Physical Layer

COMP90007 Internet Technologies

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Semester 2, 2024

What is the Physical Layer ?

- Recall the layer hierarchy from network reference models
  - In OSI model?
  - In TCP/IP model?

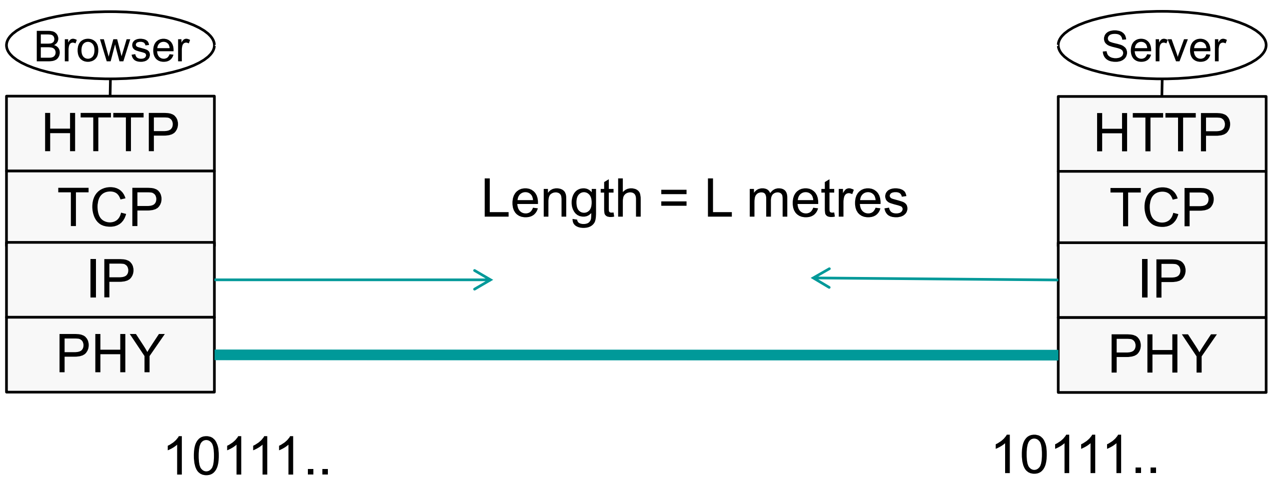
- The physical layer is concerned with the **electrical, timing and mechanical interfaces** of the network
  - Electrical: voltage levels, signal strength …
  - Timing: data rate …
  - Mechanical: material, cable length …

Outline

- Timing aspect
  - Bandwidth and Latency
- Mechanical aspect: transmission media
  - Twisted pair
  - Co-axial
  - Fibre optics
  - Wireless: EM waves, satellites
- Electrical aspect
  - Data communication using signals
  - Digital modulation
- Capacity of a channel
  - Maximum data rate
  - Multiplexing

Link Model

- Abstract the physical channel as a link
- Simplified Link Model: Consider the network as a connected link between computers



Link Model

- **Bandwidth**: the rate of transmission in bits/second.

- **Delay**: the time required for the first bit to travel from computer A to computer B.

Example

- We need about 1 kbit/sec to transmit voice.
- Bandwidth of single mode fibre can reach 1 Tbit/sec.
- How many voice calls can be transmitted through a Fibre Optic Cable?

Message Latency

- Latency is the time delay associated with sending a message over a link
  - **Transmission delay**
    - T-delay = Message length in bits / Rate of transmission
  - **Propagation delay**
    - P-delay= Length of the channel / Speed of signals
    - Speed of signals: e.g. 2/3 of the speed of light (C) for wire
      C = 300000 km/sec
  - **Latency** = T-delay + P-delay

Example-1

- A home computer is connected to an ISP server through 56 K bps modem. Given a frame size of 5600 bits, compute P-Delay and T-Delay for the link. Assume speed of signal = 2/3 C and length of the link is 5 K metres.

Example-2

- Now for the previous question, assume a countrywide optical broadband link of length 1000 kms and bandwidth 100 M bps. Given a frame size of 5600 bits, compute P-Delay and T-Delay for the link. Assume speed of signal is C.

The Growth of Bandwidth

- CPU speeds increase by a factor of ~20 per decade
  - 1981: PC 4.77MHz vs. 2020: PC 4GHz
  - Current CPU speed now approaching physical limits - constrained by physical properties pertaining to granularity of engraving on silicon
- Bandwidth increases by a factor of ~125 per decade
  - 1981: Modem 56kbps
  - Current bandwidth available up to 65 Tbps - vastly exceeding the rate at which we can convert electrical impulses to optical pulses

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Transmission Media

- How many different types of physical media can you think of?
  - Wired: twisted pair, co-axial, fibre optics
  - Wireless: electromagnetic waves and satellites

- Various physical media can be used to transmit data, but the performance is affected by physical properties.

Signal Attenuation

- The loss or reduction in the amplitude (strength) of a signal as it passes through a medium.
- Signal attenuation impacts how far and how much data a medium can carry.

