in the order of GHz.

# Optical fiber



Commonly used for:

1. Long-distance network backbones.
2. Wired Metropolitan Area Networks (MANs).
3. High-performance LANs.

Fiber is becoming increasingly popular in multiple application domains

Bandwidth in the order of 100 GHz.

# Wireless transmission

Different frequencies means different properties.

1. Radiowave
   - AM radio
   - FM radio
2. Microwave
   - Satellite dishes
3. Infrared
   - Remote controls
4. Visible light
5. …

Example?

Q: Can you think of a (dis)advantage compared to wired transmission?

# Wireless transmission

Different frequencies means different properties.

1. **Radiowave**
   AM radio
   FM radio
2. **Microwave**
   Satellite dishes
3. Infrared
   Remote controls
4. Visible light
5. …

# Radio

AM radio ($f \approx 1\ MHz$)

FM radio ($f \approx 100\ MHz$)

Q: Can you think of (dis)advantages?

Both can travel reasonably long distances

# Microwave $(f \approx 10\ GHz)$

Needs line of sight

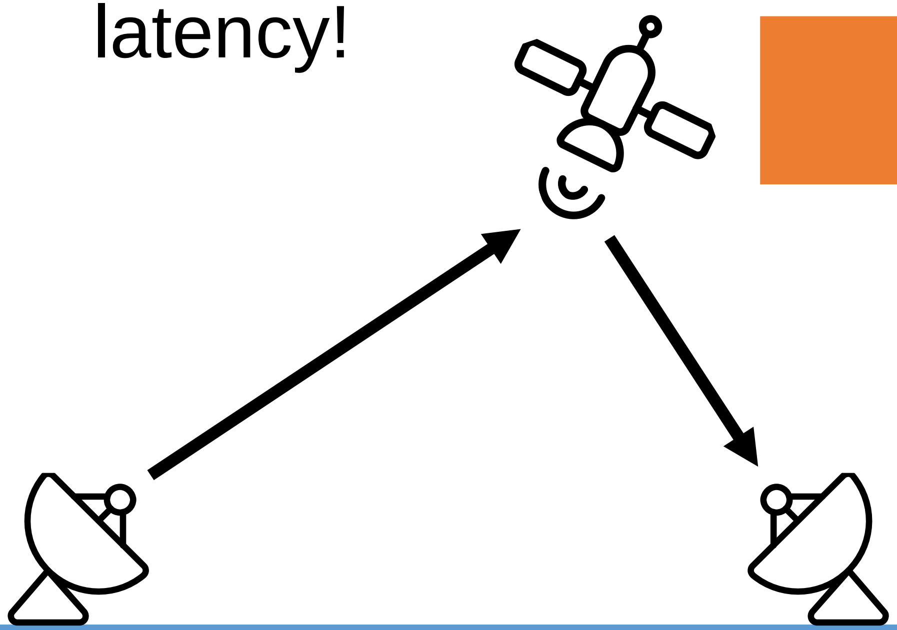
Q: Can you think of (dis)advantages?

# Satellite Networks

Q: What are its properties?

Radio waves allow for high bit rates and have (relatively) low attenuation.

But sending signals to artificial satellites and back has significant latency!



Lower latency requires lower orbits requires more satellites

# Physical Layer Lecture

1. Physical Properties of Different Mediums
2. **Communication Speed Limits**
3. Digital Modulation
4. Multiplexing

# Fundamental speed limits

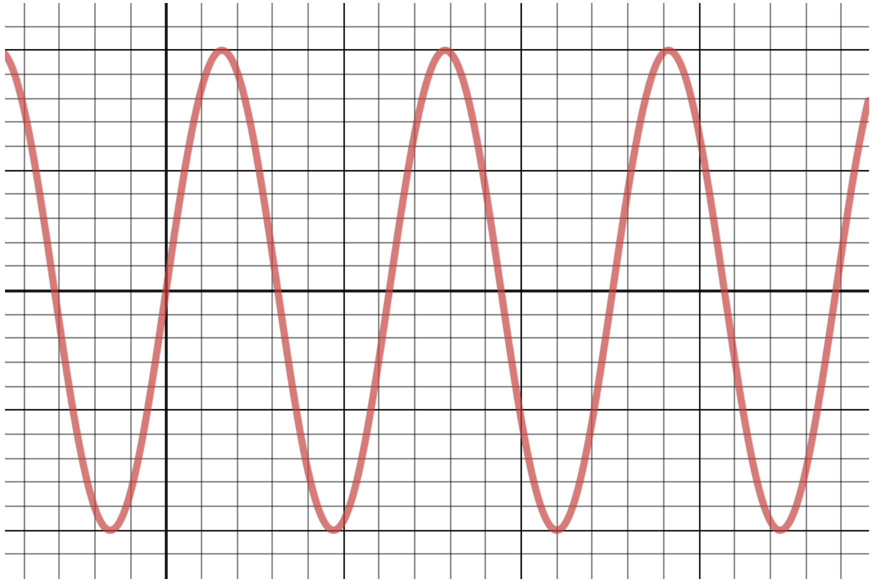
# Properties of Waves

**Q: What are properties of waves?**

Properties:

1. Amplitude $(A)$
2. Frequency $(f)$
3. Phase $(\varphi)$

Frequency and phase are not independent



$$y(t) = A \cdot \sin(2\pi f t + \varphi)$$

Q: Which properties can we modulate simultaneously?

# Nyquist’s theorem

Computing the *maximum data rate* for a noiseless channel

$$R = 2B \times \log_2(V)$$

$R$ = maximum data rate ← Measured in bits/s

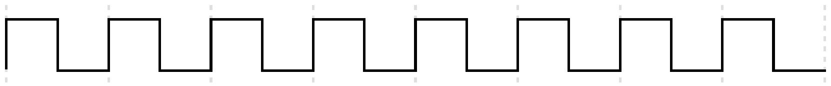
$B$ = bandwidth ← Measured in Hz

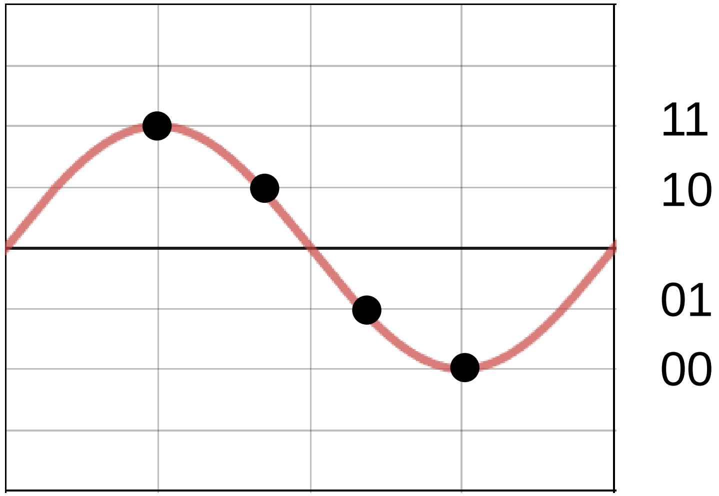
$V$ = number of discrete signal levels

# Nyquist’s theorem
# An intuition

For a binary signal, V=2

101010101010101






$$R = 2B \times \log_2(V)$$

# Nyquist's Theorem Example

Signal that uses 4 signal levels over a wired channel with 500kHz bandwidth

$$R = 2B \times \log_2 V$$
$$B = 500{,}000 \quad V = 4$$
$$R = 2 \times 500{,}000 \times \log_2 4$$
$$R = 2{,}000{,}000$$
$$R = 2\text{Mbps}$$

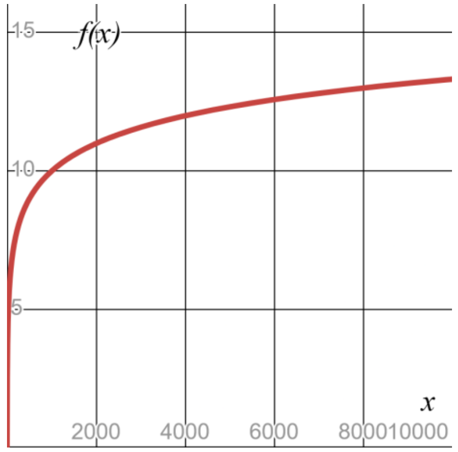
Q: Can we exceed the maximum Nyquist data rate? Under what assumptions does this model hold?

# Shannon’s theorem

Q: Should we reduce noise or increase bandwidth?

Shannon’s Theorem + signal attenuation → limited cable length

In practice, *noise* reduces the maximum data rate.




$$R = B \times \log_2\left(1 + \frac{S}{N}\right)$$

The signal to noise ratio ($S/N$ or SNR) is expressed in decibel.
SNR of $40$ dB means $S/N = 10^4$

Q: Why use decibels?

I.e., Signal power is 10,000 times stronger than Noise power

# Shannon's Theorem Example

Signal level not used!

