MODULE III

Foundations Of Data Communications And The Physical Layer

Motivation And Model

What Is Data Communications?

- Broad field of study
- Usually associated with the Physical Layer
- Touches on
  - Physics
  - Mathematics
  - Engineering
- Includes
  - Transmission of signals
  - Encoding data
  - Modulation and multiplexing

Motivation

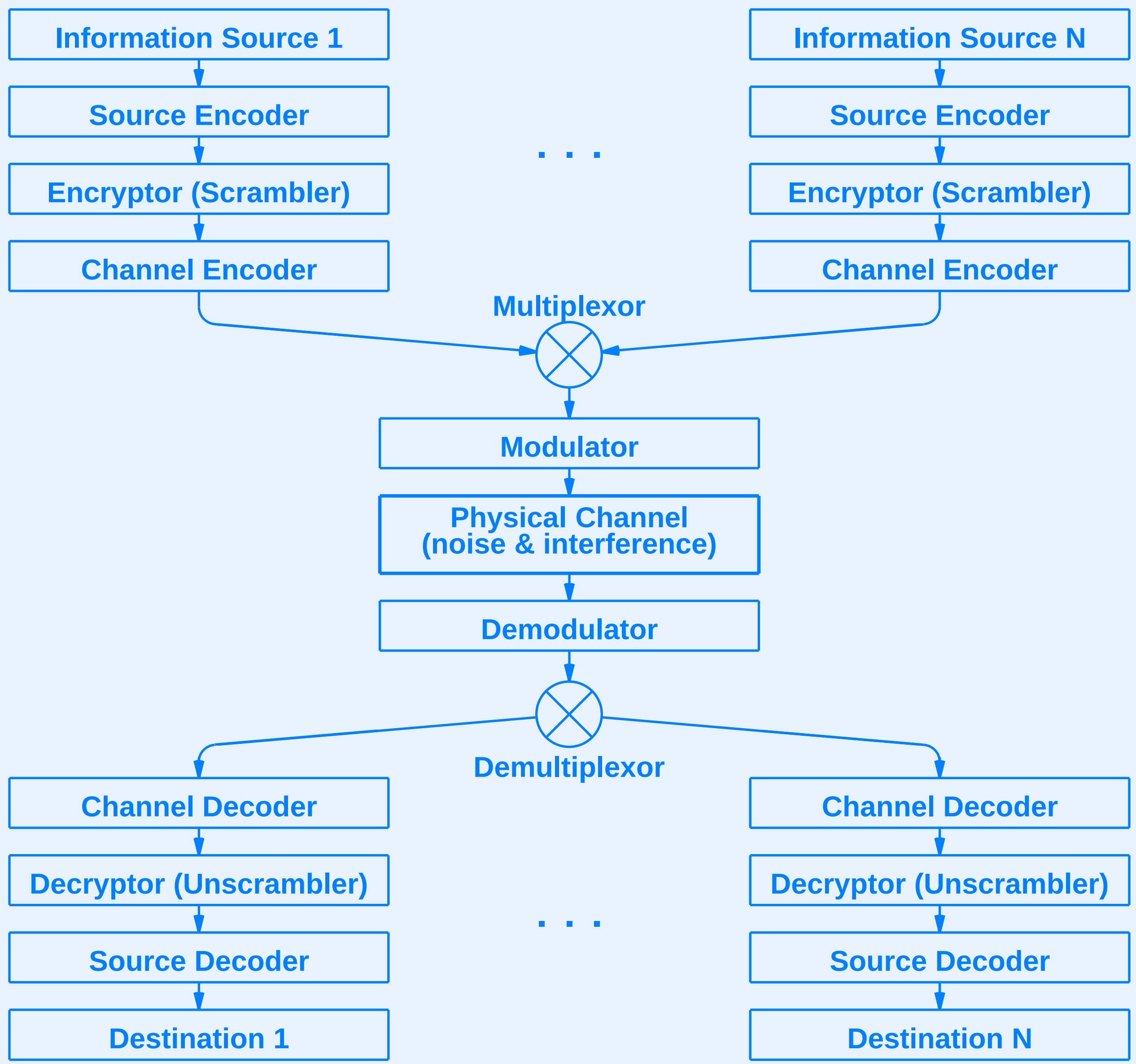
- Find ways to transmit analog and digital information
  - Using natural phenomena (e.g., electromagnetic radiation)
  - Allow multiple senders to share a transmission medium
- Data communications provides
  - A conceptual framework
  - Mathematical basis

Key Concept

Although we tend to think of analog and digital communication separately, ultimately, all communication uses the same physical phenomena, usually electromagnetic energy.

- Differences lie in the way the physical phenomena are used
  - Analog: use all values in a continuous range
  - Digital: restrict use to a fixed set of values, usually two
- Data communications covers both analog and digital

Conceptual Framework For Data Communications

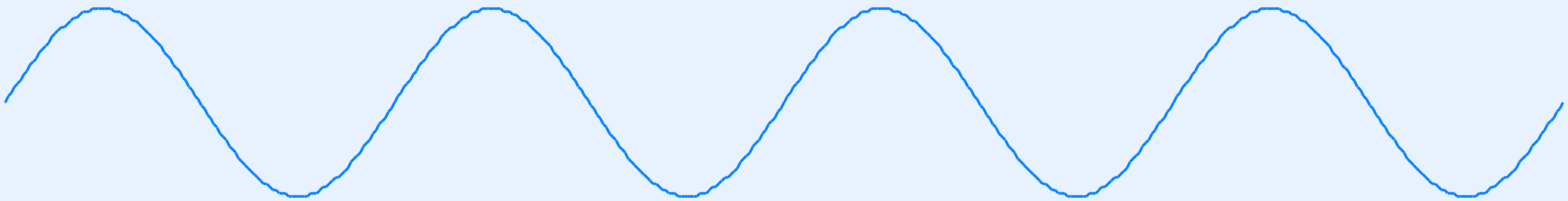


Information Sources
And Signals

Sources Of Information

- An input signal can arise from
  - Transducer such as a microphone
  - Receiver such as an Ethernet interface
- We use the term *signal processing* to describe the recognition and transformation of signals

Sine Waves



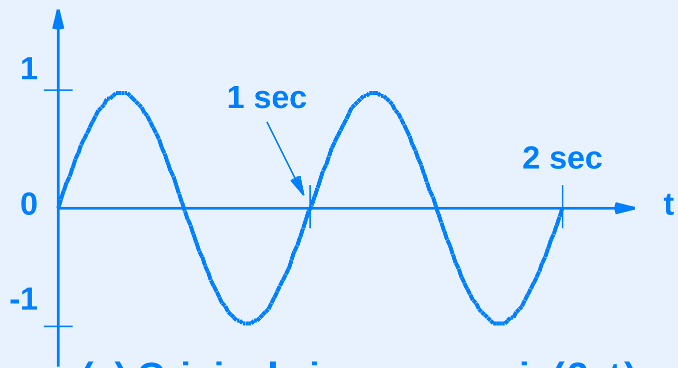
- Fundamental because sine waves characterize many natural phenomena
- Examples
  - Audible tones
  - Radio waves
  - Light energy

Fourier Analysis

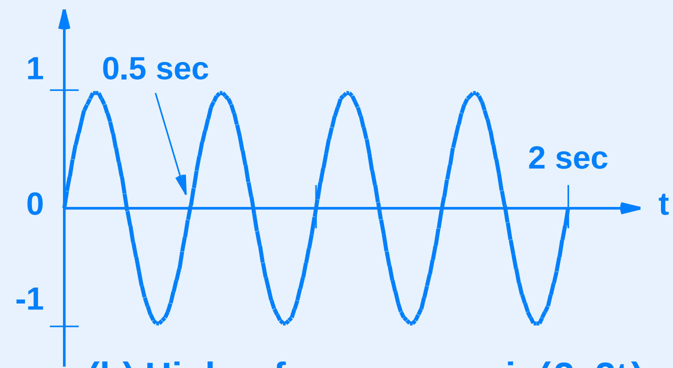
- Multiple sine waves can be added together
  - Result is known as a *composite* wave
  - Corresponds to combining multiple signals (e.g., playing two musical tones at the same time)
- Mathematician named Fourier discovered how to decompose an arbitrary composite wave into individual sine waves
- Fourier analysis provides the mathematical basis for *signal processing*
- Bad news: according to Fourier, a digital wave decomposes into an infinite set of sine waves

Sine Wave Characteristics

- Three important characteristics are used in networks: frequency, amplitude, and phase



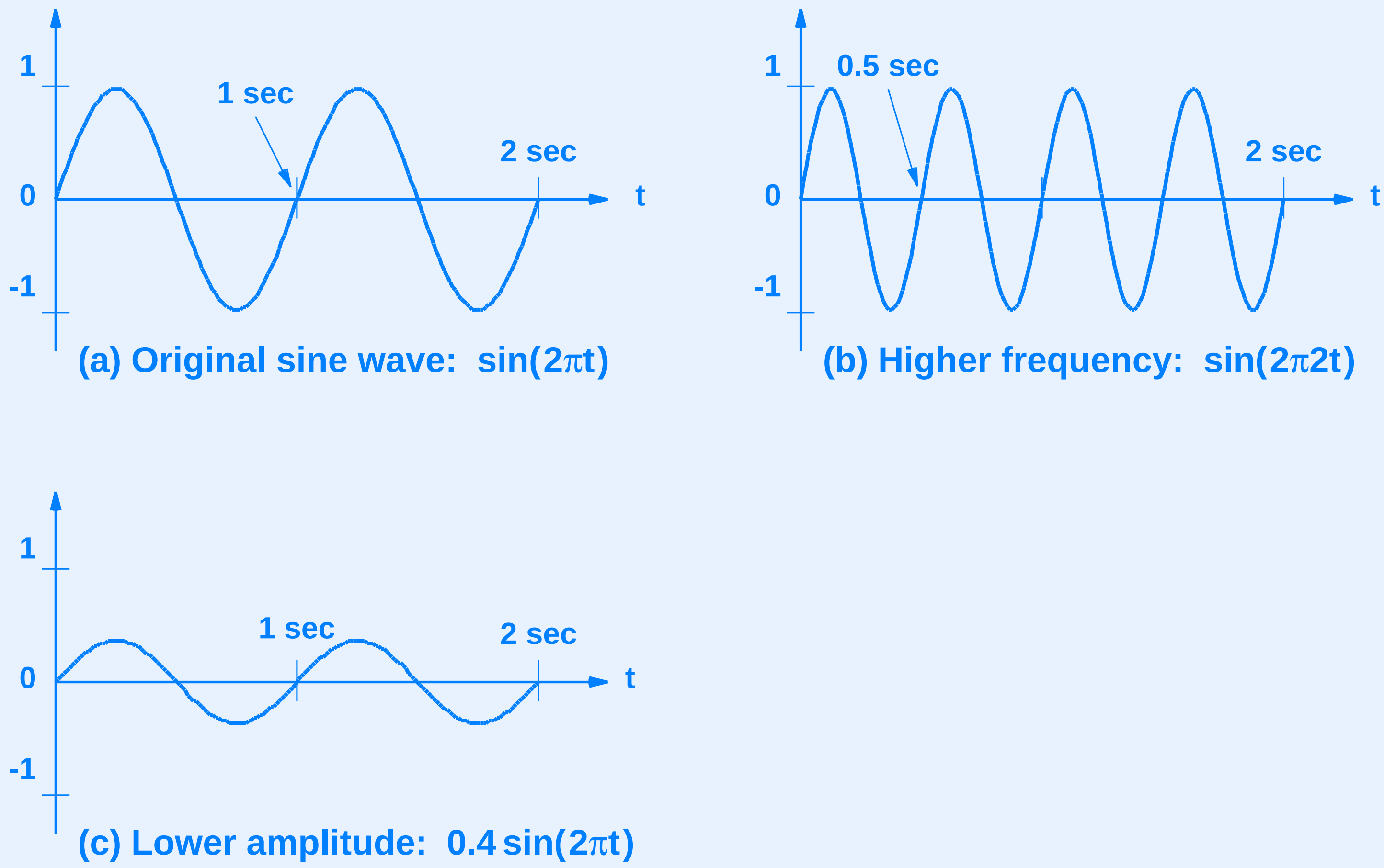
(a) Original sine wave: sin(2πt)