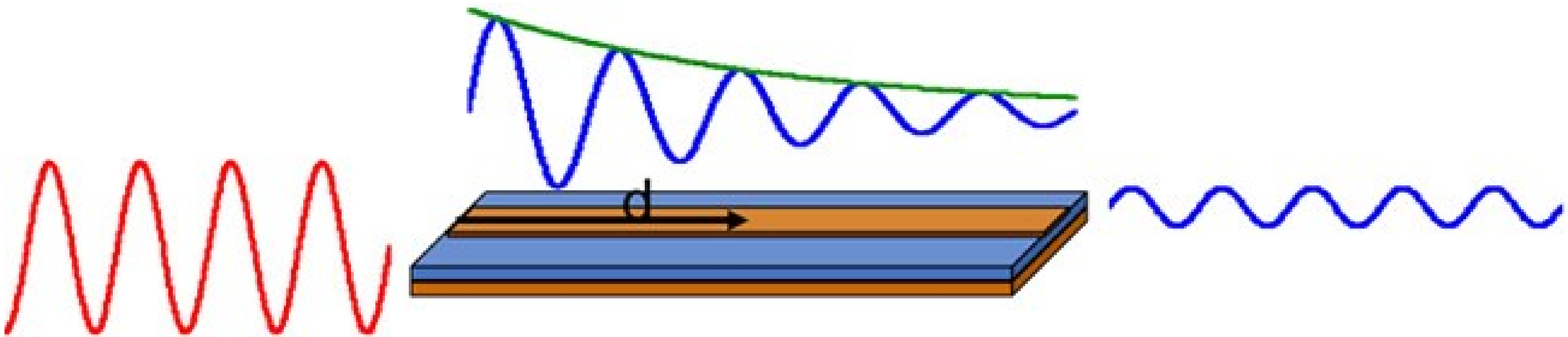
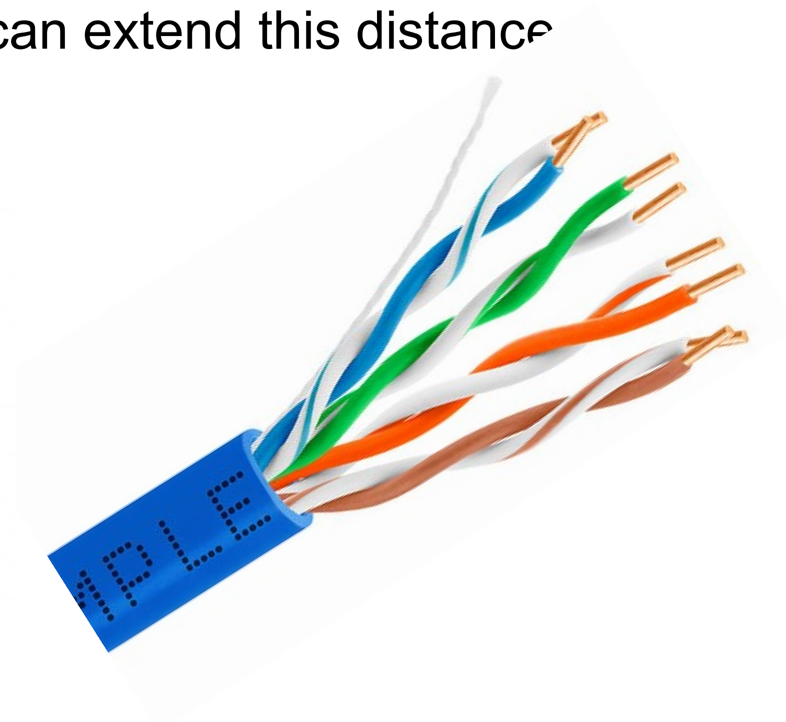


Image source: https://www.signalintegrityjournal.com/articles/1734-how-to-reduce-attenuation-in-a-differential-channel

Twisted Pair

- Two insulated copper wires twisted in helical form
- Twisting reduces interference: canceling out electromagnetic interference from external sources
- Distance up to 5km, repeaters can extend this distance



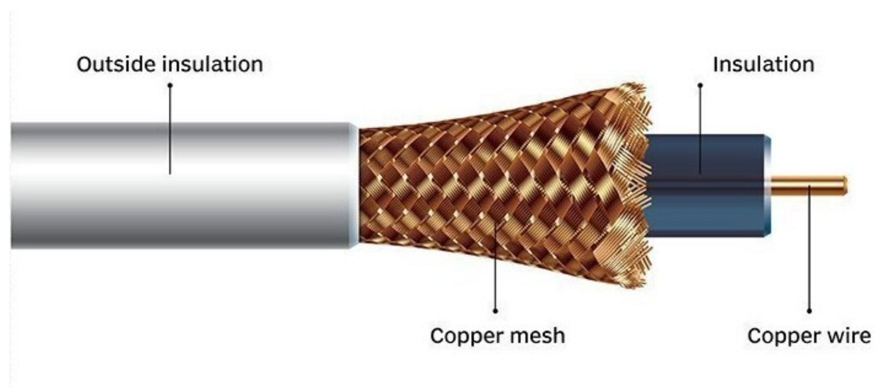
Properties and Types of Twisted Pair

- Bandwidth depends on distance, wire quality and density
- Cat 3 - 2 wires, 4 pairs in sheath, 16MHz
- Cat 5 - 2 wires, 4 pair in sheath, more twists = less interference, higher quality over longer distance, 100 MHz
- Cat 8 – 2000 MHz

Don't worry about this unit for now, just higher value is better!

Coaxial Cable

- Copper core with insulation, mesh, and sheath
- Better shielding than twisted pair = higher speeds over greater distances
- Bandwidth approaches 1GHz
- Still widely used for cable TV/Internet

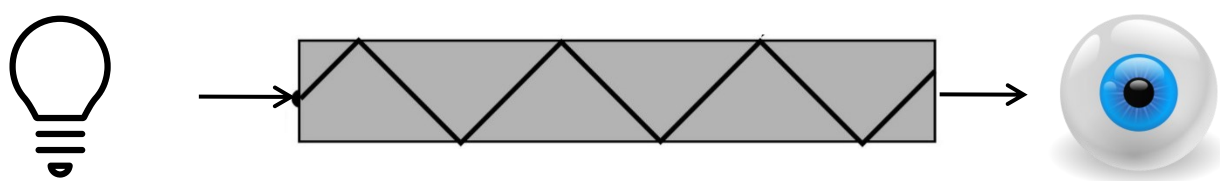


Fibre Optics

- Fibre has enormous bandwidth (THz) and tiny signal loss
- Data transmission over a fibre of glass
- Common for high rates and long distances
  - e.g. backbone links between ISP facilities, Fibre-to-the-Home

Transmission of Light Through Fibre

- 3 components: light source, transmission medium, detector
- Signalling using LED's or semiconductor lasers
- Semantics: light = 1, no light = 0 (basic binary system)
- A detector generates electrical pulse when light hits it
- Refraction between air/silica boundary is compensated for by design - total internal reflection



Light source (LED, laser)

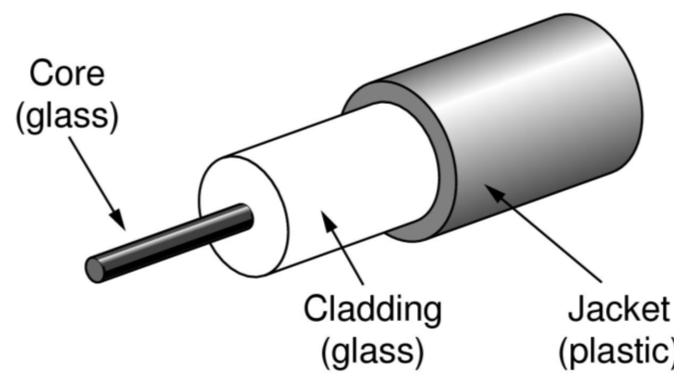
Light trapped by total internal reflection