Consider the signal and channel from before (4 signal levels, 500kHz bandwidth). What happens if the SNR is 40dB?

$$R = B\log_2\left(1 + \frac{S}{N}\right)$$
$$B = 500{,}000$$
$$\frac{S}{N} = 40\text{dB} = 10^{\frac{40}{10}} = 10{,}000$$
$$R = 500{,}000\log_2(1 + 10{,}000)$$
$$R \approx 500{,}000 \times 13 = 6{,}500{,}000\text{bps} = 6.5\text{Mbps}$$

$$\log_2 10001 \approx 13.29 \approx 13$$
$$2^{10} = 1024,\ 2^3 = 8,\ 2^4 = 16$$
$$2^{13} = 8192,\ 2^{14} = 16348$$

# Physical Layer Lecture

1. Physical Properties of Different Mediums
2. Communication Speed Limits
3. **Digital Modulation**
4. Multiplexing

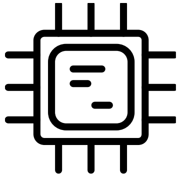
# Digital Modulation

Translating Between Bits and Signals

Key responsibility of the physical layer

# Digital Modulation

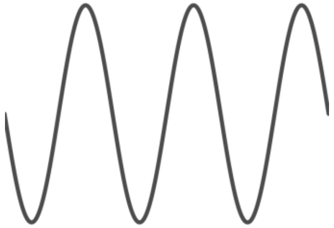
**Q: How to communicate bit strings (e.g., 101011101) between computer systems?**



Bits and Bytes

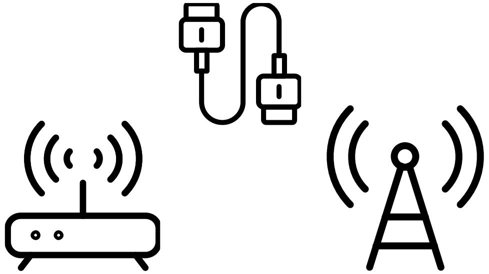
11010101

Waves and Signals



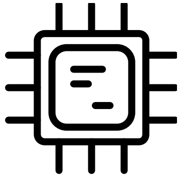
Modulation

Put information onto a carrier signal



Bits and Bytes

11010101



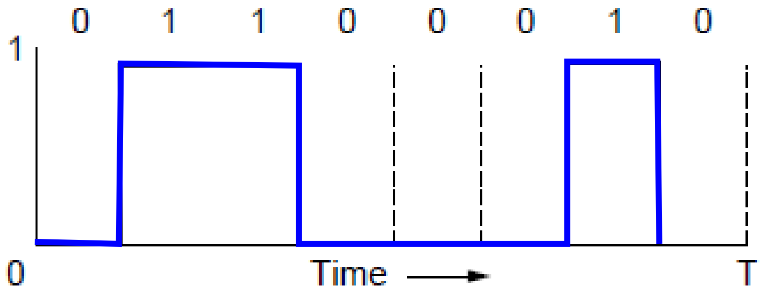
Demodulation

Extract information from a carrier signal

# Digital Modulation: Baseband Transmission

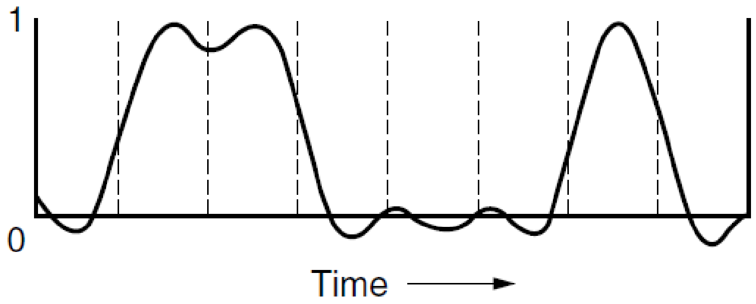
# Representing Bits Using Signals

Data
01100010




**Q: Why send an approximation?**

An approximation of the original signal




**Q: How close must the approximation be?**

# Baseband transmission

Q: Can you think of a problem with this approach?

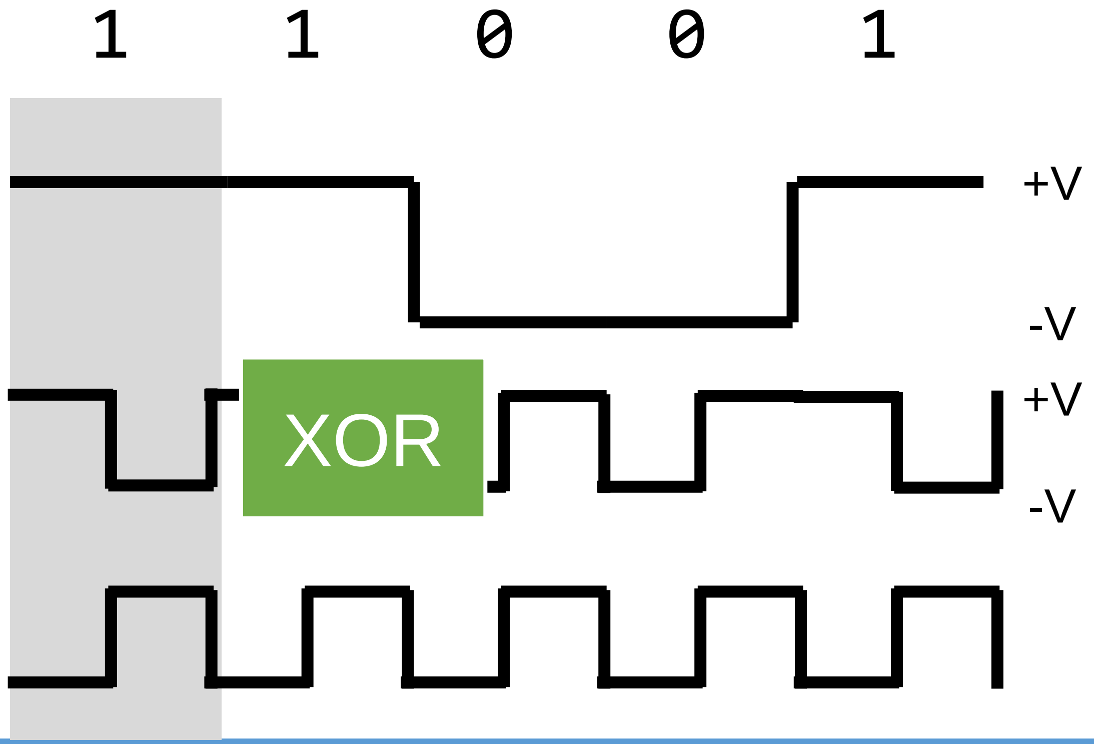
Idea: send *signals* that represent one or more *bits.*

Bit stream:

Non-Return to Zero:

Manchester encoding:

clock:



# Baseband transmission

Non-Return to Zero has **clock recovery** problems.

Manchester encoding halves the available *bandwidth.*

Q: Can you think of a better solution?

Bit stream: 1 1 0 0 1

NRZ Invert:

# 4B/5B encoding

**Q: What are the (dis)advantages of this approach?**

Use a translation table to map sequences of 4 data bits to 5-bit codewords.

| Data | | Codeword |
|---|---|---|
| 1010 | → | 10110 |
| 0000 | → | 11110 |
| 1111 | → | 11101 |

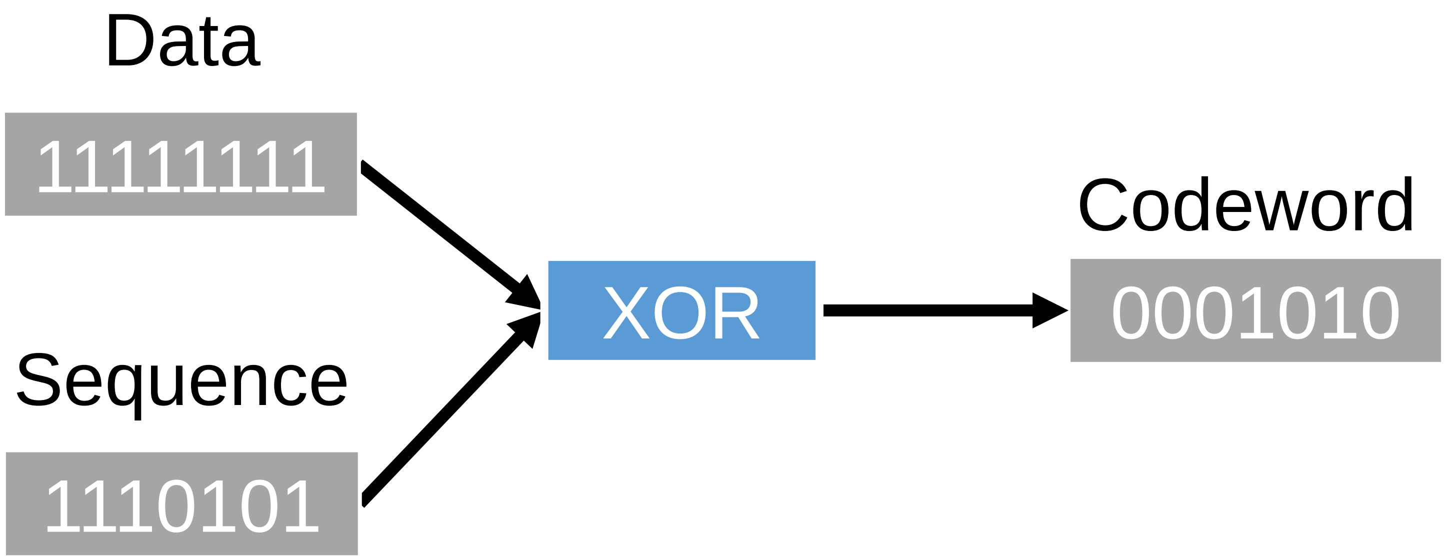
**Q: Could we use a different mapping?**

# Scrambling

Q: What are the (dis)advantages of this approach?

XOR the data with a random bit sequence.

E.g., use sequence `1110101`.



# Digital modulation: Passband transmission

# Passband transmission

Low-frequency signals not always practical.

Q: Why not?

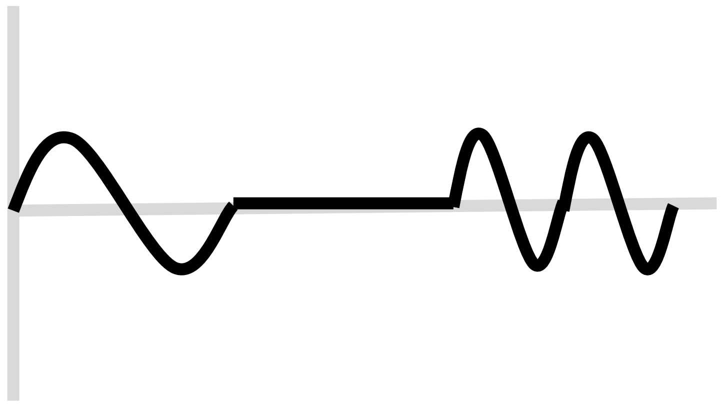
Not practical for wireless channels:

1. Antenna size
2. Interference
   - Noise
   - Other channel users!

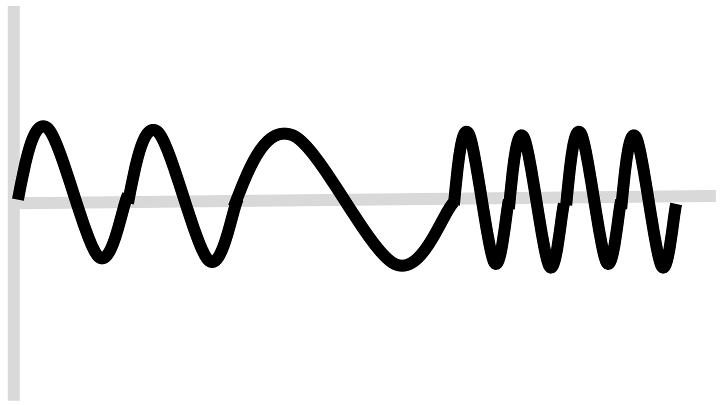
The *passband*

# Passband transmission

Solution: move from **[0, B] Hz** to **[S, S+B] Hz**.