(b) Higher frequency: sin(2π2t)

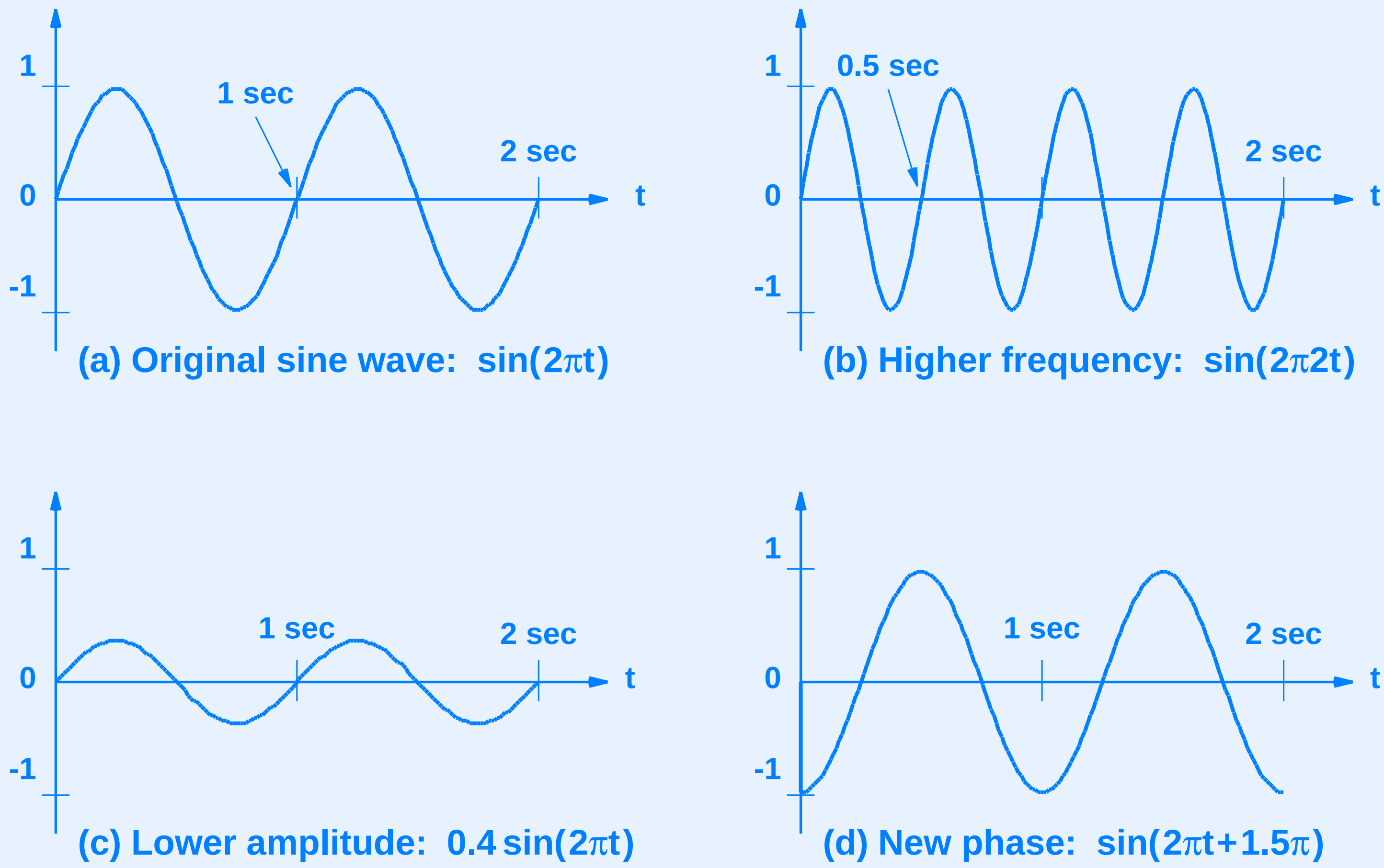
Sine Wave Characteristics

- Three important characteristics are used in networks: frequency, amplitude, and phase



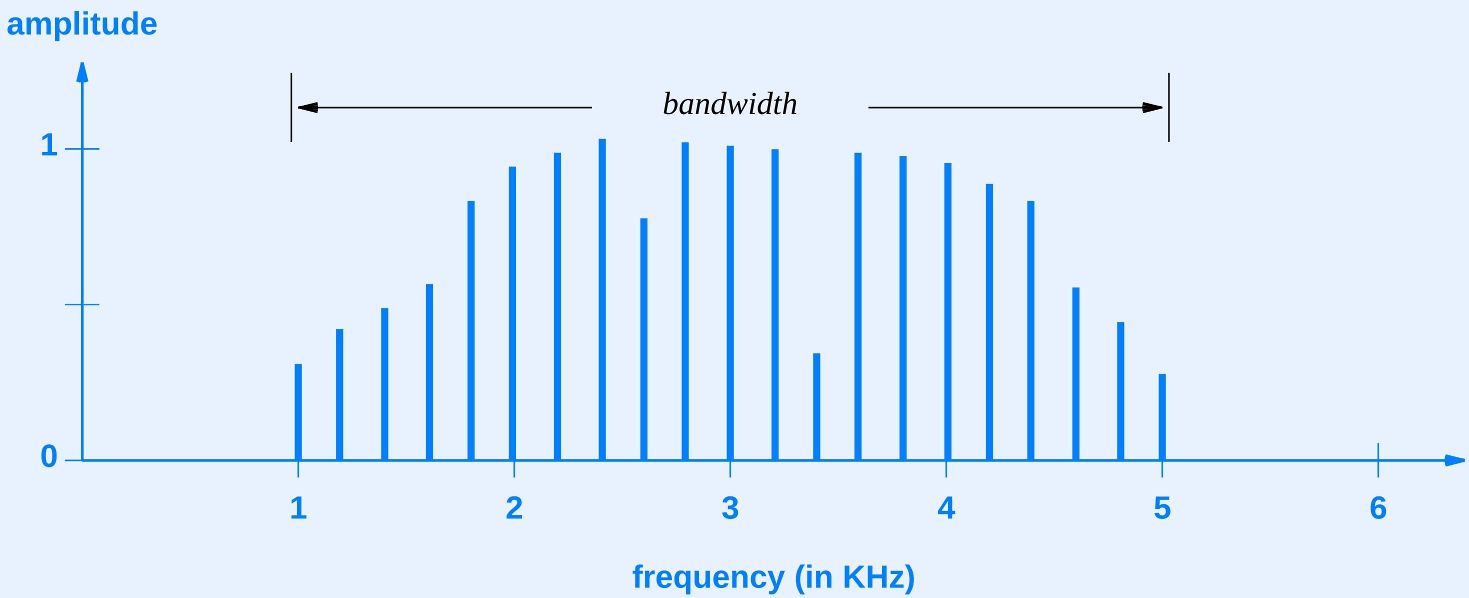
Sine Wave Characteristics

- Three important characteristics are used in networks: frequency, amplitude, and phase



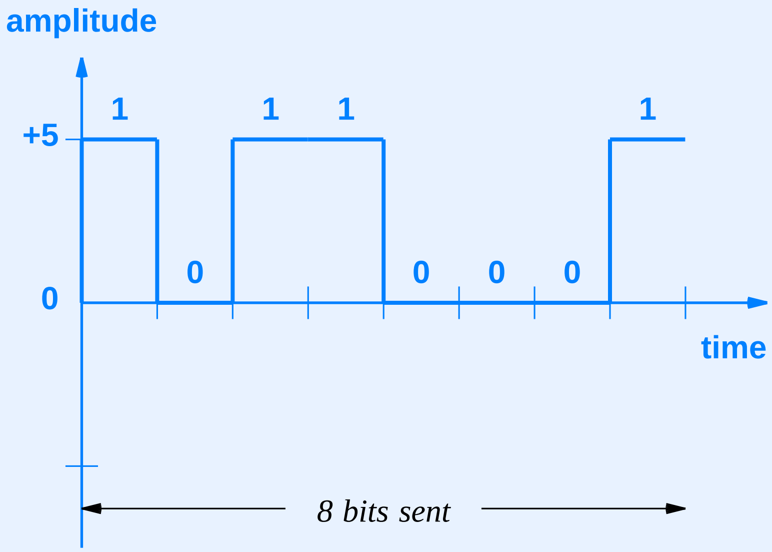
Definition Of Analog Bandwidth

- Decompose a signal into a set of sine waves and take the difference between the highest and lowest frequency
- Easy to compute from a *frequency domain plot*
- Example signal with bandwidth of 4 Kilohertz (KHz):