Photodetector

Fibre Optic Cables

Single-mode
- Narrow core (10um), light can't even bounce around
- Used with lasers for long distances, e.g., 100km

Multi-mode
- 50um core, light can bounce
- Used with LEDs for cheaper, shorter distance links



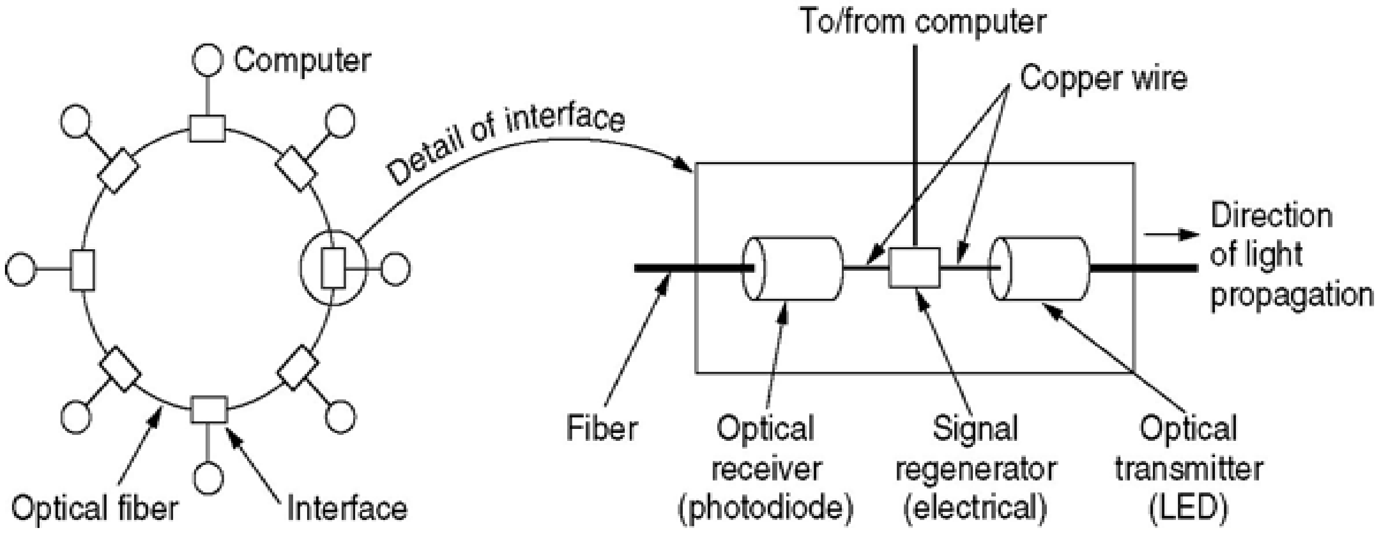
Fibre Optic Connections

- Connectors and Fibre Sockets (10-20% loss)
- Mechanical Splice (10% loss)
- Fusion (<1% loss)

Example: mechanical splice

Fibre Optic Networks

- Fibre optic cable is a scalable network media - LAN, WAN, long distances
- Fibre optic cable networks can be organised either as a ring or as a bus network (series of point-to-point connections)



Fibre Optic Ring

Comparison: Wires and Fibre

Comparison of the properties of wires (twisted pairs and co-ax cable) and fibre:

Property	**Wires**	**Fibre**
Distance	Short (100s of m)	Long (tens of km)
Bandwidth	Moderate	Very High
Security	Easy to tap	Hard to tap
Cost	Inexpensive	More Expensive
Convenience	Easy to use	Harder to use

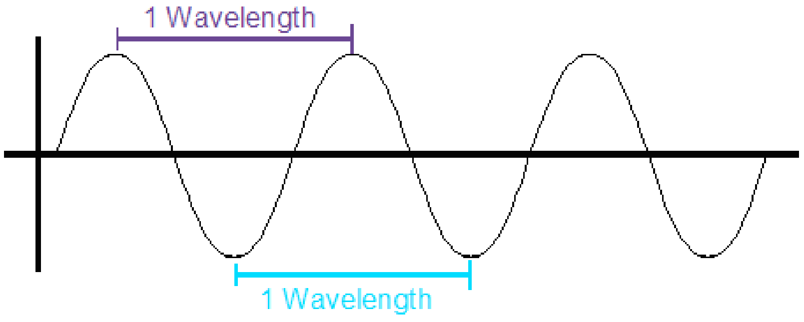
Wireless Transmission

- Mobile users require a **mobility** enabled network - contrast with the wired networks

- Wireless data transmission networks have a common basis - **electromagnetic wave propagation**
  - Wireless signals are broadcasted over a region
  - Potential signal collisions – needs regulations