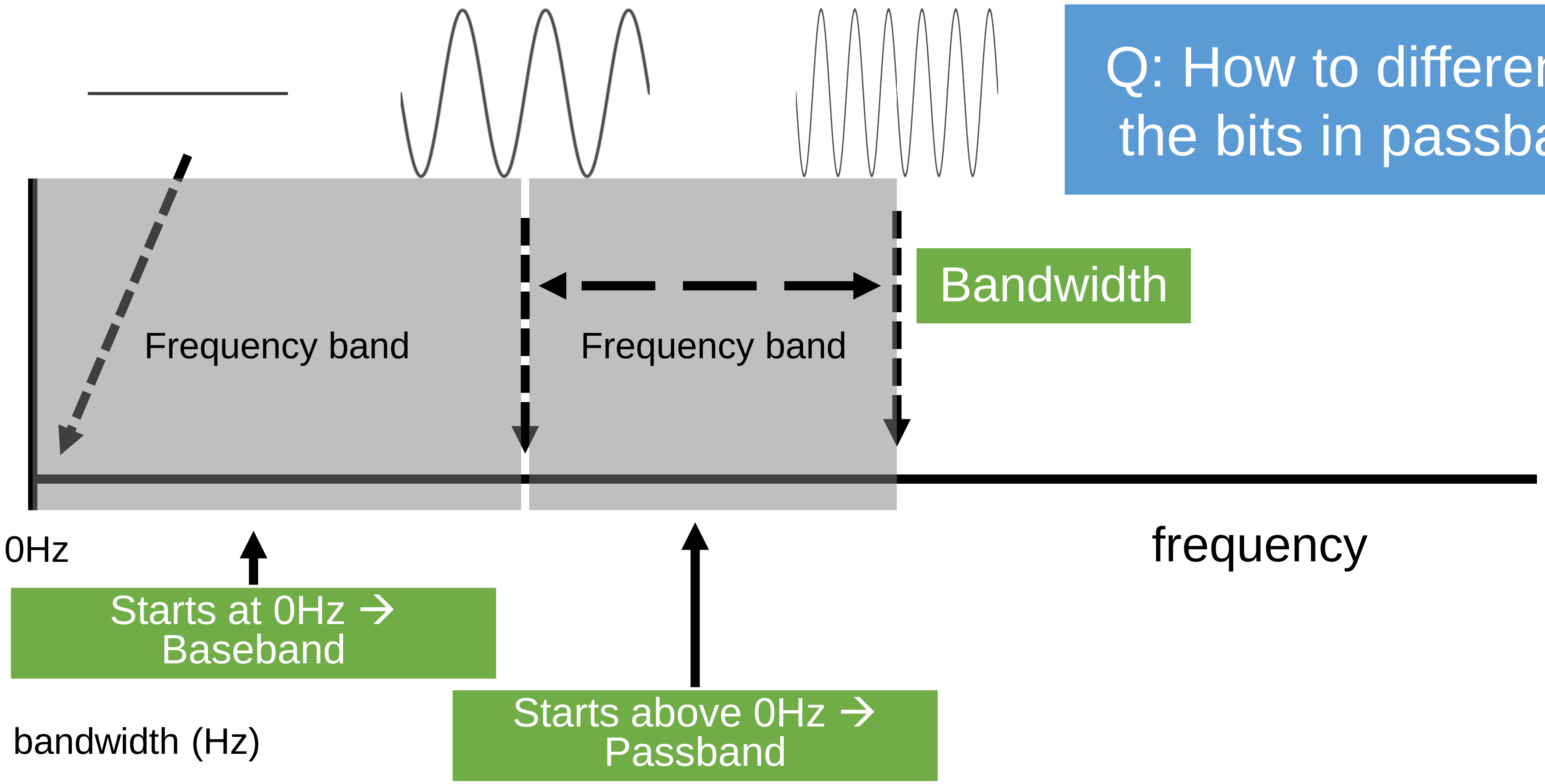


Frequency can be 0 Hz



Minimum frequency of $S$ Hz

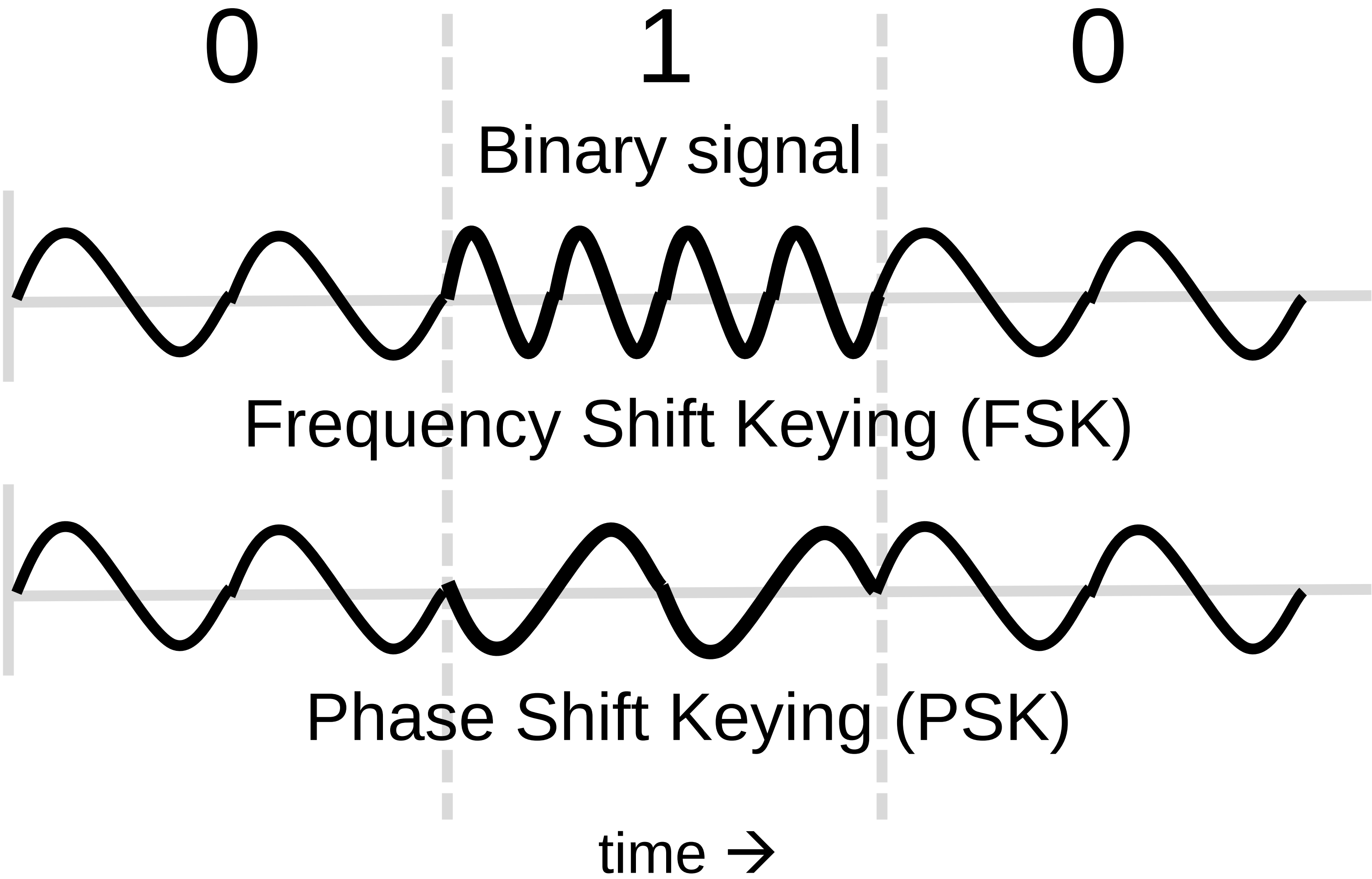
# Baseband, Passband, and Bandwidth*




Q: How to differentiate the bits in passband?

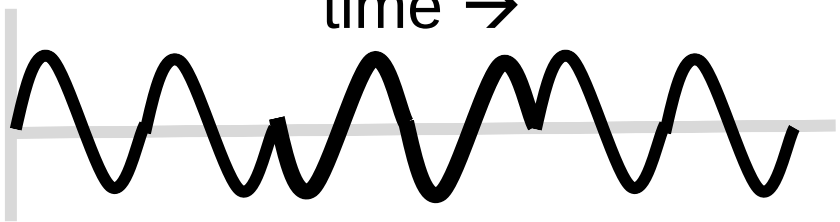
*Analog bandwidth (Hz)