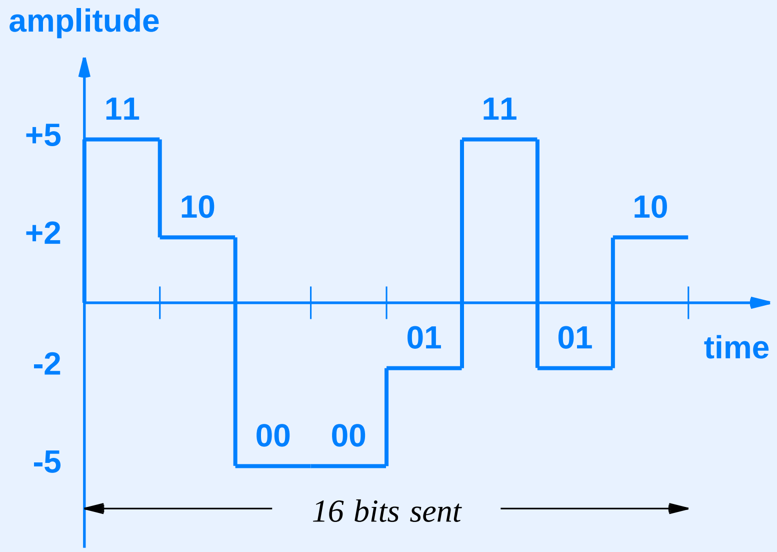


Digital Signals And Signal Levels

- A digital signal level can represent multiple bits
- Example



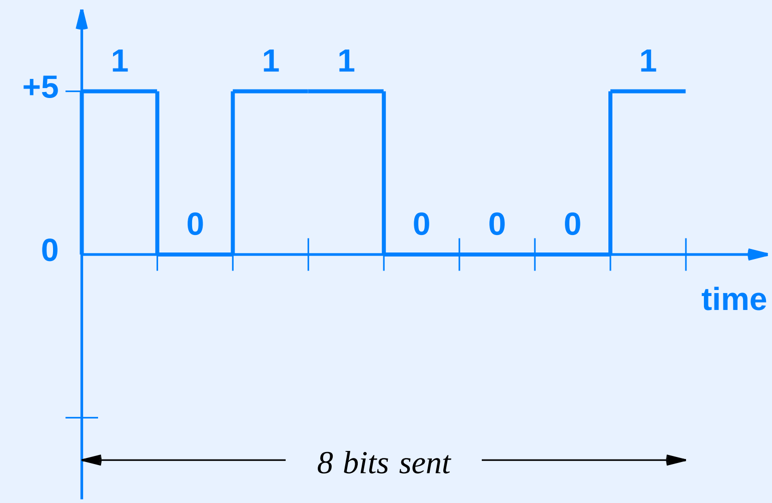
two levels with a
single bit per level



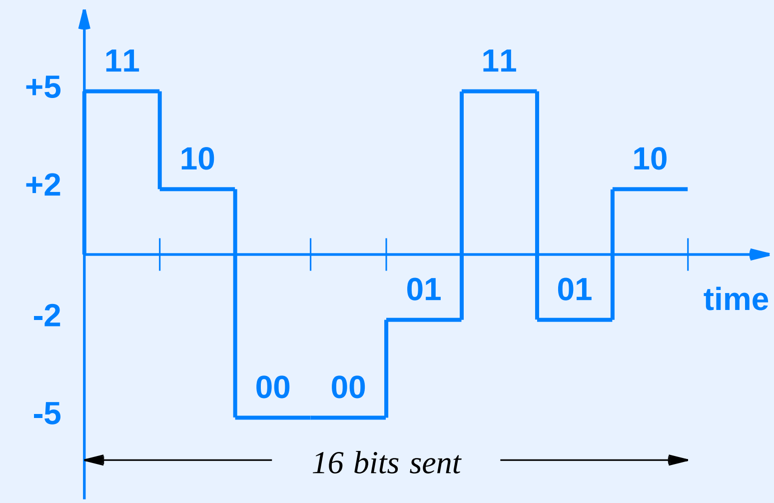
four levels with
two bits per level

Digital Signals And Signal Levels

- A digital signal level can represent multiple bits
- Example



two levels with a
single bit per level



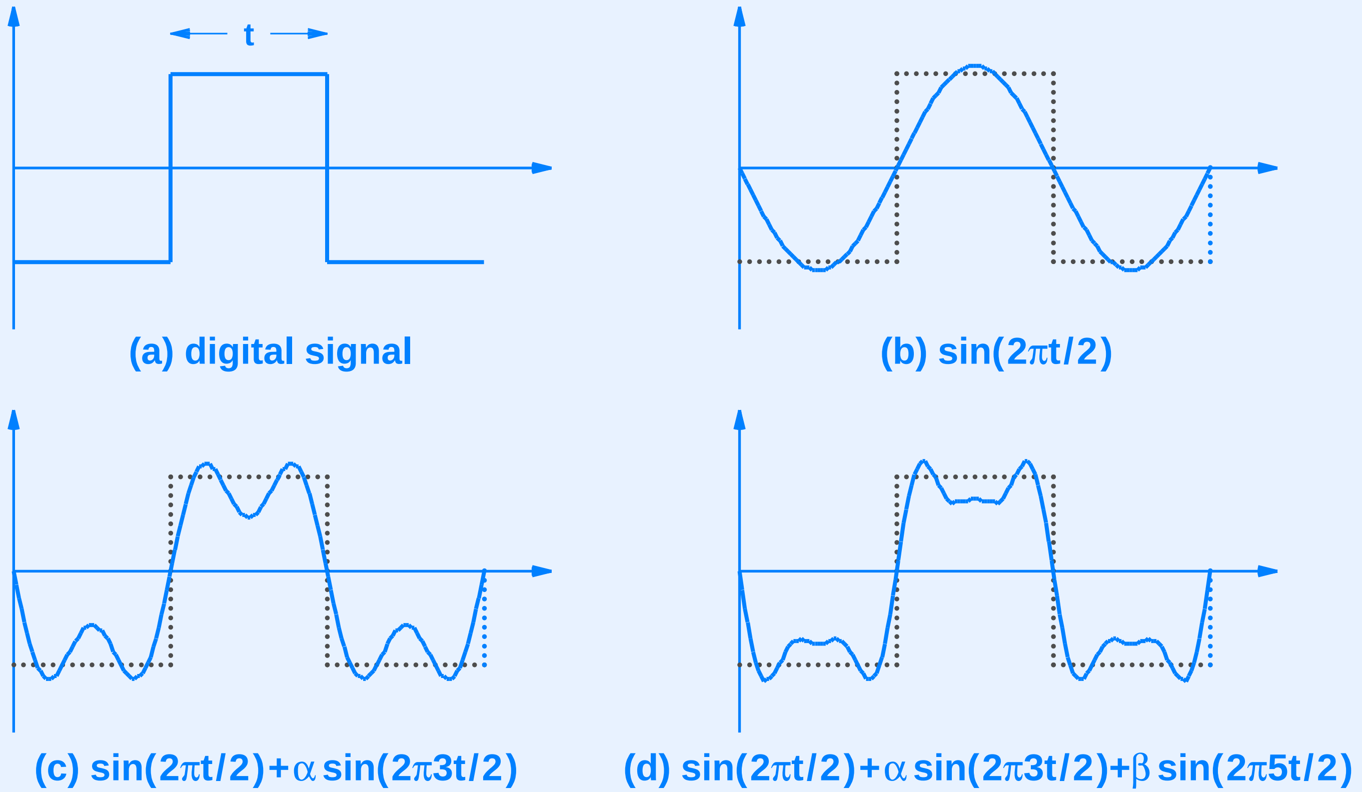
four levels with
two bits per level

- *Baud rate* is number of times signal changes per second;

$$\text{data rate in bits per second} = \mathit{baud} \times \left\lfloor \log_2(\mathit{levels}) \right\rfloor$$

Converting Digital To Analog

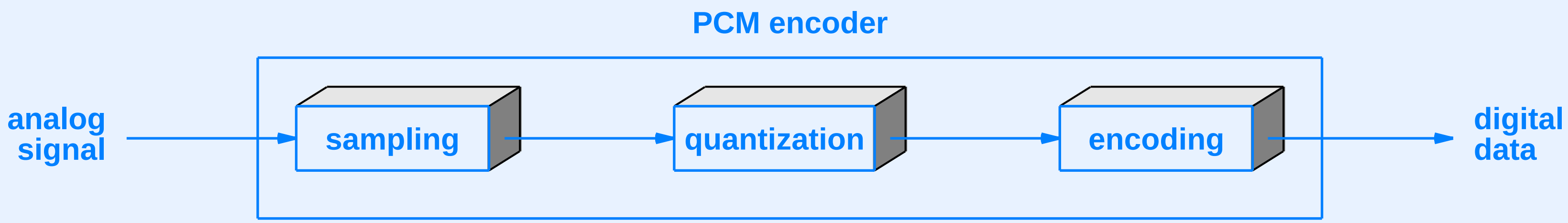
- Approximate digital signal with a composite of sine waves:



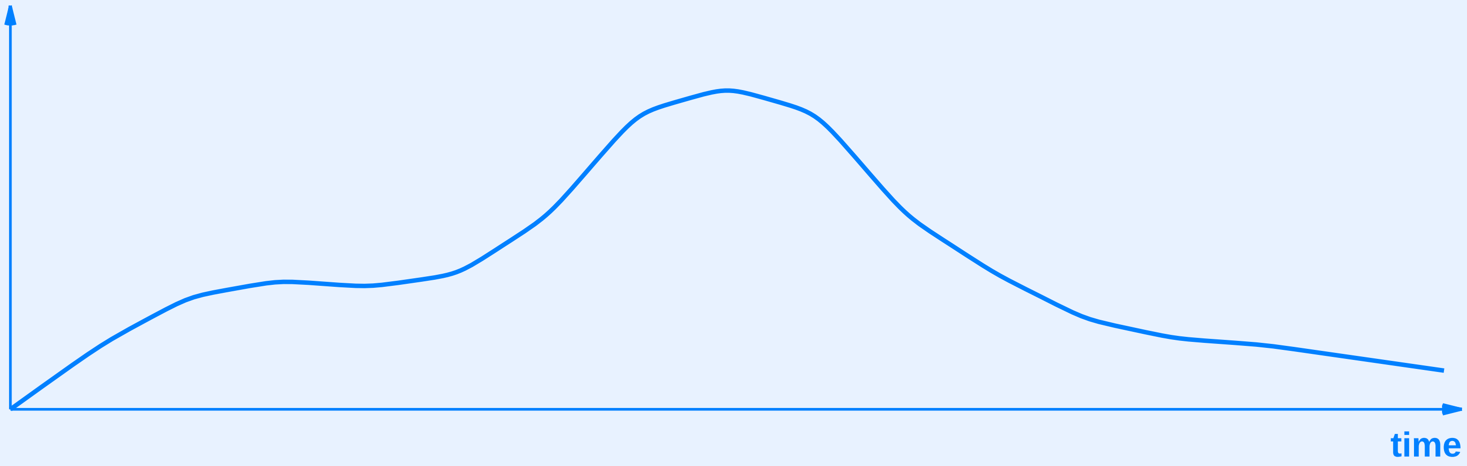
- Mathematically, the bandwidth of a digital signal is infinite