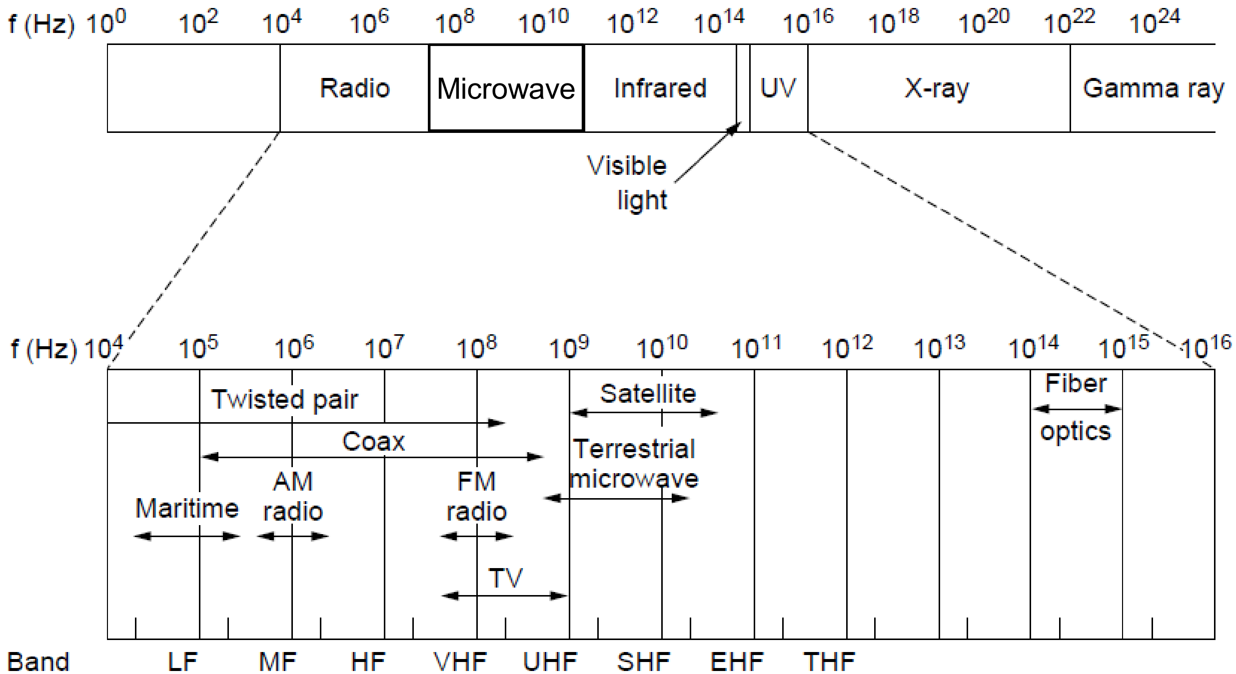
Basics of Electromagnetic Waves

- **Frequency:** Number of oscillations per second of a wave, measured in Hertz (Hz).
- **Wavelength:** Distance between two consecutive minima or maxima.
- **Speed:** All EM waves travel at the same speed - the speed of light ~ 3×10^8 m/s
- **Fundamental relationship**:
  - Wavelength x Frequency = Speed of Light
  - Units: (m) x (1/s) = (m/s)



Electromagnetic Spectrum

- Different bands have different uses
  - Radio: wide-area broadcast
  - Microwave: LANs and 3G/4G
  - Infrared/Light: line-of-sight



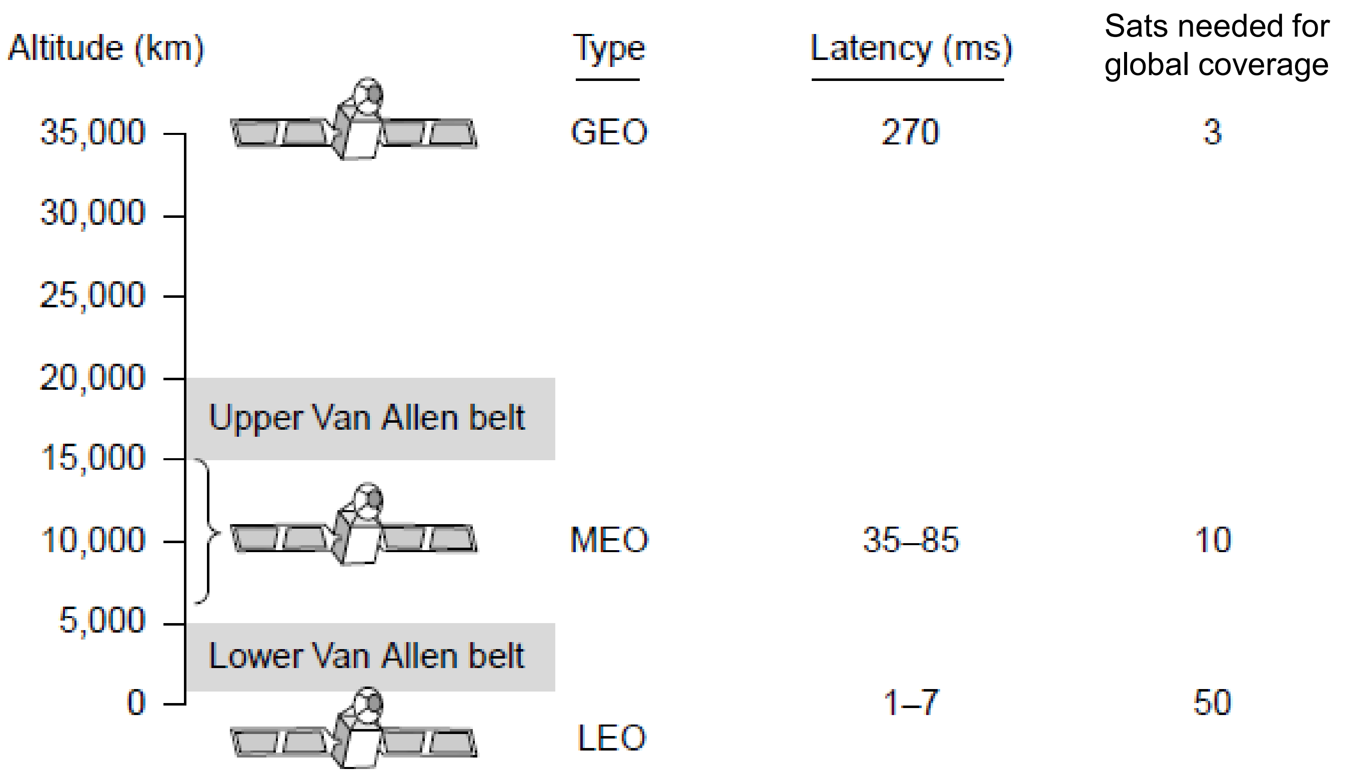
Communication Satellites

Satellites are effective for broadcast distribution and anywhere anytime communications

- Types of satellites:
  - Geostationary (GEO) Satellites
  - Medium-Earth Orbit (MEO) Satellites
  - Low-Earth Orbit (LEO) Satellites