# Digital Modulation



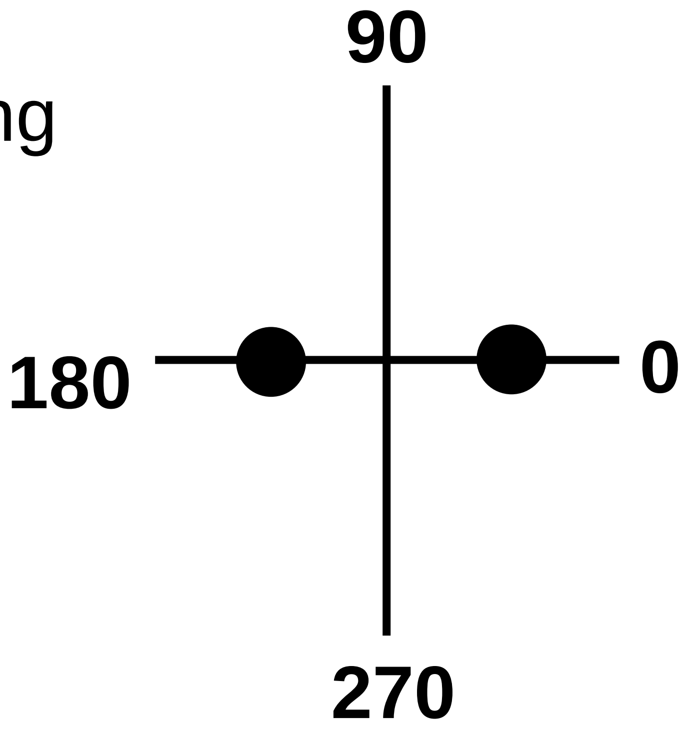

…

# Sending multiple bits per symbol

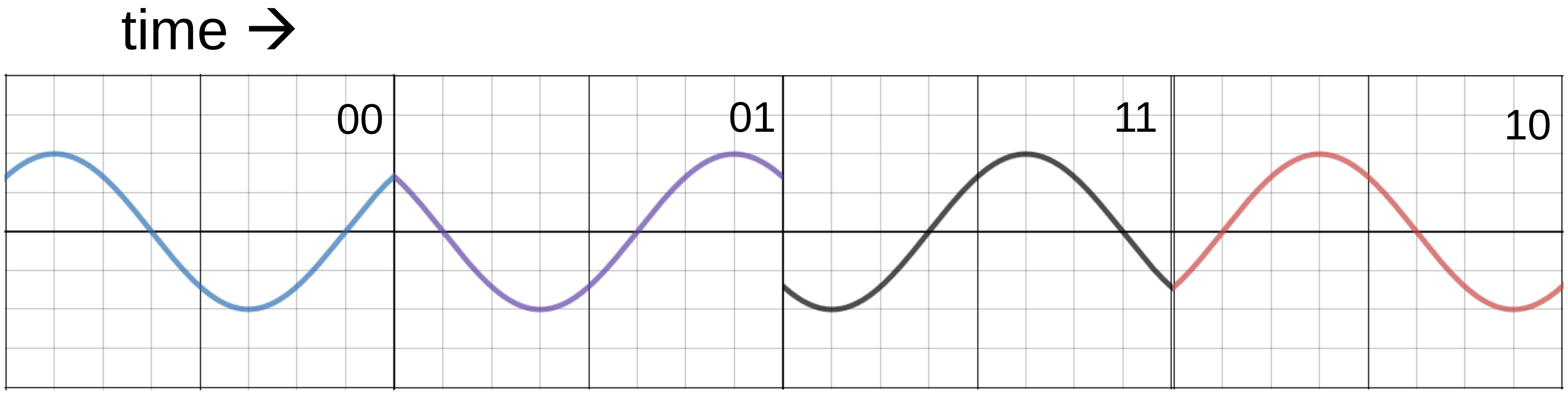



Binary Phase Shift Keying
(BPSK)

BPSK
2 symbols
1 bit/symbol

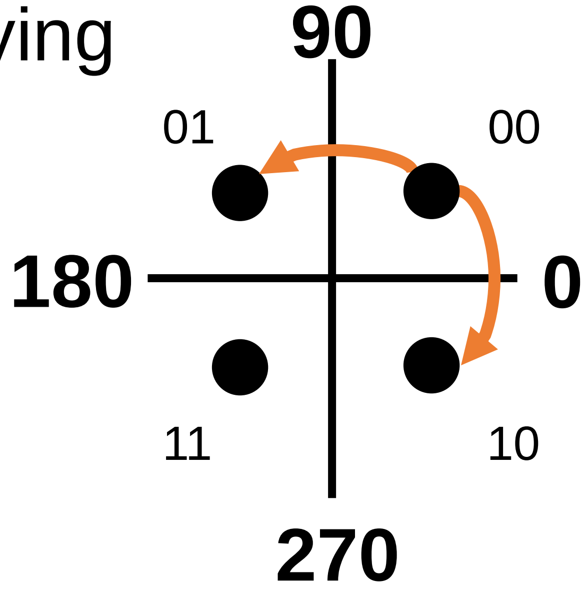


# Sending multiple bits per symbol




Quadrature Phase Shift Keying
(QPSK)

QPSK
4 symbols
2 bit/symbol




Gray encoding

Every adjacent pair of symbols only differs by one bit

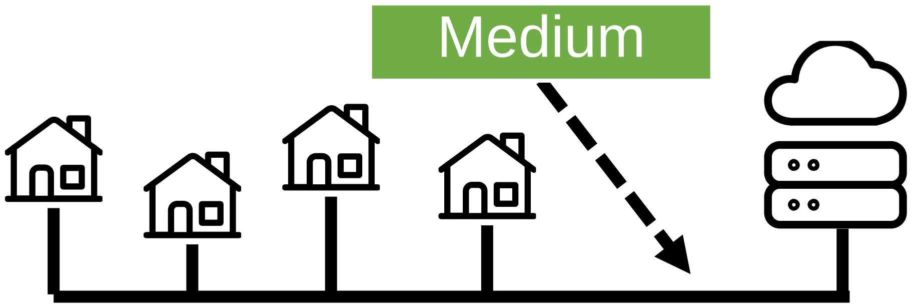
# Physical Layer Lecture

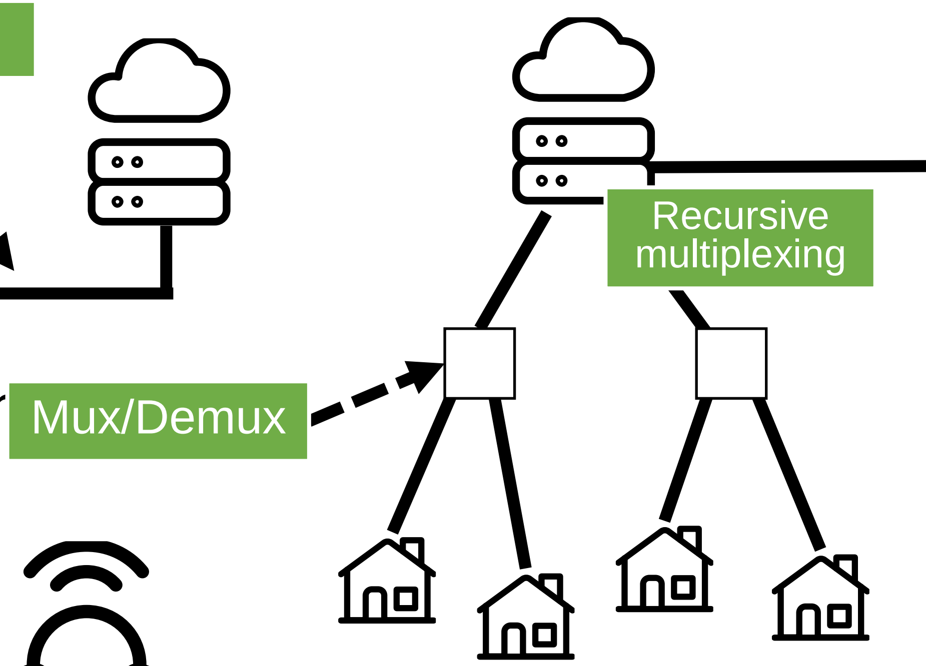
1. Physical Properties of Different Mediums
2. Communication Speed Limits
3. Digital Modulation
4. **Multiplexing**