Converting Analog To Digital

- Three steps taken during conversion

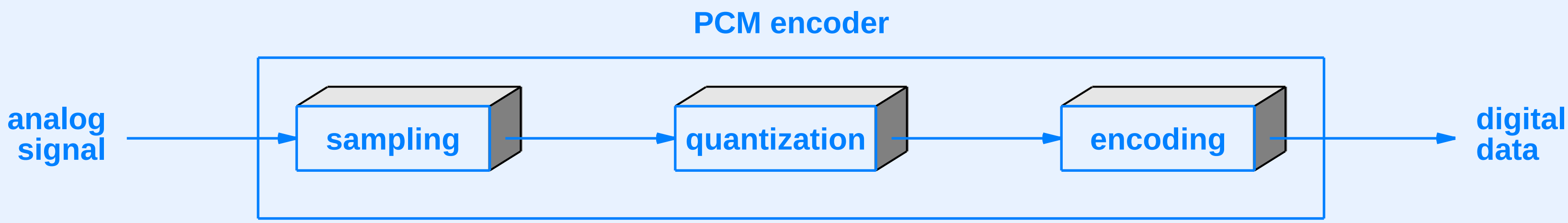


- Example sampling using eight levels

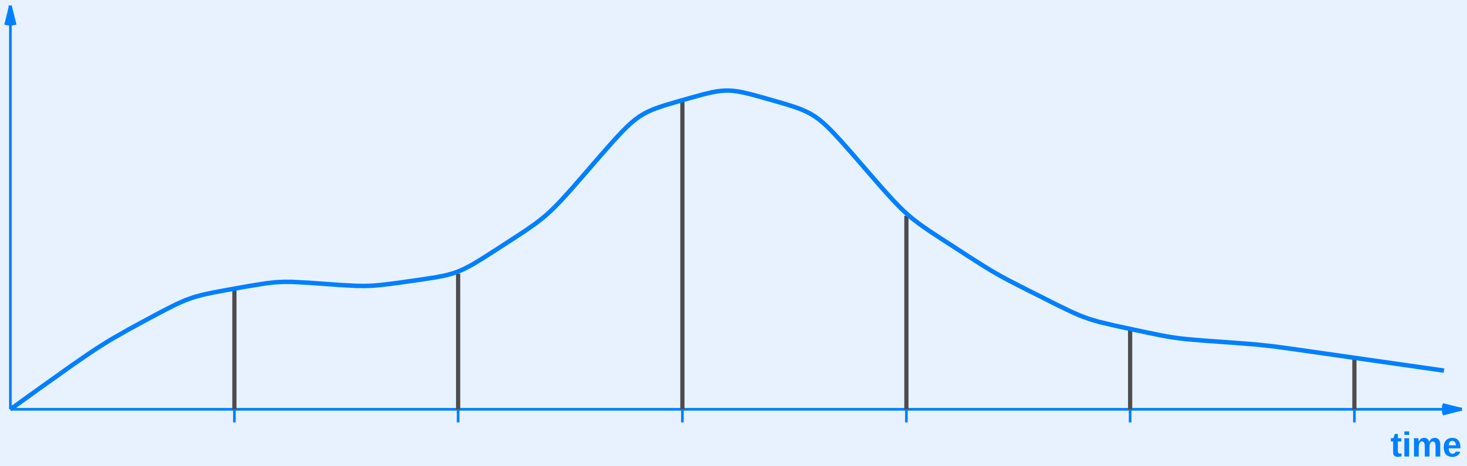


Converting Analog To Digital

- Three steps taken during conversion

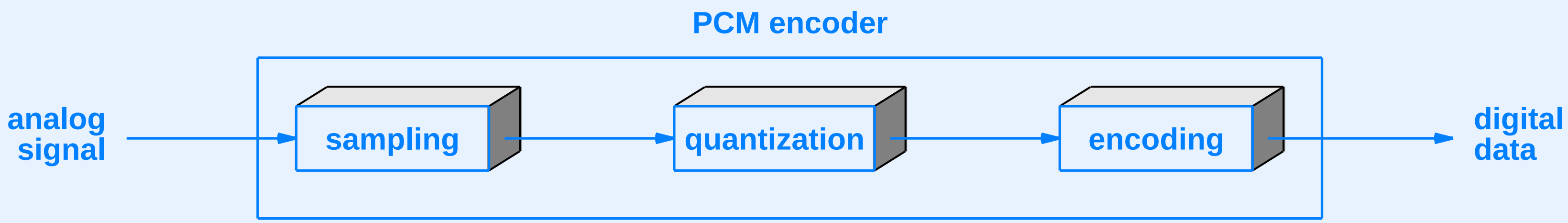


- Example sampling using eight levels

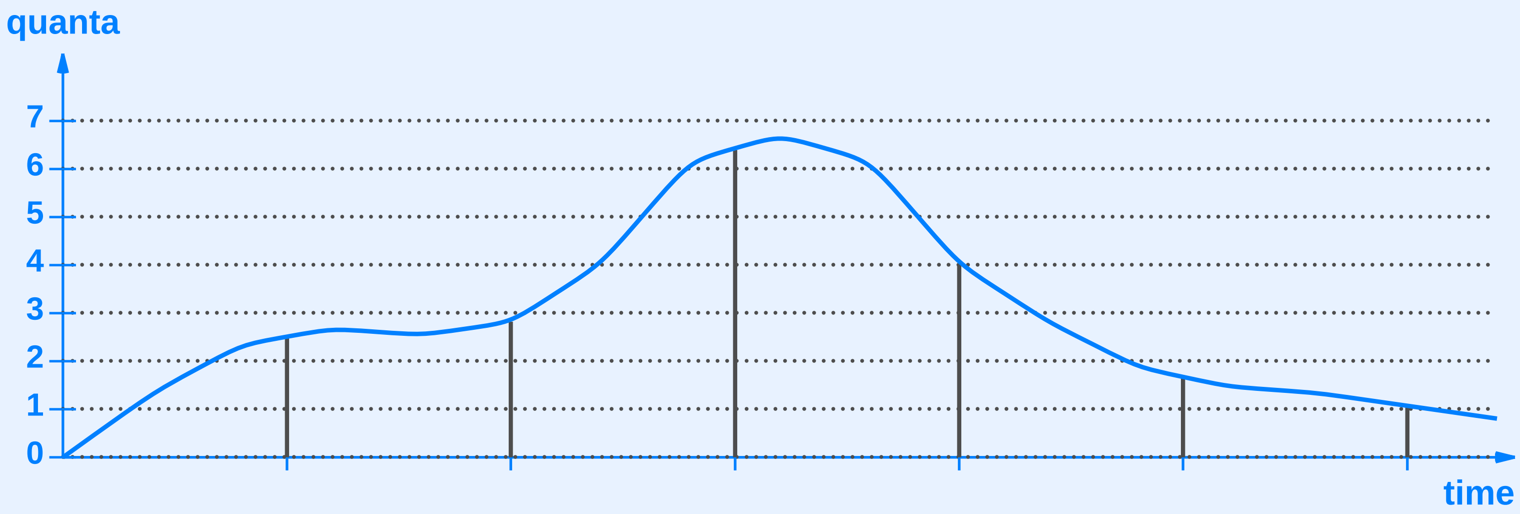


Converting Analog To Digital

- Three steps taken during conversion



- Example sampling using eight levels



Sampling Rate And Nyquist Theorem

- How many samples should be taken per second?

Sampling Rate And Nyquist Theorem

- How many samples should be taken per second?
- Mathematician named Nyquist discovered the answer:

$$\textit{sampling rate} \ = \ 2 \times f_{\mathrm{max}}$$

where f_{max} is highest frequency in the composite signal

Sampling Rate And Nyquist Theorem

- How many samples should be taken per second?
- Mathematician named Nyquist discovered the answer:

$$sampling\ rate \ = \ 2 \times f_{\text{max}}$$

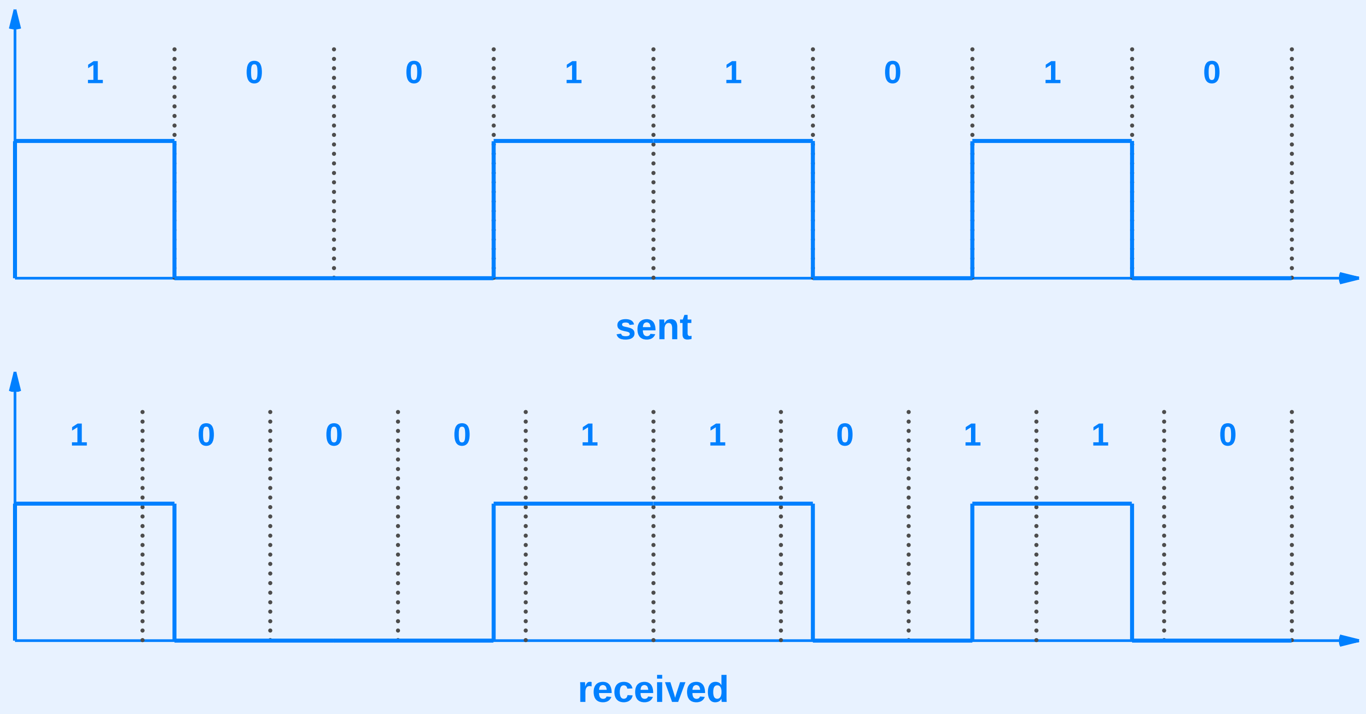
where f_{max} is highest frequency in the composite signal

- Example: to capture audio frequencies up to 4000 Hertz, a digital telephone system samples at 8000 samples per second
- Amount of data generated by a single digitized voice call:

$$data\ rate \ = \ 8000 \frac{samples}{second} \times 8 \frac{bits}{sample} \ = \ 64{,}000 \frac{bits}{second}$$

Synchronization Errors And Line Coding

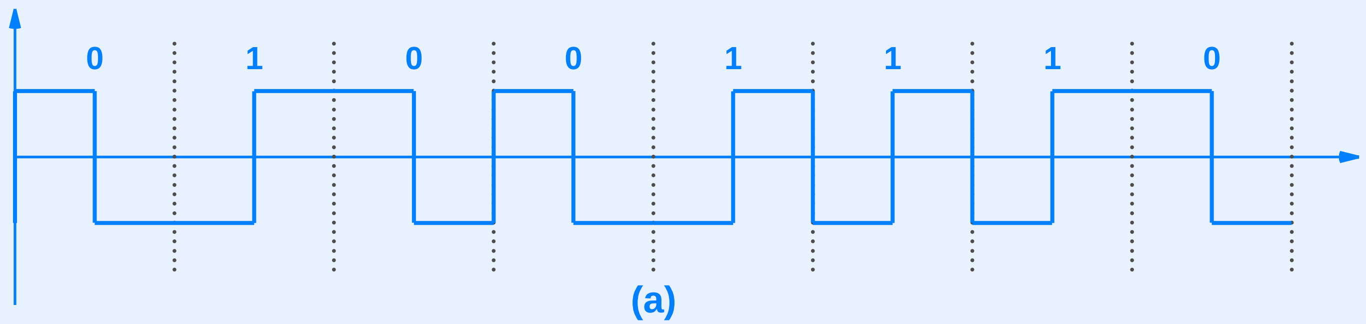
- Synchronization error occurs when receiver and sender disagree about bit boundaries (clocks differ)



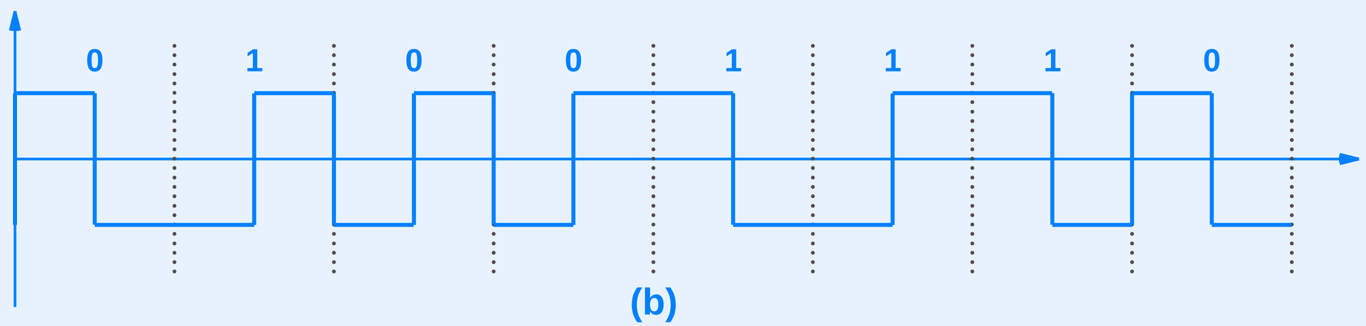
- Line coding techniques prevent synchronization errors

Example Line Coding: Manchester Encoding

- Used with Ethernet
- Synchronizes receiver with sender (transition represents bit)
- Example of (a) Manchester Encoding, and (b) differential Manchester Encoding:



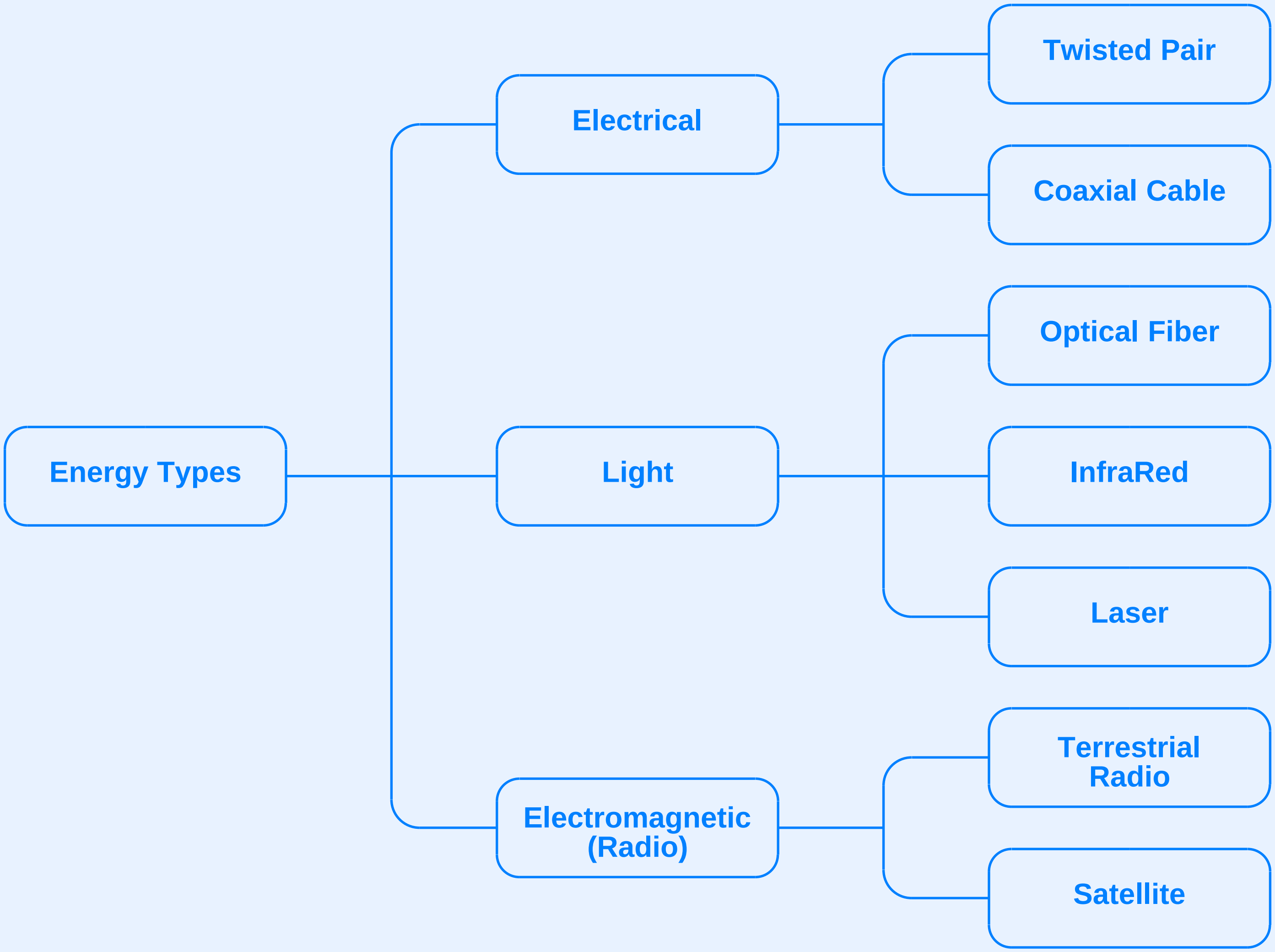
(a)



(b)

Transmission Media

A Taxonomy Of Transmission Media



- Is anything omitted?

Loss, Interference, And Electrical Noise

- Problems in the electrical and electromagnetic worlds
  - Resistance (leads to loss)
  - Capacitance (leads to distortion)
  - Inductance (leads to interference)
- Random electromagnetic radiation is called *noise*
  - Can be generated by specific sources such as electric motor
  - Background radiation is an inescapable feature of the universe

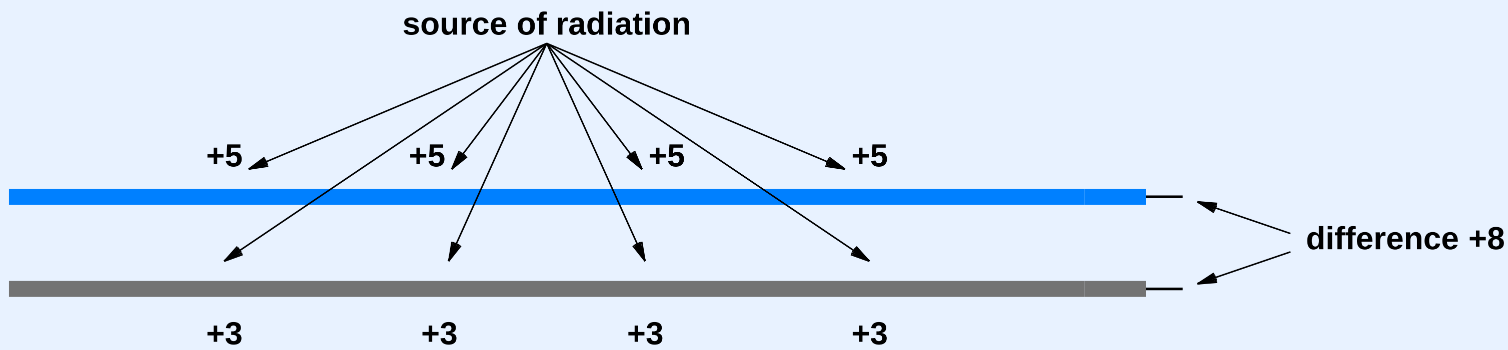
Examples

- When electrical signals propagate down a wire, electromagnetic energy is radiated (i.e., the wire acts like an antenna)
- When electromagnetic radiation encounters metal, a small electrical current is induced that can interfere with signals being carried on the wire
- When an electrical pulse is sent down an unterminated wire, reflection comes back
- When a signal passes across the connection between two wires, reflection and loss occur
- Note: a network diagnostic tool uses reflection to find the distance to the point where a cable has been cut

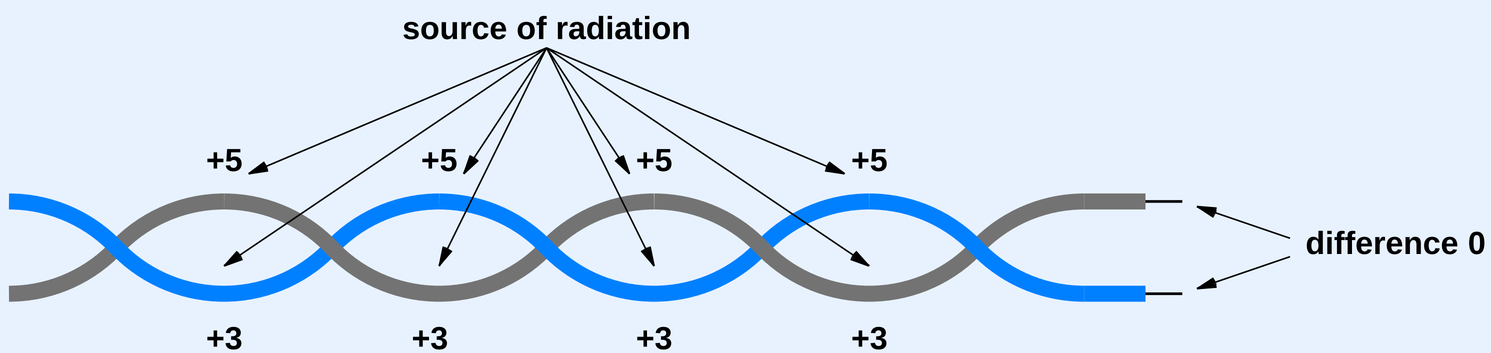
How Can We Reduce The Effect Of Noise On Copper Wiring

- Several techniques have been invented
  - Unshielded Twisted Pair (UTP)
  - Coaxial cable
  - Shielded Twisted Pair (STP)
- All are used in computer networks

How Twisted Pair Helps



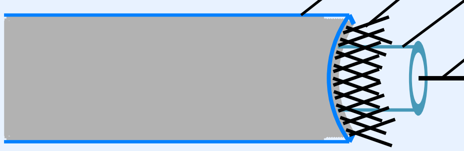
- In an untwisted pair of wires, more current is generated in first wire the interference hits



- Twisting exposes each wire equally

Coaxial Cable And Shielding

- Better protection: wrap a metal shield around the wire



- Shielding can be added to twisted pair
  - Around entire cable containing many pairs
  - Around each pair as well as around cable
- Shielding determines maximum data rate

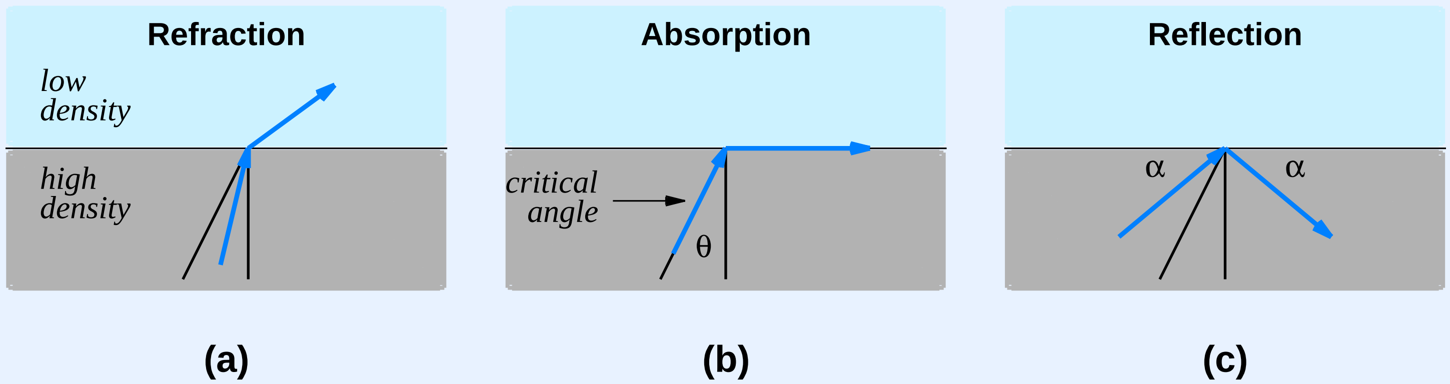
Wiring Standards And Data Rates

Category	Description	Data Rate (in Mbps)
CAT 1	Unshielded twisted pair used for telephones	< 0.1
CAT 2	Unshielded twisted pair used for T1 data	2
CAT 3	Improved CAT2 used for computer networks	10
CAT 4	Improved CAT3 used for Token Ring networks	20
CAT 5	Unshielded twisted pair used for networks	100
CAT 5E	Extended CAT5 for more noise immunity	125
CAT 6	Unshielded twisted pair tested for 200 Mbps	200
CAT 7	Shielded twisted pair with a foil shield around the entire cable plus a shield around each twisted pair	600

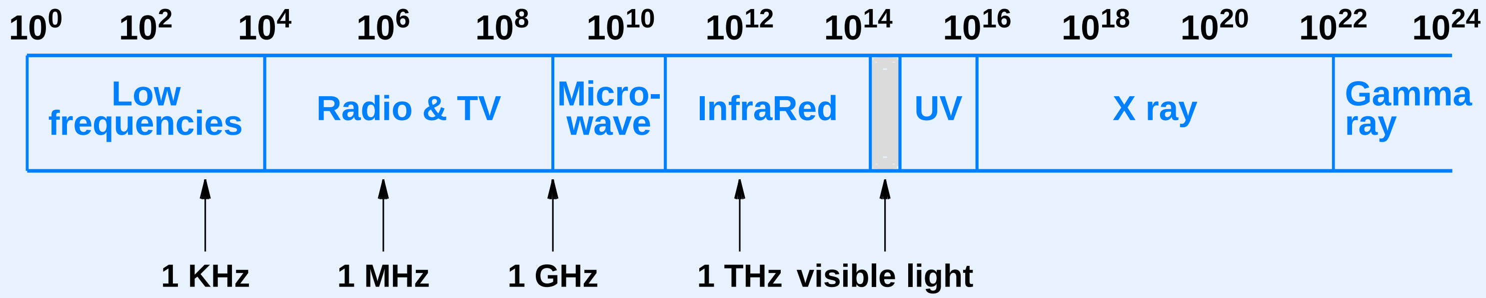
- What common data rate is missing from the list?