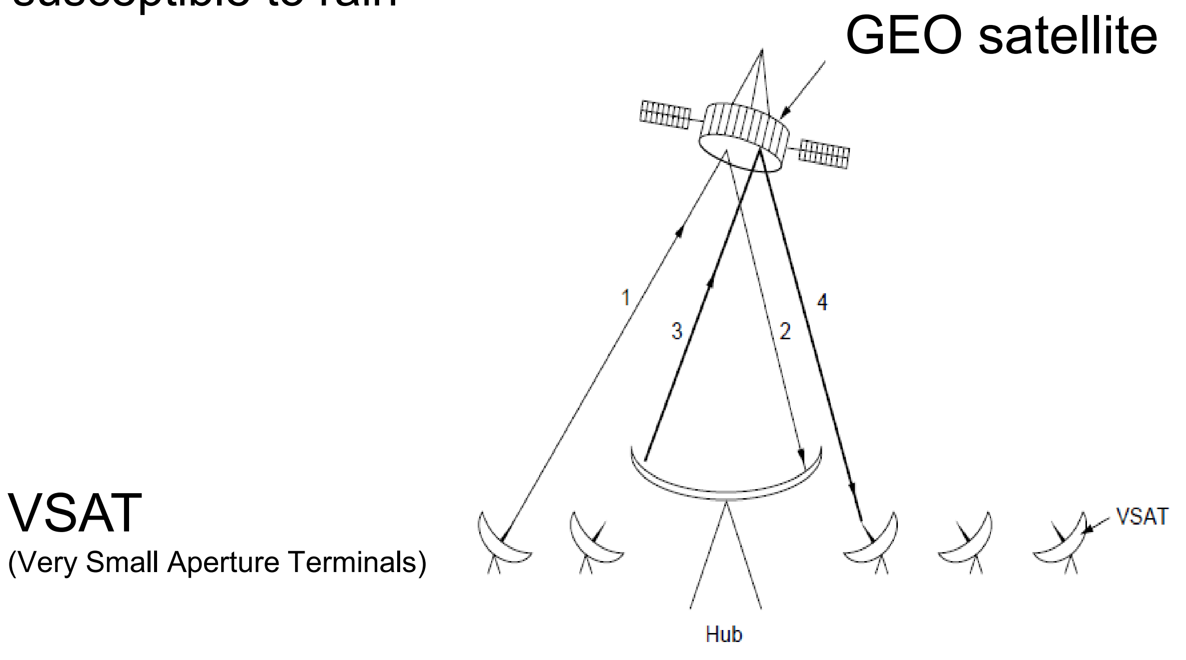
Types of Satellites

Satellites and their properties vary by altitude



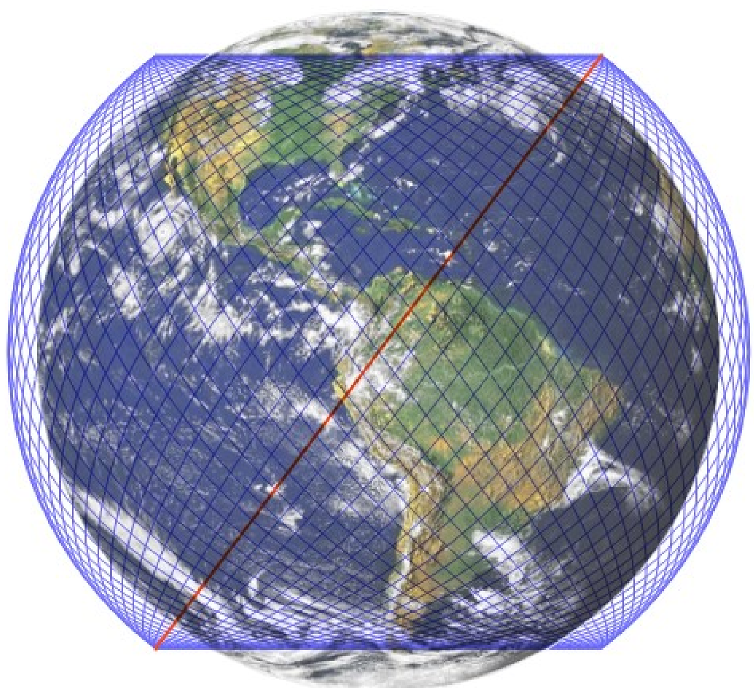
Geostationary Satellites

- GEO satellites orbit 35,800 km above a fixed location
  - VSAT (computers) can communicate with the help of a hub
  - Different bands (L, S, C, Ku, Ka) in GHz are in use but may be crowded or susceptible to rain



Low-Earth Orbit Satellites

- Systems such as Starlink constellation use many low-latency satellites for coverage and communications via them



First orbital shell: 72 orbits x 22 each = 1584 satellites, at 550 km altitude

3 more shells in phase 1!

Image source: https://en.wikipedia.org/wiki/Starlink

Satellite vs. Fibre

- Satellite:
  - \+ Can rapidly set up anywhere/anytime communications (after satellites have been launched)
  - \+ Can broadcast to large regions
  - \- Limited bandwidth and interference to manage
- Fibre:
  - \+ Enormous bandwidth over long distances
  - \- Installation can be difficult in rural areas

Wireless vs. Wired

Wireless:

- \+ Naturally supports mobility
- \+ Naturally supports broadcast
- \+ Easy and inexpensive to deploy
- \- Transmissions interfere and must be managed
- \- Signal strengths and data rates vary greatly

Wired:

- \+ Easy to maintain a fixed data rate
- \+ Support point-to-point transmission
- \- Can be expensive to deploy, esp. over distances
- \- Doesn’t readily support mobility or broadcast

Outline

- Timing aspect
- Mechanical aspect: transmission media
- Electrical aspect
- Capacity of a channel
  - Maximum data rate
  - Multiplexing

Data Communication using Signals (1)