# Multiplexing

Key concept: resource sharing

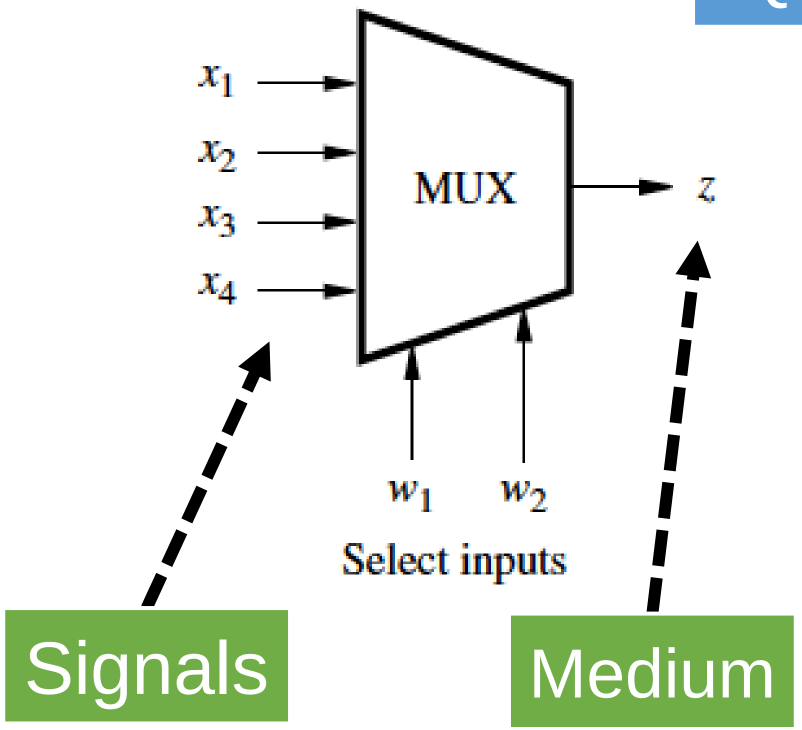
# Multiplexing



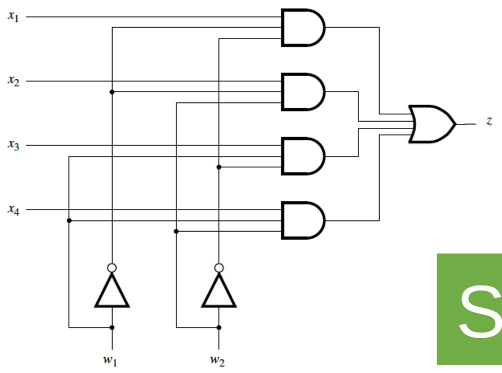



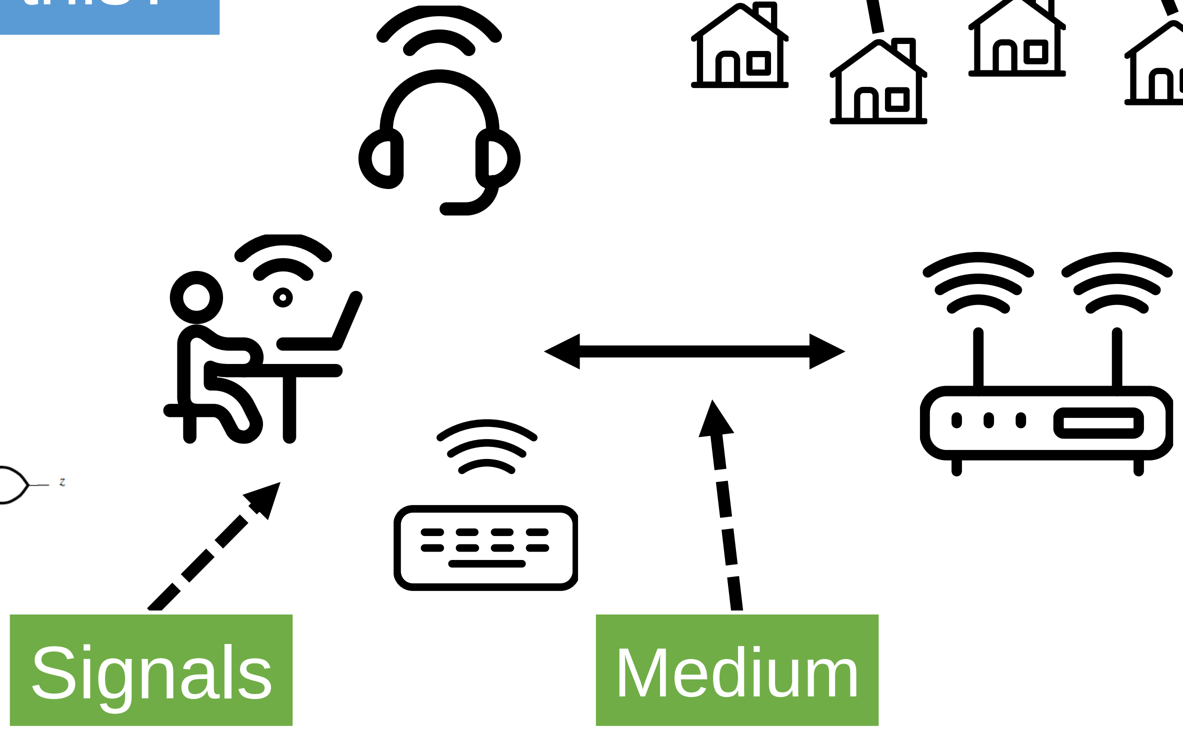

Sending multiple signals via a single medium

Q: Why (not) do this?




| $w_1$ | $w_2$ | $z$ |
|---|---|---|
| 0 | 0 | $x_1$ |
| 0 | 1 | $x_2$ |
| 1 | 0 | $x_3$ |
| 1 | 1 | $x_4$ |





# Simplex and Duplex Channels

**Simplex channels** only allow data to pass through in one direction.

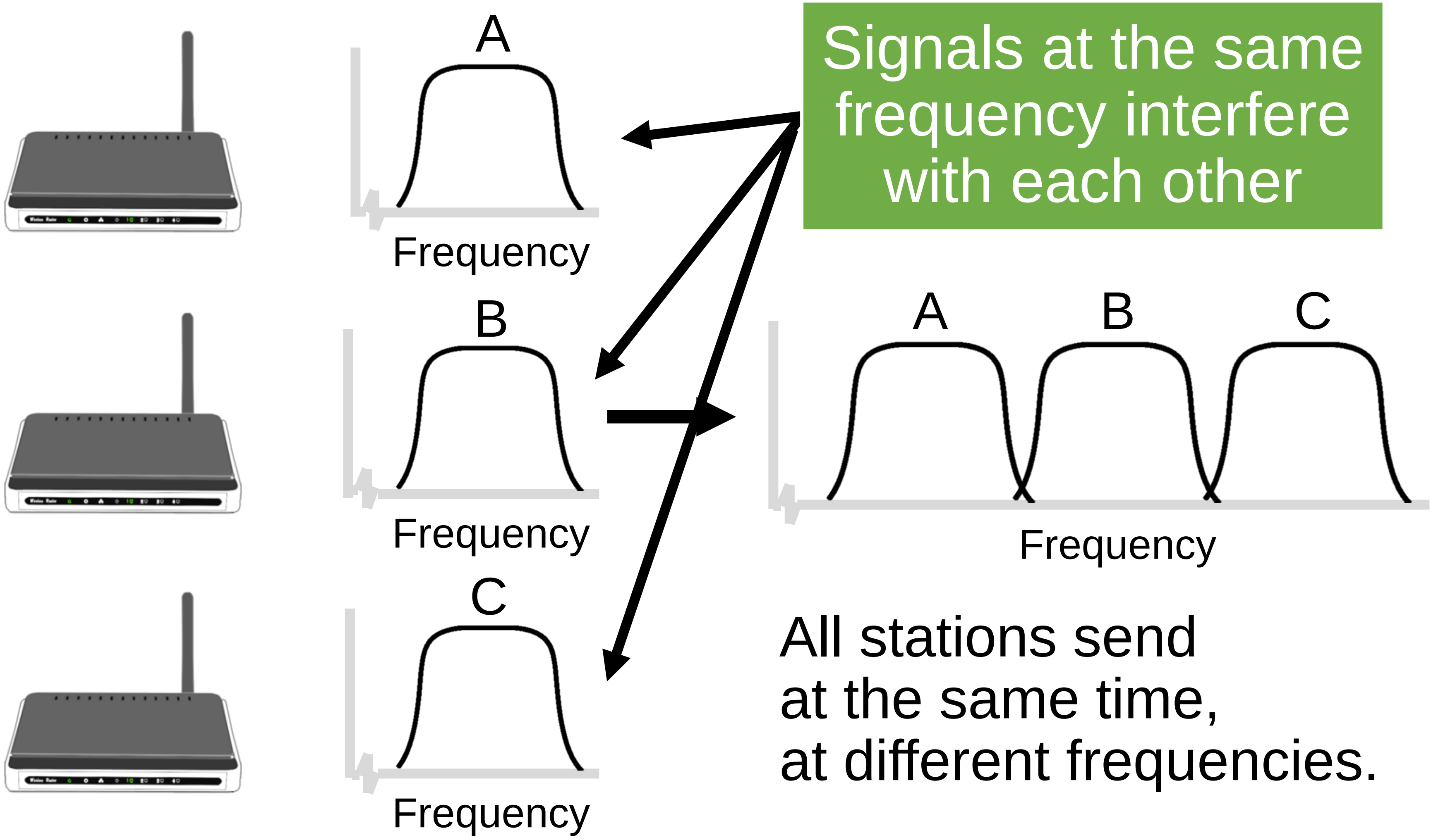
**Duplex channels** allow data to pass through in both directions at the same time.

Q: Can you think of a simple way to build a duplex channel?

**Half-duplex channels** allow data in both directions, but not at the same time.

# Frequency Division Multiplexing

4G
ADSL
…

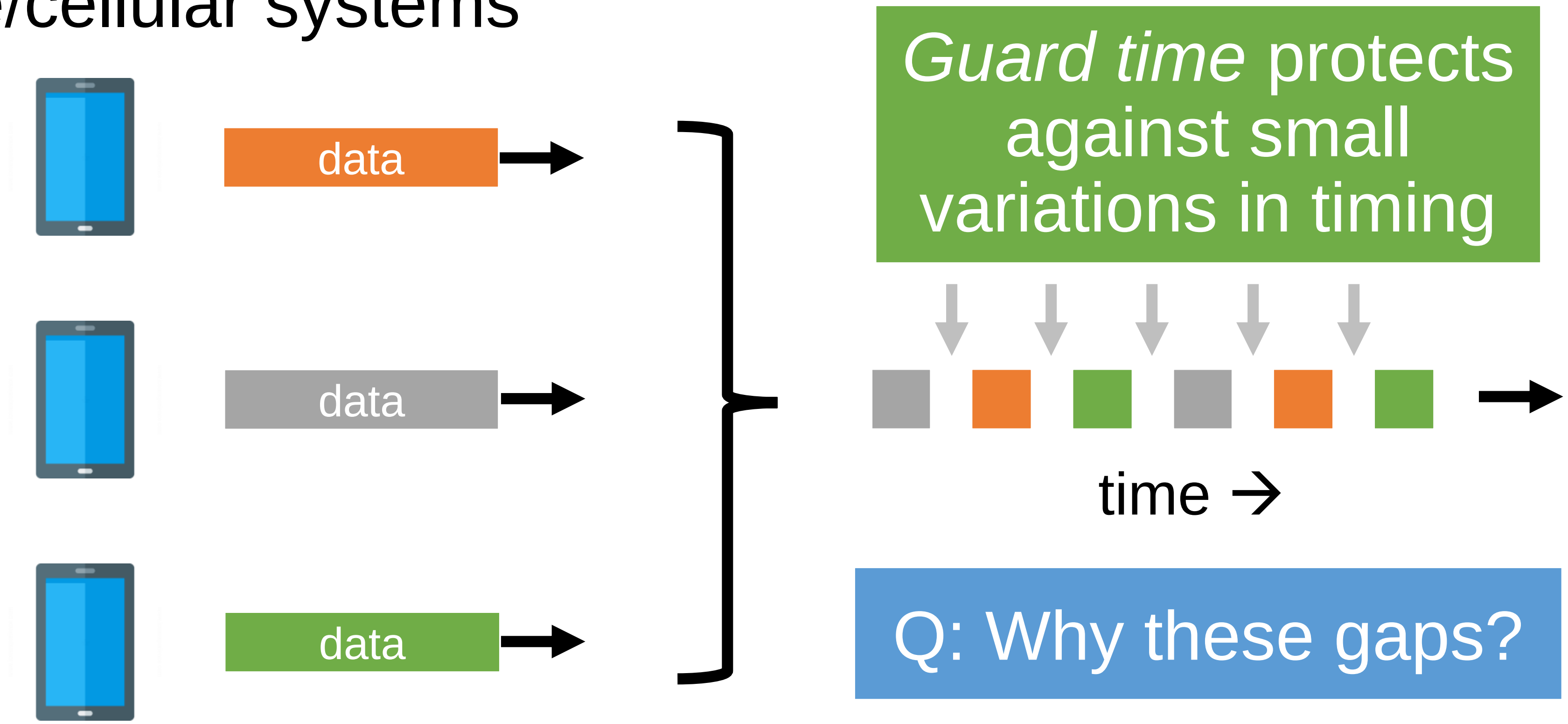



All stations send
at the same time,
at different frequencies.

# Time Division Multiplexing

Q: How does each station know when to send?