Media Using Light Energy

- InfraRED transmission (short range and low data rate)
- Point-to-point lasers (useful between buildings)
- Optical fiber (high data rate and long distance)
- Why light stays in a fiber:



Electromagnetic Spectrum And Properties



Classification	Range	Type Of Propagation
Low Frequency	< 2 MHz	Wave follows earth's curvature, but can be blocked by unlevel terrain
Medium Frequency	2 to 30 MHz	Wave can reflect from layers of the atmosphere, especially the ionosphere
High Frequency	> 30 MHz	Wave travels in a direct line, and will be blocked by obstructions

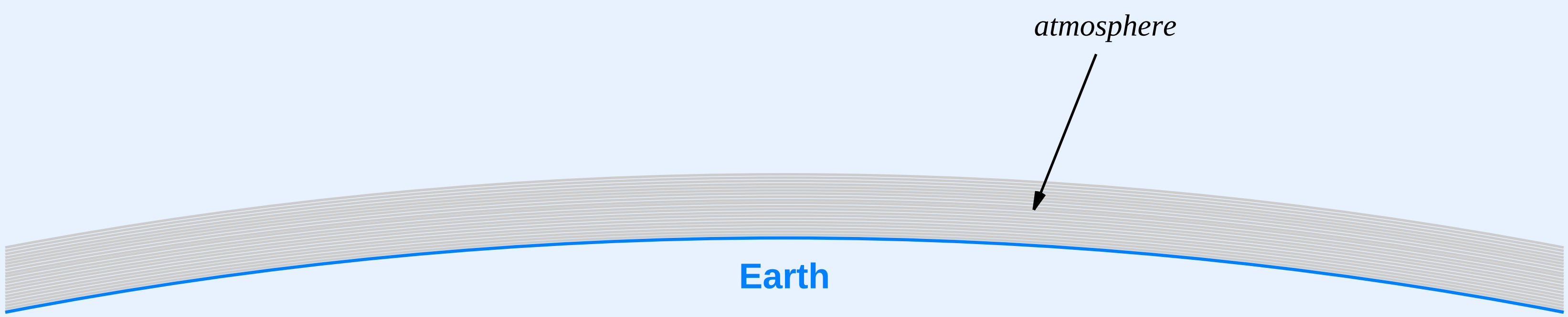
Satellite Communication

- Three types of communication satellites

Orbit Type	Description
Low Earth Orbit (LEO)	Has the advantage of low delay, but the disadvantage that from an observer's point of view on the earth, the satellite appears to move across the sky
Medium Earth Orbit (MEO)	An elliptical (rather than circular) orbit primarily used to provide communication at the North and South Poles
Geostationary Earth Orbit (GEO)	Has the advantage that the satellite remains at a fixed position with respect to a location on the earth's surface, but the disadvantage of being farther away

GEO Satellites

- Figure below shows the earth's atmosphere drawn to scale
- Where would a GEO satellite be in the figure?



GEO Satellites
(continued)

- Distance to GEO satellite is 35,785 km or 22,236 miles
- Approximately 3 times earth's diameter or one-tenth of the distance to the moon
- In other words: the satellite is far off the page

GEO Satellites
(continued)

- Distance to GEO satellite is 35,785 km or 22,236 miles
- Approximately 3 times earth's diameter or one-tenth of the distance to the moon
- In other words: the satellite is far off the page
- A consequence for networking: a long round-trip time, even at the speed of light:

$$Round\ trip\ time = \frac{2 \times 35.8 \times 10^6 meters}{3 \times 10^8\ meters/sec} = 0.238\ sec$$

Measures Of Transmission Media

- *Propagation delay* - time required for a signal to traverse a medium
- *Channel capacity* - maximum data rate

Channel Capacity

- Nyquist's Theorem gives theoretical bound on maximum data rate for hardware bandwidth B and K signal levels

$$D = 2B \log_2 K$$

- Mathematical result known as *Shannon's Theorem* gives the maximum channel capacity, C, in the presence of noise

$$C = B \log_2 (1 + S/N)$$

- Quantity S/N is known as the *signal-to-noise ratio*

Assessment

- Nyquist’s Theorem gives us hope: using more signal levels can increase the data rate
- Shannon’s Theorem is sobering: electrical noise in the universe limits the effective channel capacity of any practical communication system

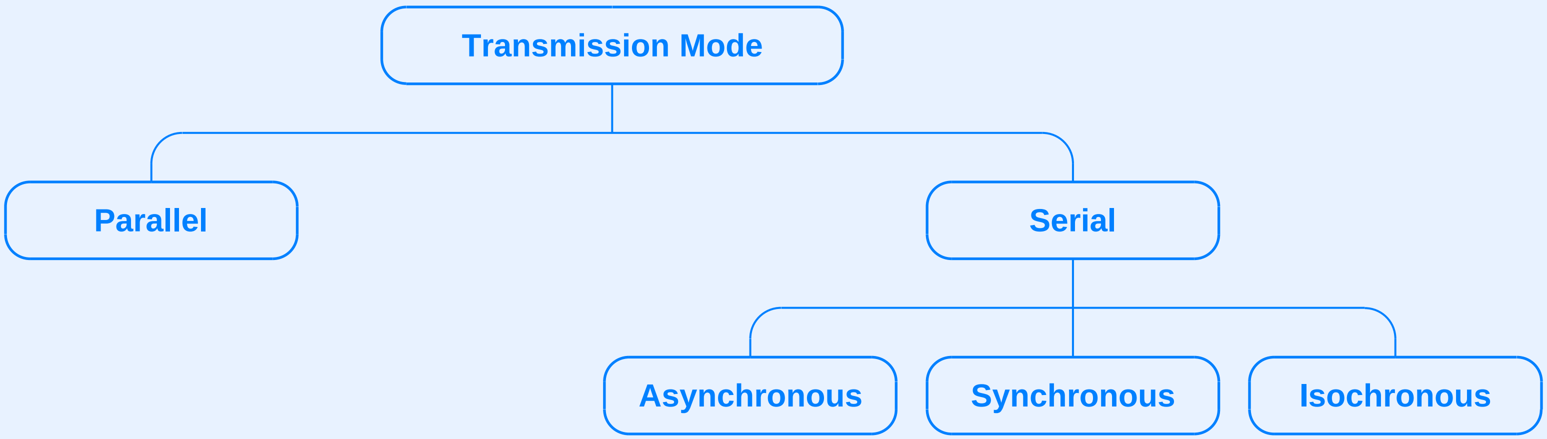
Transmission Modes

Terminology

- Serial - one bit at a time
- Parallel - multiple bits at a time

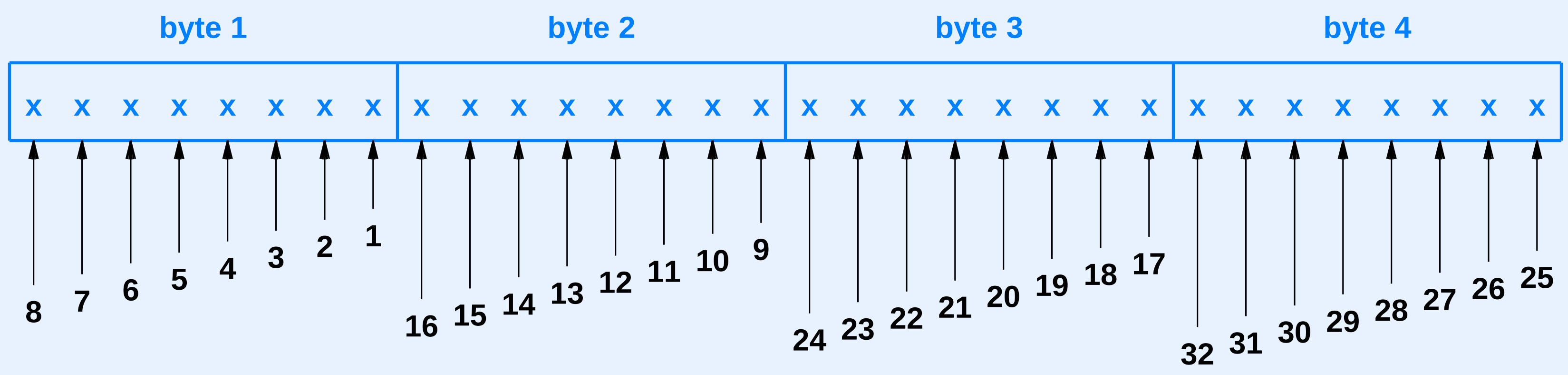
Terminology

- Serial - one bit at a time
- Parallel - multiple bits at a time
- Taxonomy of transmission methods:



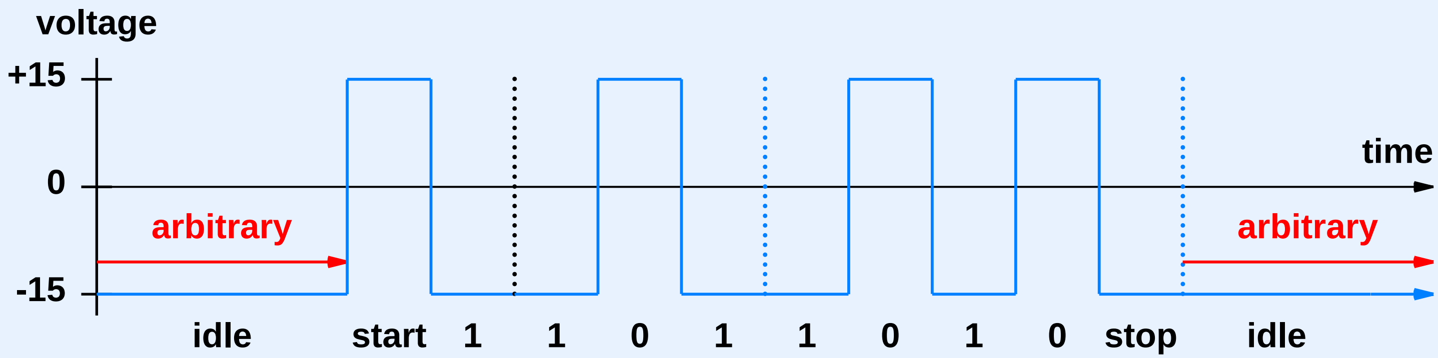
Serial Ordering Of Bits And Bytes

- Both sides must agree on order in which bits are transmitted
- Two approaches known as *big-endian* and *little-endian*
- Example: Ethernet uses byte big-endian and bit little-endian order