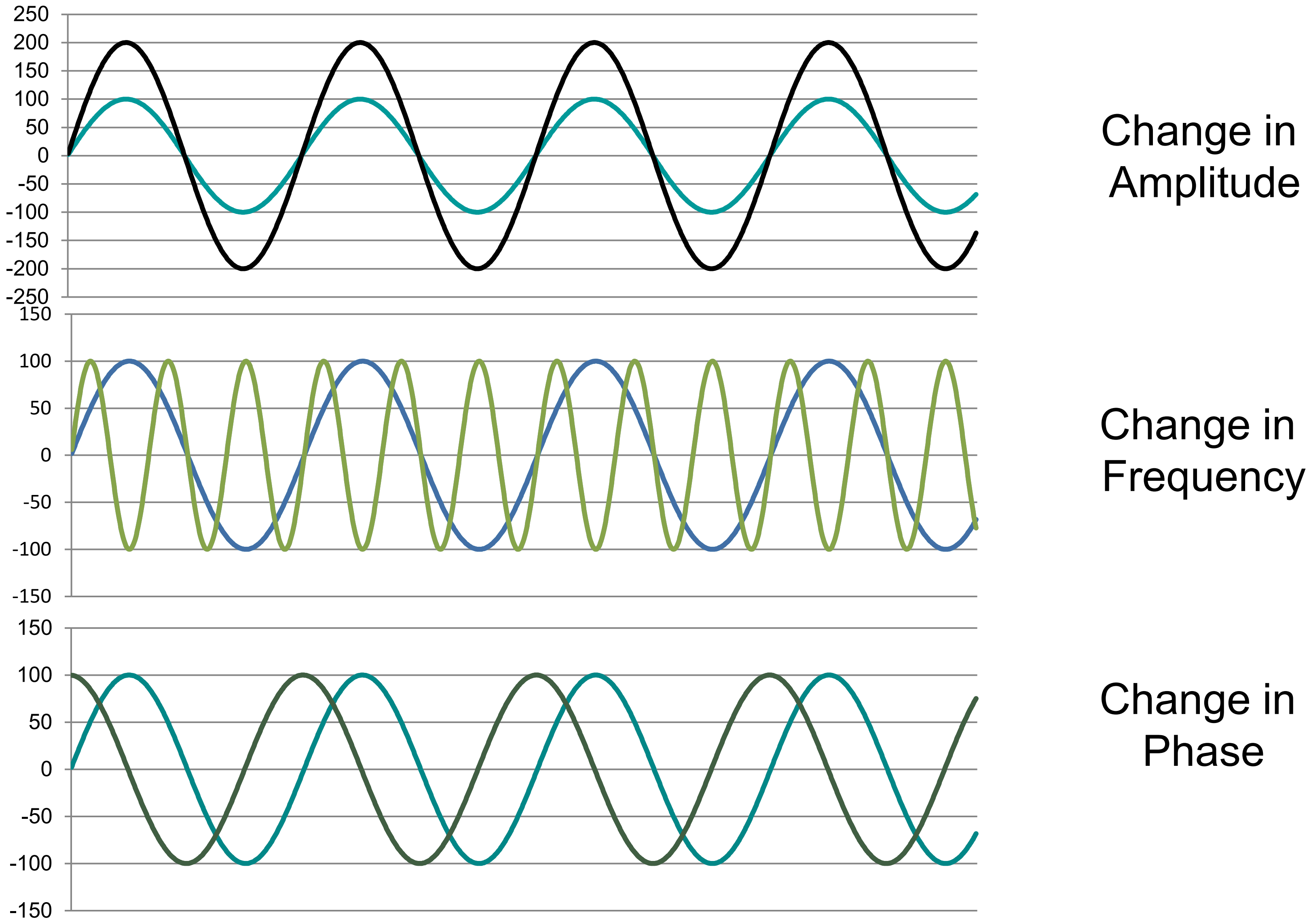
- Information is transmitted by varying a physical property e.g. voltage, current

- For a sinewave :

$$f(t) = c * \sin(a * t + b)$$

c - amplitude, $a/(2\pi)$ - frequency, b - phase change the behaviour of the function

Data Communication using Signals (2)



Digital Modulation

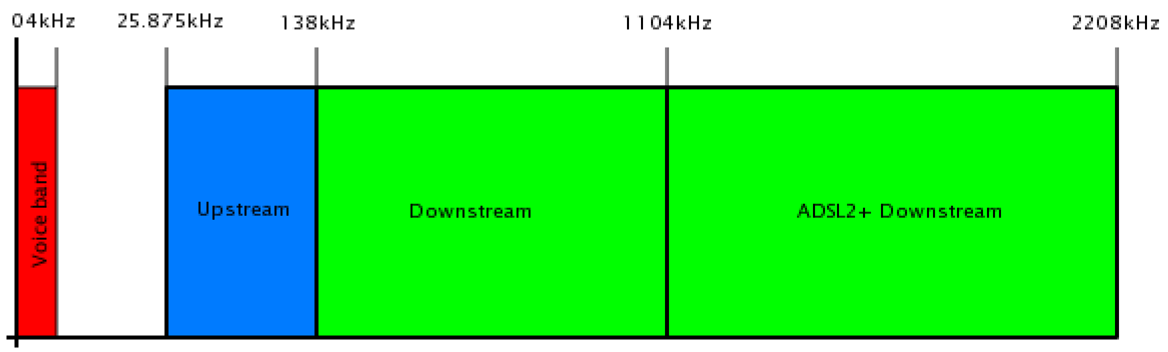
Modulation schemes send bits as signals

Baseband Transmission

- Signals that run from 0 up to a maximum frequency
- E.g., Telephone system: 0 ~ 4kHz

Passband Transmission

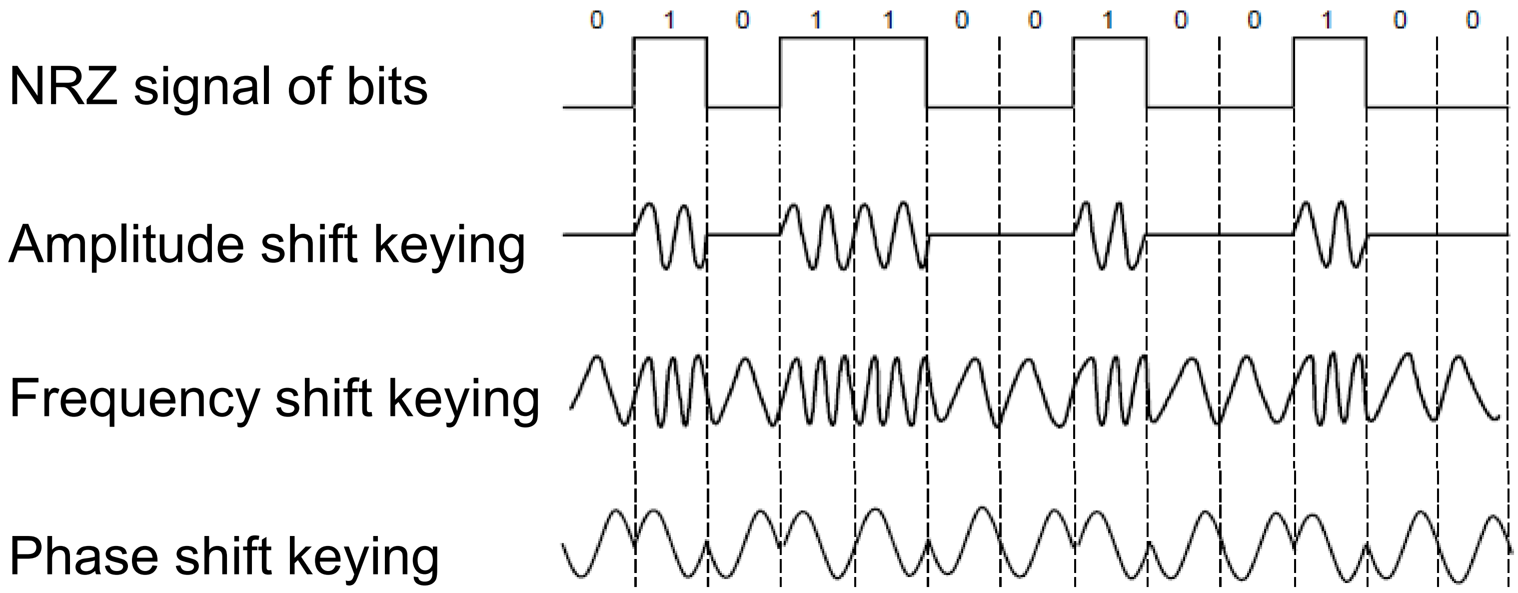
- Signals that are shifted to occupy a higher range of frequencies



Example: ADSL

Modulation Types

- Modulate the amplitude, frequency/phase of a carrier signal to send bits in a passband



Data Communication using Signals (3)

- How would the receiver handle the signal to understand its meaning?