Stations take turns on a *fixed schedule*. Widely used in telephone/cellular systems




Q: Why these gaps?

# Code Division Multiplexing

Also called “Code Division Multiple Access” (CDMA)

Stations send at the same time, at the same frequency

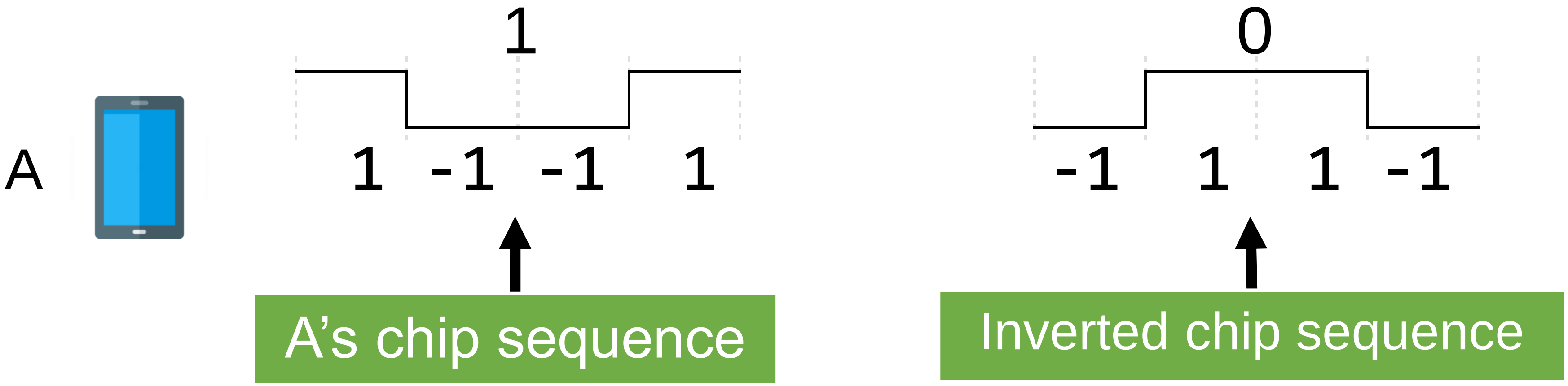
Receiver figures out who sent what

- If a station sends **1**, the receiver computes **1**
- If a station sends **nothing**, receiver computes **0**
- If a station sends **0**, the receiver computes **-1**

# Code Division Multiplexing

Also called “Code Division Multiple Access” (CDMA)

Every bit is split into *chips*. Each station is assigned a *chip sequence*.



# Code Division Multiplexing

Also called “Code Division Multiple Access” (CDMA)

Every bit is split into *chips*. Each station is assigned a *chip sequence*.

| | | 1 | 0 |
|---|---|---|---|
| A |  | 1 -1 -1 1 | -1 1 1 -1 |
| B |  | -1 -1 1 1 | 1 1 -1 -1 |
| C |  | 1 -1 1 -1 | -1 1 -1 1 |

# Code Division Multiplexing

Also called “Code Division Multiple Access” (CDMA)

Every bit is split into *chips*. Each station is assigned a *chip sequence*.

| | | | 1 | | | | 0 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| A |  | 1 | 1 | -1 | -1 | 1 | -1 | 1 | 1 | -1 |
| B |  | - | -1 | -1 | 1 | 1 | 1 | 1 | -1 | -1 |
| C |  | 0 | 1 | -1 | 1 | -1 | -1 | 1 | -1 | 1 |

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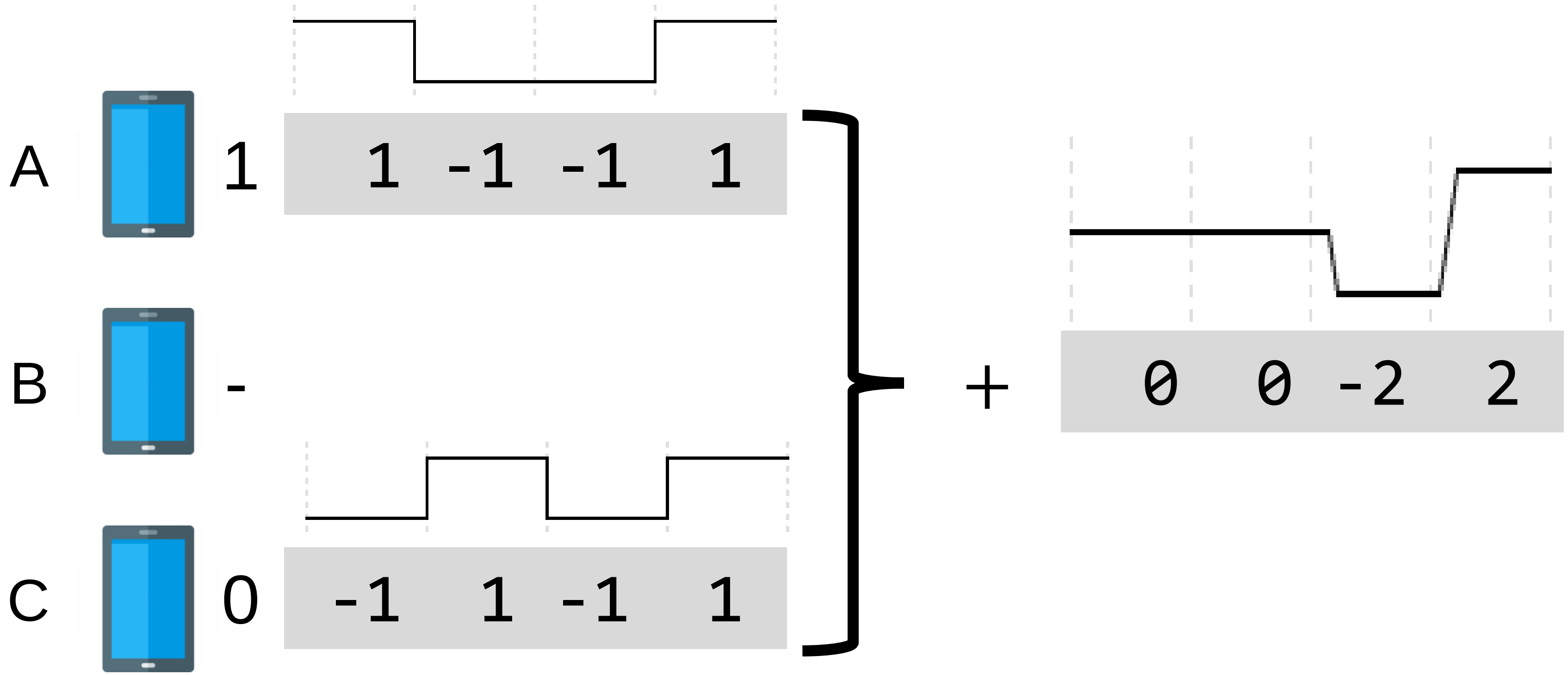

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# Code Division Multiplexing

Also called “Code Division Multiple Access” (CDMA)

Every bit is split into *chips*. Each station is assigned a *chip sequence*.

A 1

B -

C 0

0 0 -2 2

# Code Division Multiplexing

Also called "Code Division Multiple Access" (CDMA)

Every bit is split into *chips*. Each station is assigned a *chip sequence*.

$S =$ `0 0 -2 2`

1

| | | | | | | |
|---|---|---|---|---|---|---|
| A | | 1 | 1 | -1 | -1 | 1 |
| B | | - | -1 | -1 | 1 | 1 |
| C | | 0 | 1 | -1 | 1 | -1 |

$A \cdot S$

$$\frac{0 - 0 + 2 + 2}{4}$$

If a station sends **1**, the receiver computes **1**.

# Code Division Multiplexing

Also called "Code Division Multiple Access" (CDMA)

Every bit is split into *chips*. Each station is assigned a *chip sequence*.

$S =$ 0 0 -2 2

1

A 1 1 -1 -1 1

B - -1 -1 1 1

C 0 1 -1 1 -1

$B \cdot S$

$$\frac{0 - 0 - 2 + 2}{4}$$

If a station sends **nothing**, the receiver computes **0**.

# Code Division Multiplexing

**Also called "Code Division Multiple Access" (CDMA)**

Every bit is split into *chips*. Each station is assigned a *chip sequence*.

$S =$ `0 0 -2 2`

1

A  1   1 -1 -1 1

B  -   -1 -1 1 1

C  **0**   1 -1 1 -1

If a station sends **0**, the receiver computes **-1**.

$C \cdot S$

$$\frac{0 - 0 - 2 - 2}{4}$$

# Code Division Multiplexing

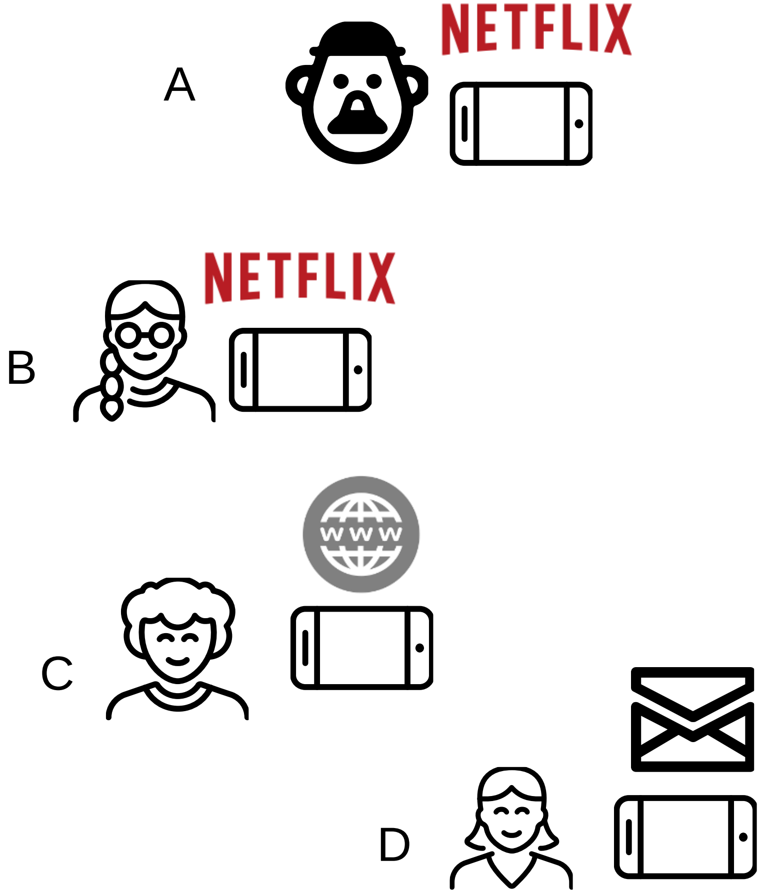
Also called "Code Division Multiple Access" (CDMA)