Asynchronous And Synchronous Transmission

- Asynchronous: line idle when not in use; data starts at arbitrary time



- Synchronous: each bit slot used

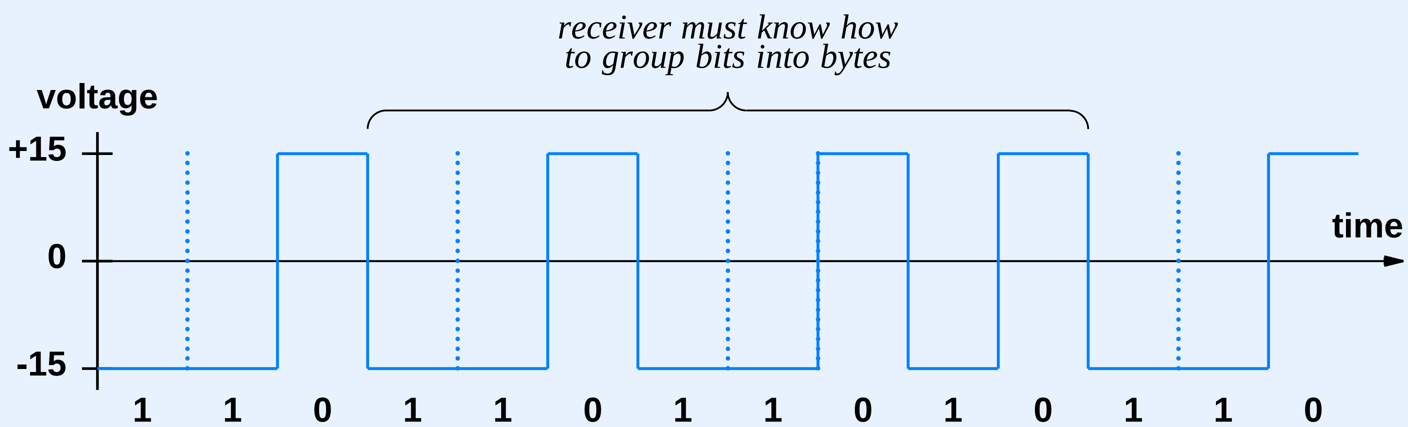
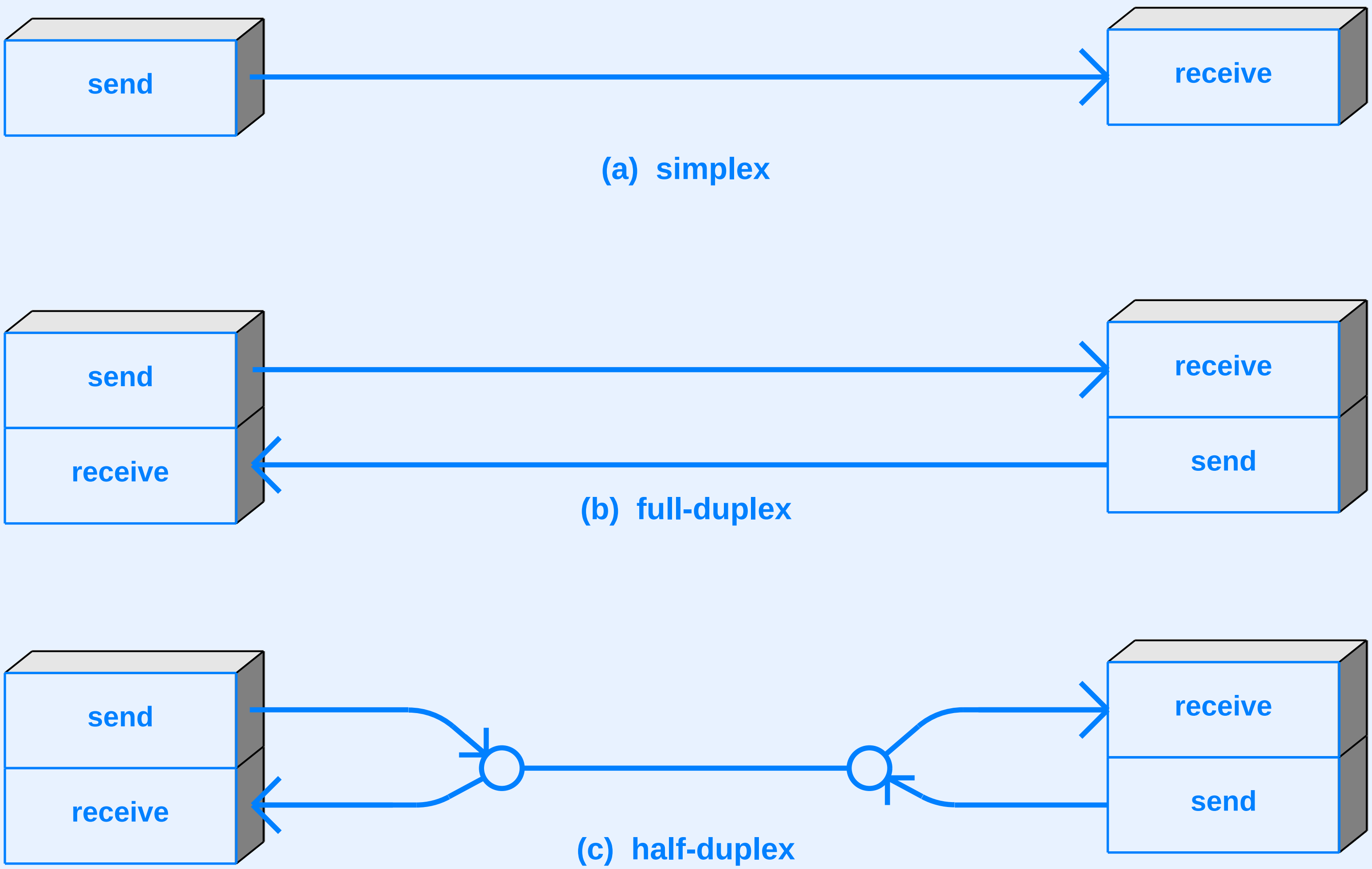


Illustration Of Simplex And Duplex Modes



Modulation And Demodulation

Illustration Of Amplitude Modulation

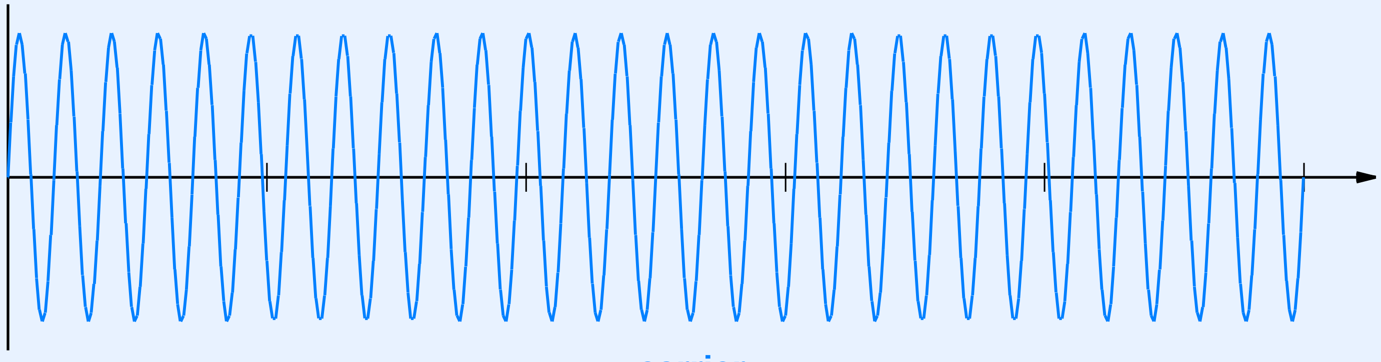


Illustration Of Amplitude Modulation

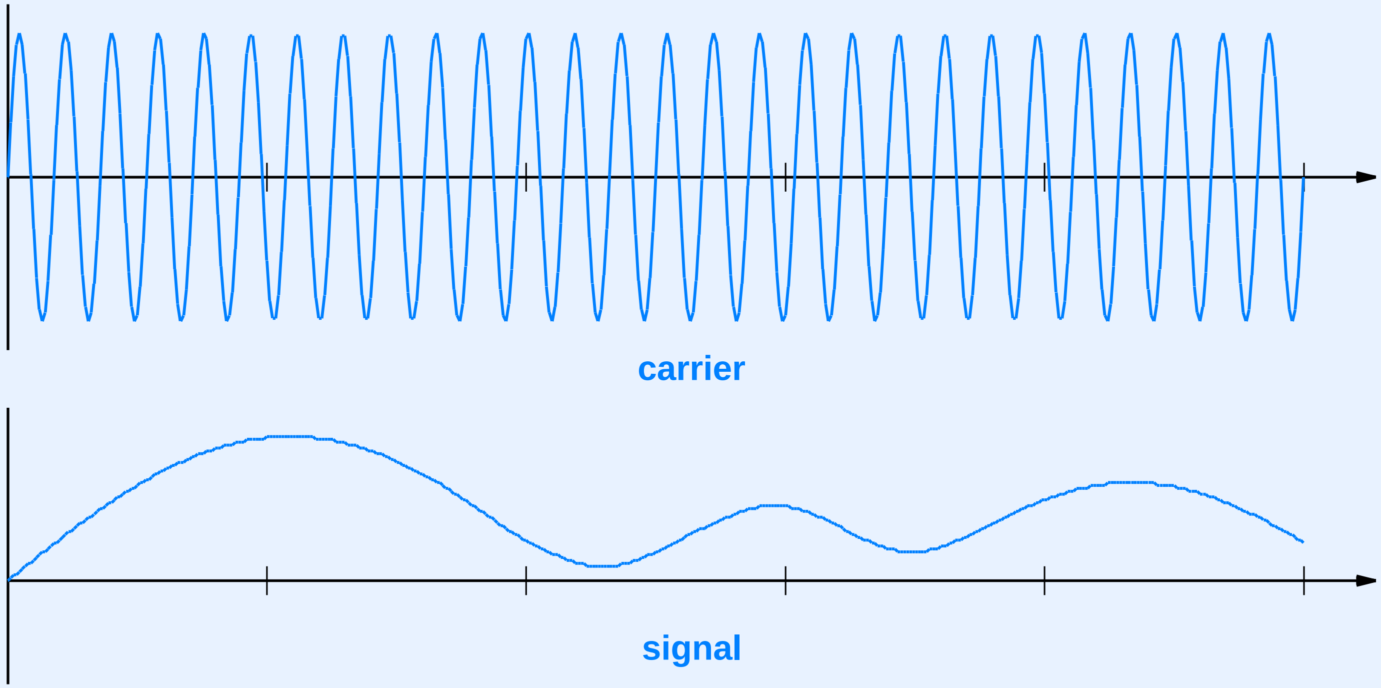


Illustration Of Amplitude Modulation

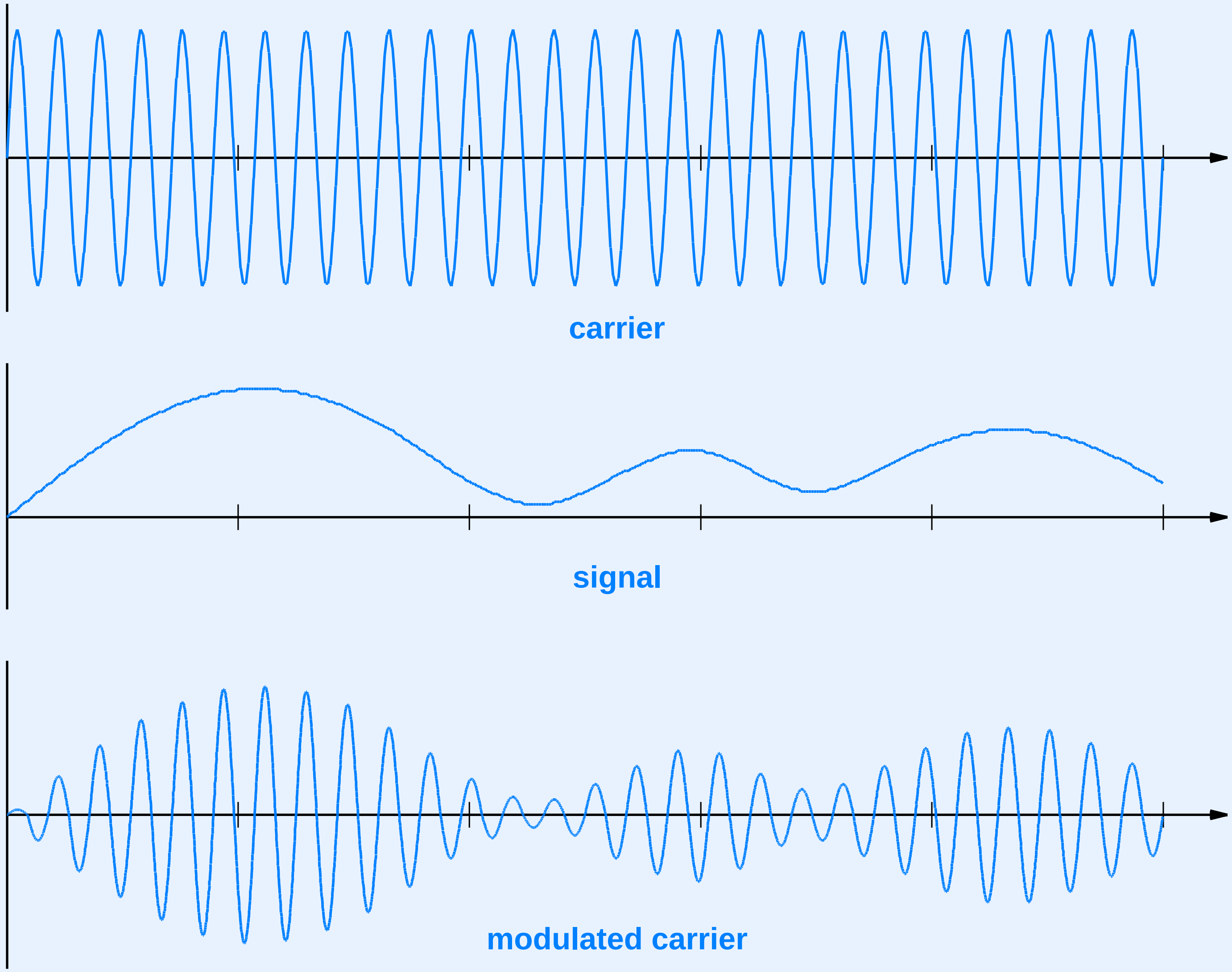
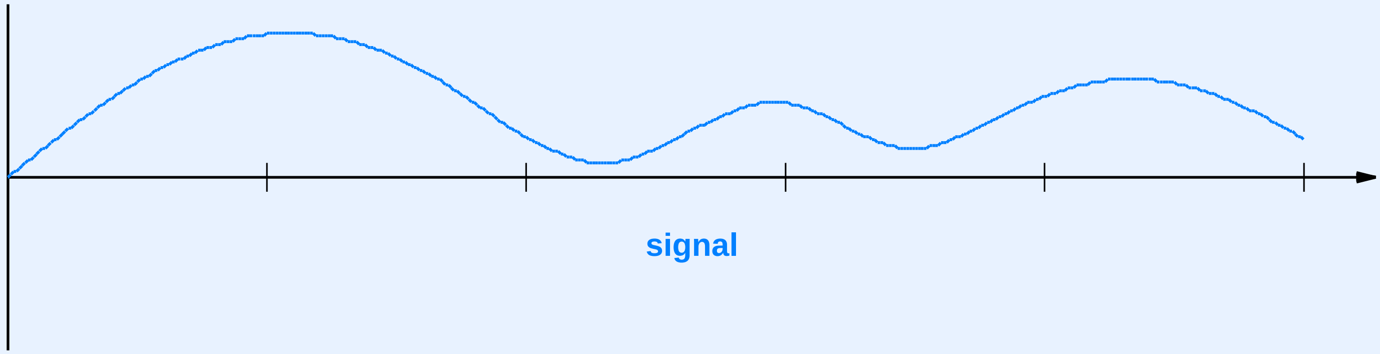
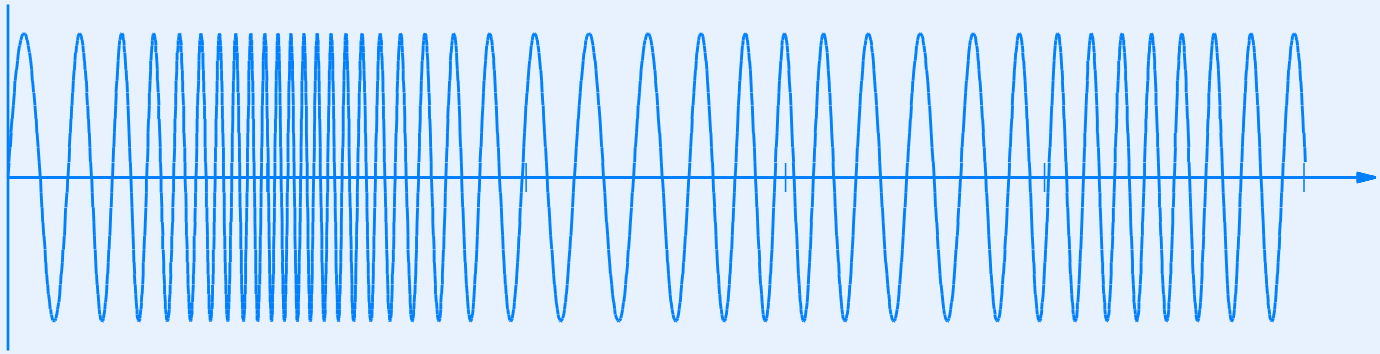