- How many different types of signals are there in each example?

Symbol Rate

- One symbol (signal element) can represent multiple bits (data elements)
- Symbol Rate (Baud Rate): number of signal changes per second
- Data Rate: number of bits per second

$$\text{Data Rate} = \log_2 V * \text{Symbol Rate}$$

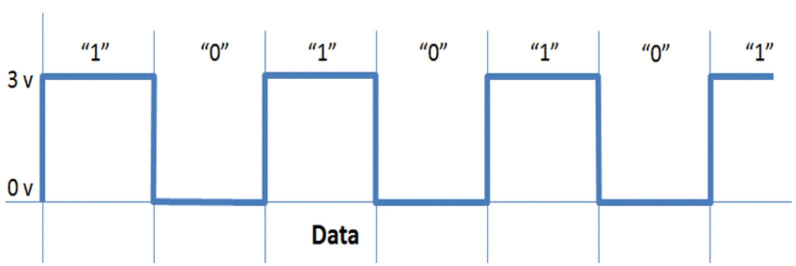


Figure 1. Data bits where logical "0" and "1" are represented by 0 volts and 3 volts respectively

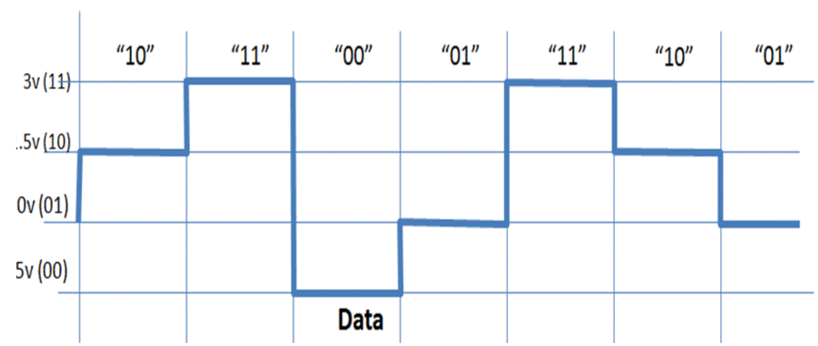


Figure 2. Four signaling levels per clock cycle can represent two data bits.

Image source: http://mason.gmu.edu/~rmorika2/Baud_Versus_Bits_per_second.htm

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How much can we put on a Channel?

- Harry Nyquist
- Early theoretical work on determining fundamental limits for the bandwidth required for communication

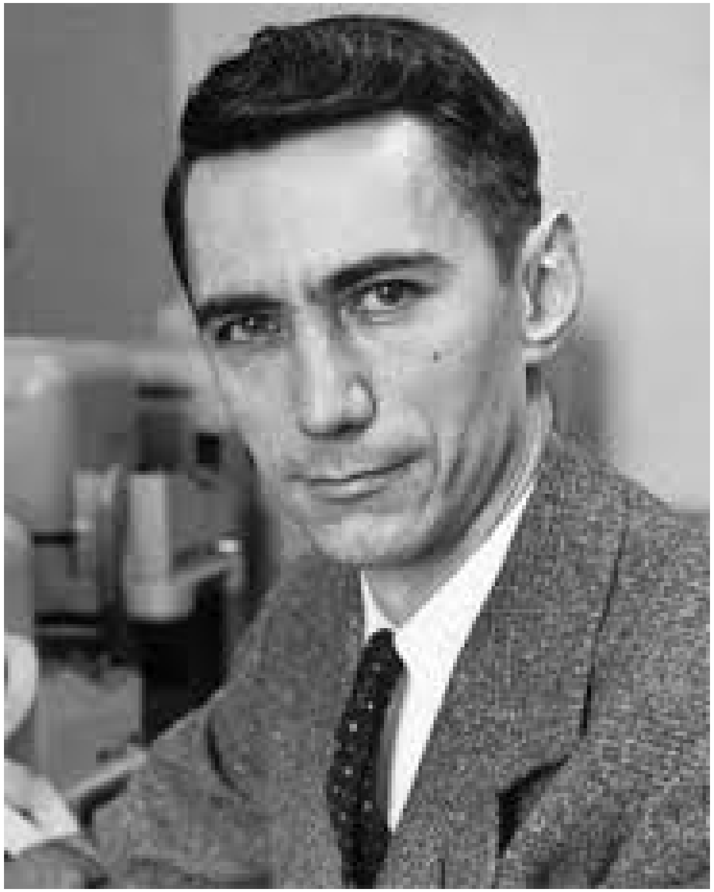
Maximum Data Rate of a Channel

- Nyquist's theorem relates the data rate of a channel **without noise** to the bandwidth (B) and number of signal levels (V) :

$$\boxed{\text{Max. data rate} = 2B \log_2 V \text{ bits/sec}}$$

- Increase the bandwidth B can increase the data rate.
- If signal has V levels, each symbol can represent $\log_2 V$ bits.

What if there is noise?



- Claude Shannon - Father of Information Theory.
- Contributed to information theory and cryptography.