Requirements:

1. Inner product of sequence with itself is 1 (e.g., $A \cdot A = 1$)
2. All chip sequences are pairwise orthogonal (e.g., $A \cdot B = 0$)

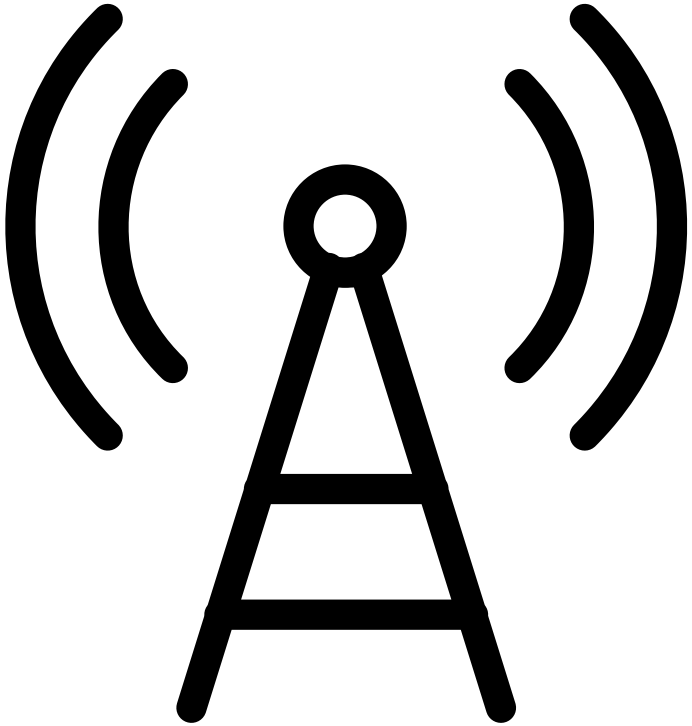
# Q: Differences Between FDM, TDM, CDM? Do they matter?

# How Does Static Multiplexing Affect Apps?

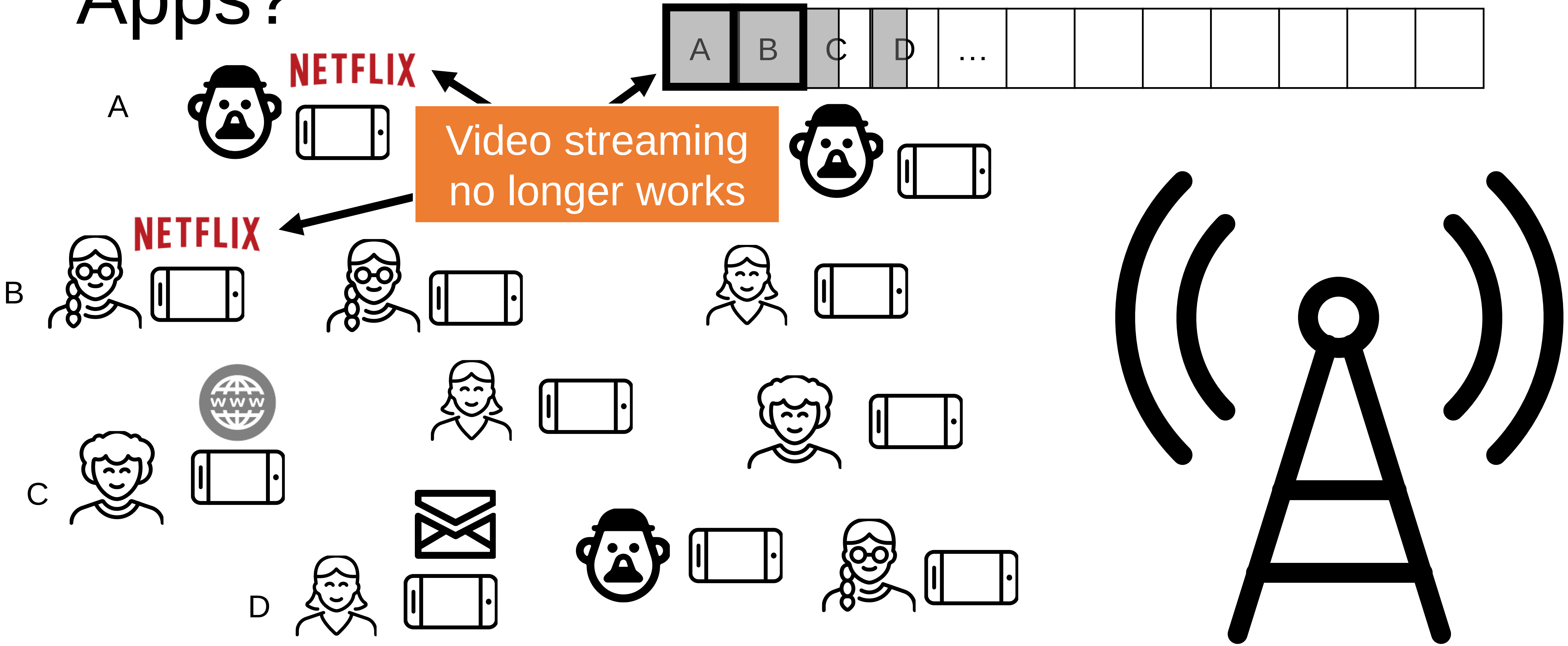



| A, video | B, video | C, www | D, email |
|---|---|---|---|

Inefficient resource usage



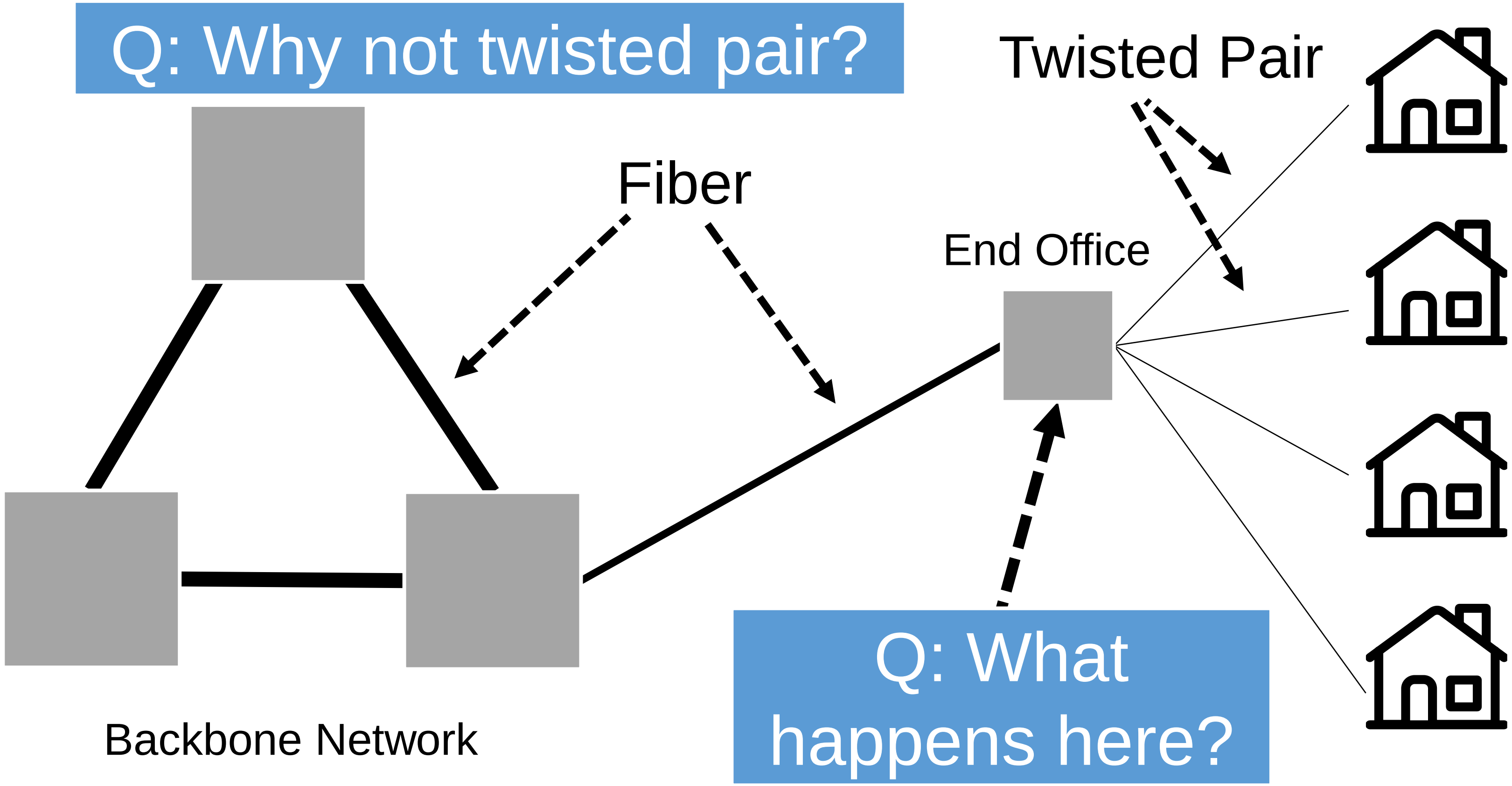
# How Does Static Multiplexing Affect Apps?