Maximum Data Rate of a Channel

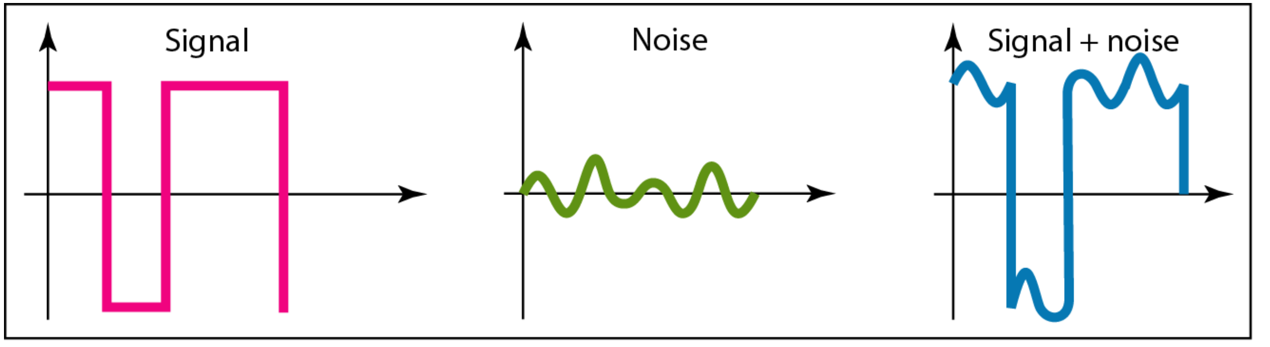
- Shannon's theorem relates the data rate to the bandwidth (B) and signal strength (S) relative to the **noise** (N):

$$\boxed{\text{Max. data rate} = B \log_2(1 + S/N) \text{ bits/sec}}$$

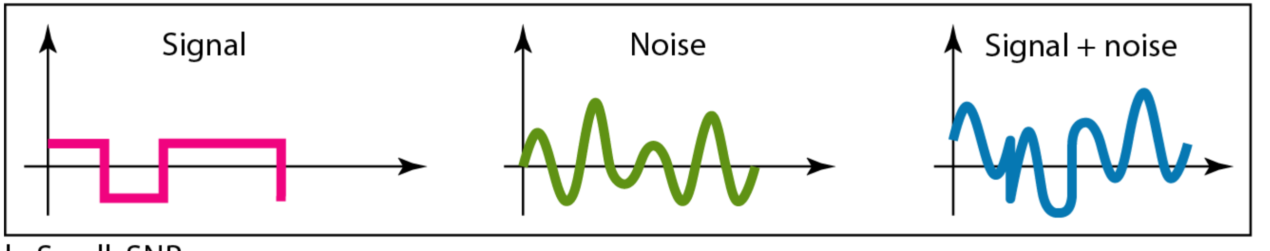
How fast signal can change

How many levels can be seen

Maximum Data Rate of a Channel



a. Large SNR



b. Small SNR

Example 1: Lets Consider Nyquist first

If a binary signal is sent over a 3-kHz channel, what is the maximum data rate?

Example 2

Given the signal-to-noise ratio (SNR) of 20 dB, and the bandwidth of 4kHz (using phone line), what is the maximum data rate according to Shannon's theorem?

Example 3

If a binary signal is sent over a 3-kHz channel whose signal-to-noise ratio is 20 dB, what is the maximum achievable data rate?

Share a Channel

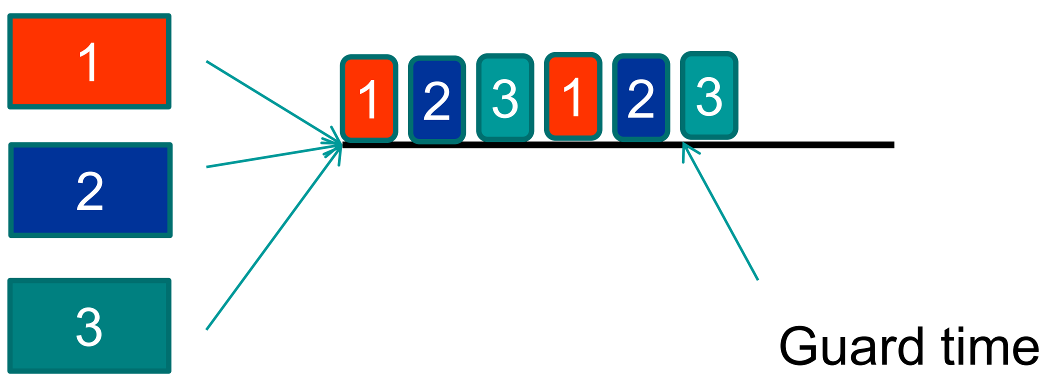
- Full-duplex link
  - Used for transmission in both directions at once
  - e.g., use different twisted pairs for each direction
- Half-duplex link
  - Both directions, but not at the same time
  - e.g., senders take turns on a wireless channel
- Simplex link
  - Only one fixed direction at all times. Not common

Share a Channel: Multiplexing

- When multiple users want to access the medium
  - Time Division Multiplexing
  - Frequency Division Multiplexing
  - Statistical Multiplexing
  - Code Division Multiple Access

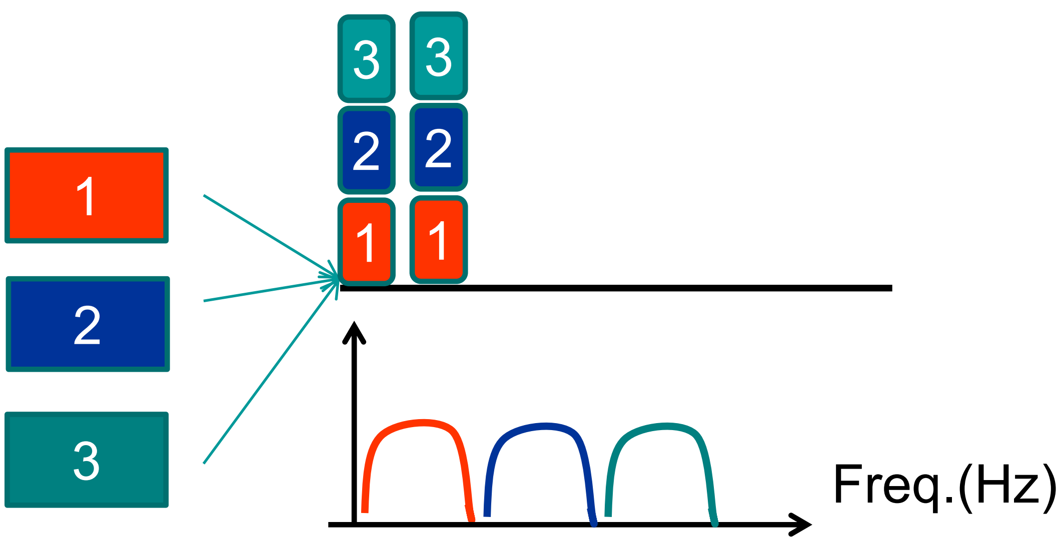
Time Division Multiplexing

- Users can send according to a fixed schedule
- Slotted access to the full speed of the channel



Frequency Division Multiplexing

- Users can only use specific frequencies to send their data
- Continuous access with lower speed



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