# Real-World Examples

# Internet over telephone system

Bandwidth bottleneck at twisted pair

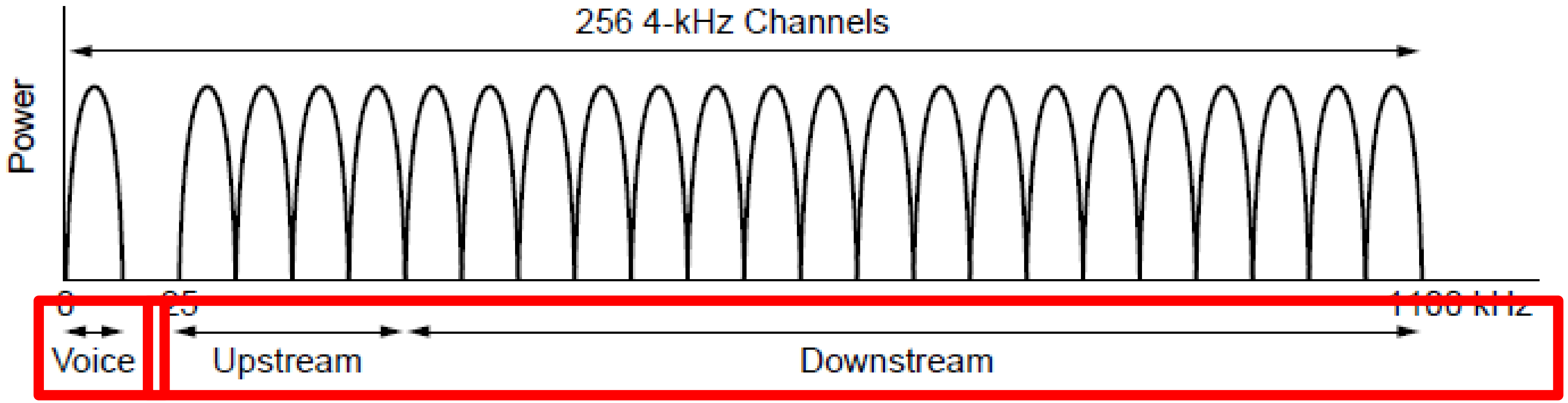


# Local loop
# Digital Subscriber Lines

Networks no longer used primarily for voice

DSL broadband sends data over the local loop to the local office using frequencies that are not used for POTS.

Uses (Orthogonal) Frequency Division Multiplexing




POTS = Plain Old Telephone System

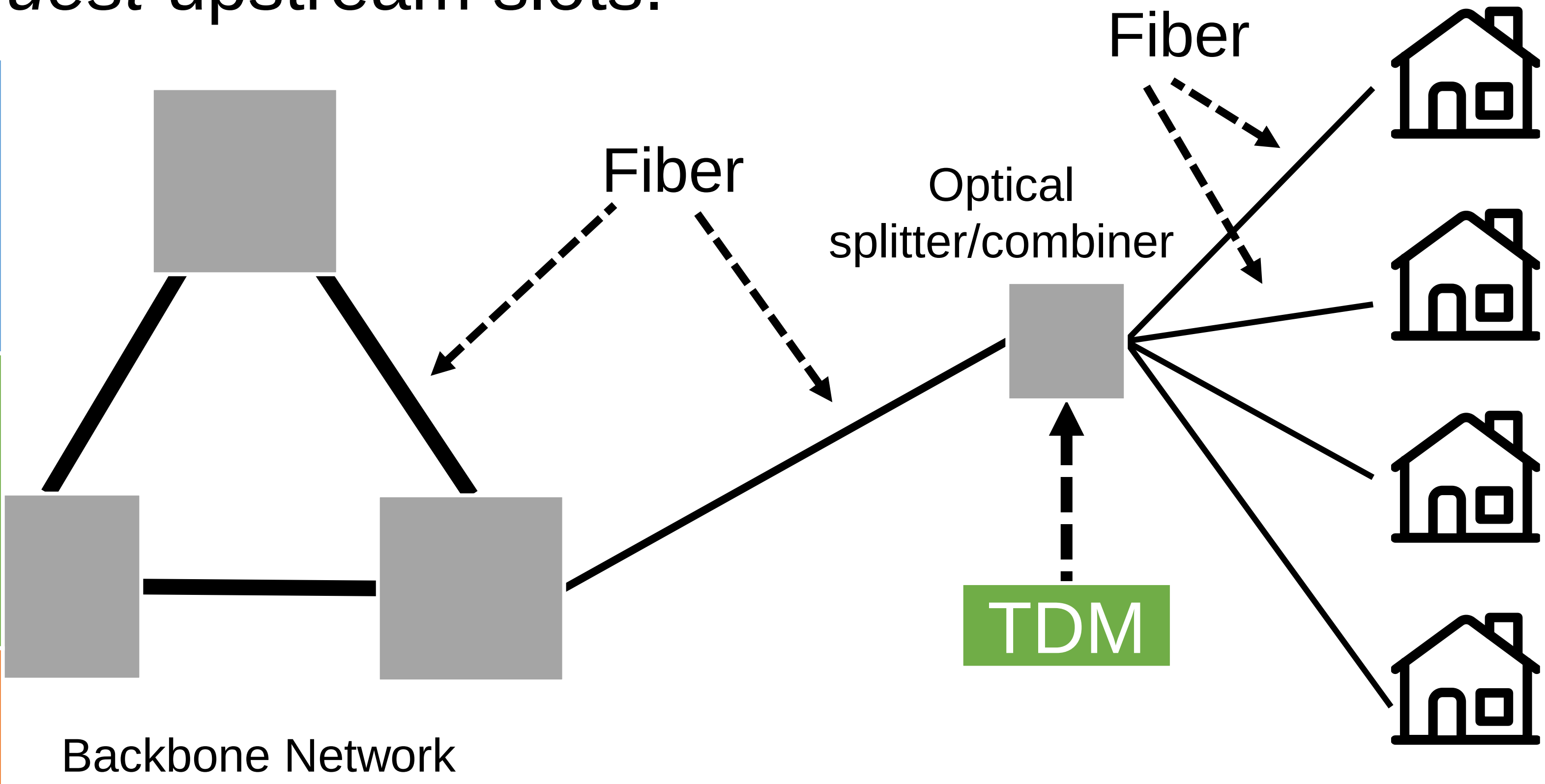
# Fiber to the Home

Uses Time Division Multiplexing for upstream data.
Modems have to *request* upstream slots.

Q: Can you think of a (dis)advantage of this approach?

Requesting slots improves efficiency. Similar to STDM

Shared channel. Home modems need to time carefully when to send



# SONET (Synchronous Optical NETwork)

Worldwide standard for carrying digital signals on optical trunks.

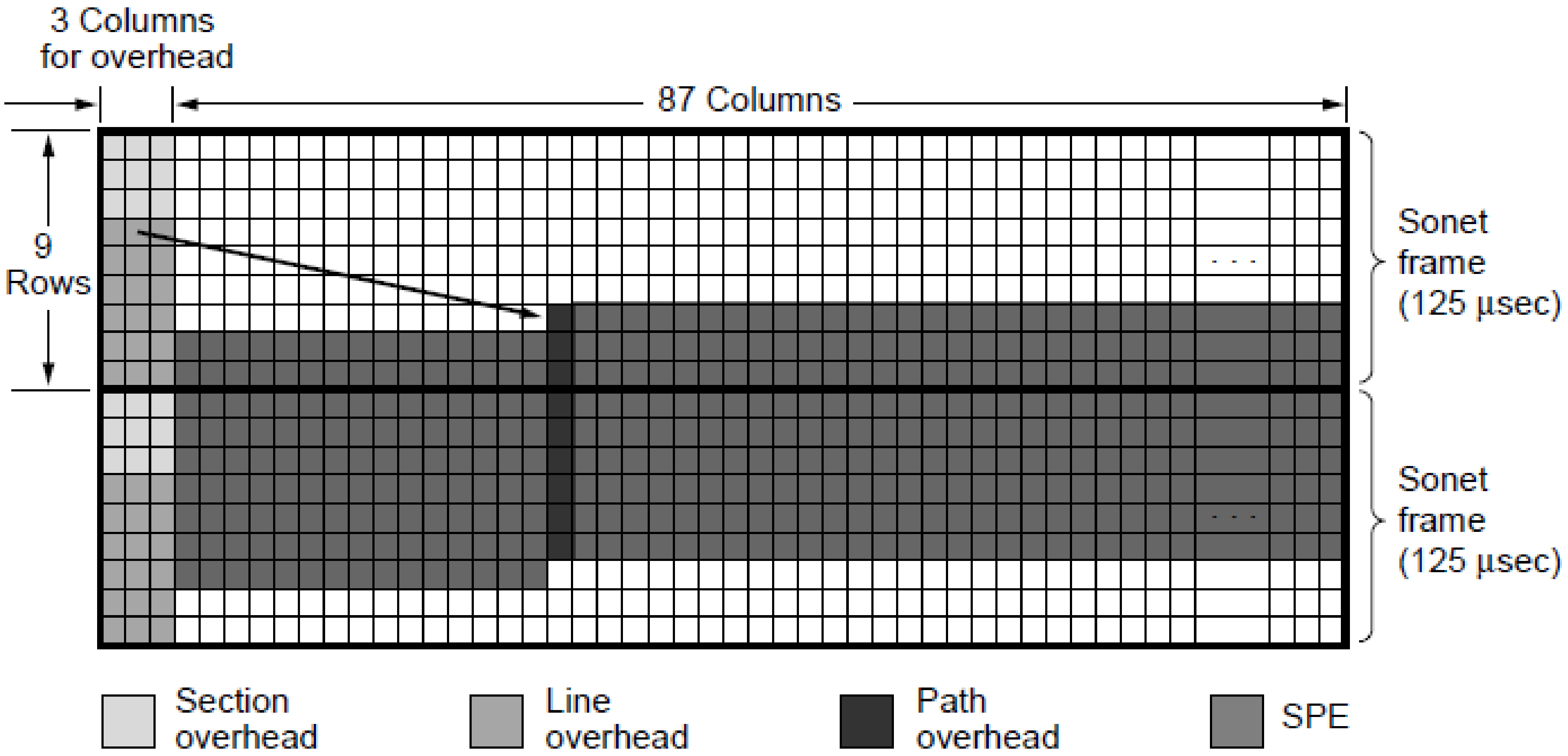
**Uses Time Division Multiplexing**
An STS-1 line sends 810-byte frames every 125µs. (52Mbps)
Time kept by a master clock. (A synchronous system.)

**Uses Frequency Division Multiplexing**
Multiple STS-1 lines are combined on a single fiber to use the available bandwidth.

# SONET

Every square is one byte

Bytes are sent left-to-right, top-to-bottom




Header (overhead) interleaved with data (SPE)

# Physical Layer Summary

1. Different transmission mediums have different properties

2. **Digital Modulation** to translate bits to and from analog signals

3. **Multiplexing** to send multiple signals through one medium