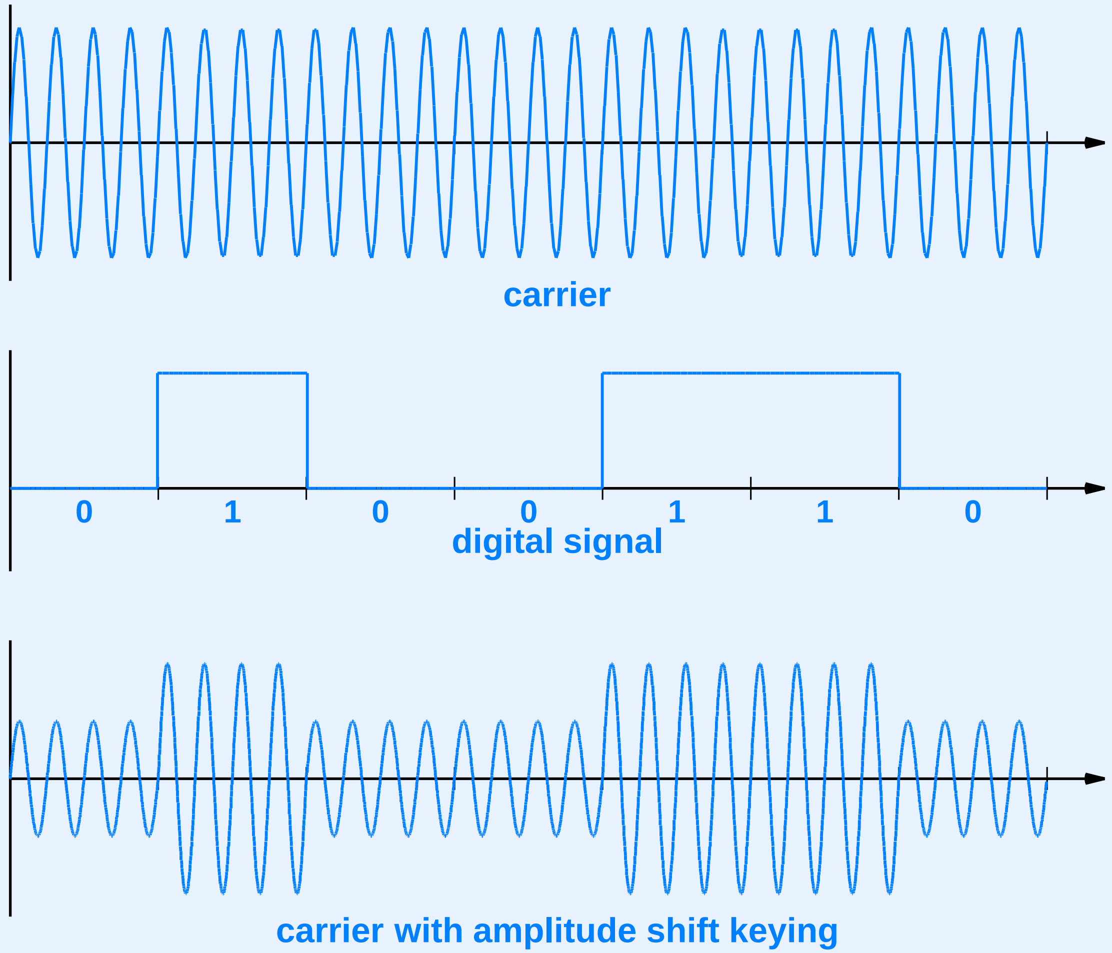
Illustration Of Frequency Modulation





Shift Keying

- Like modulation except signal is digital

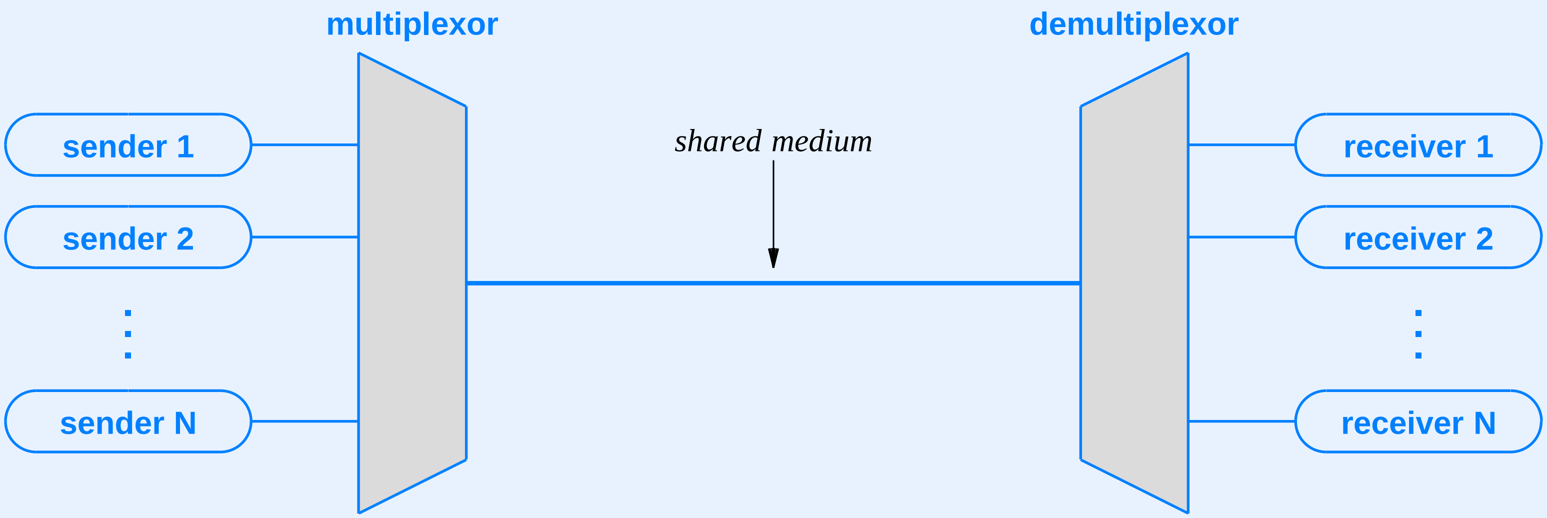


Other Modulation Topics

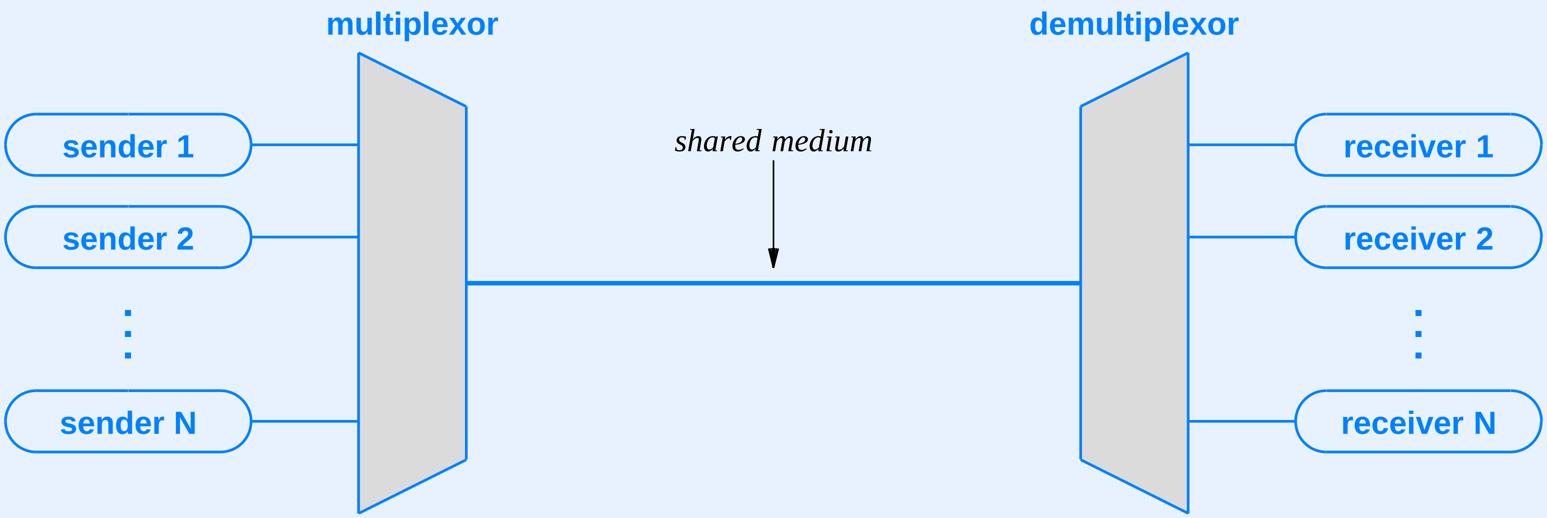
- Phase shift modulation
- Increasing bits per second by combining amplitude and phase shift (QAM techniques)
- Constellation diagrams to represent combinations
- Modems (modulator / demodulator)

Multiplexing And Demultiplexing
(Channelization)

Concept Of Multiplexing And Types



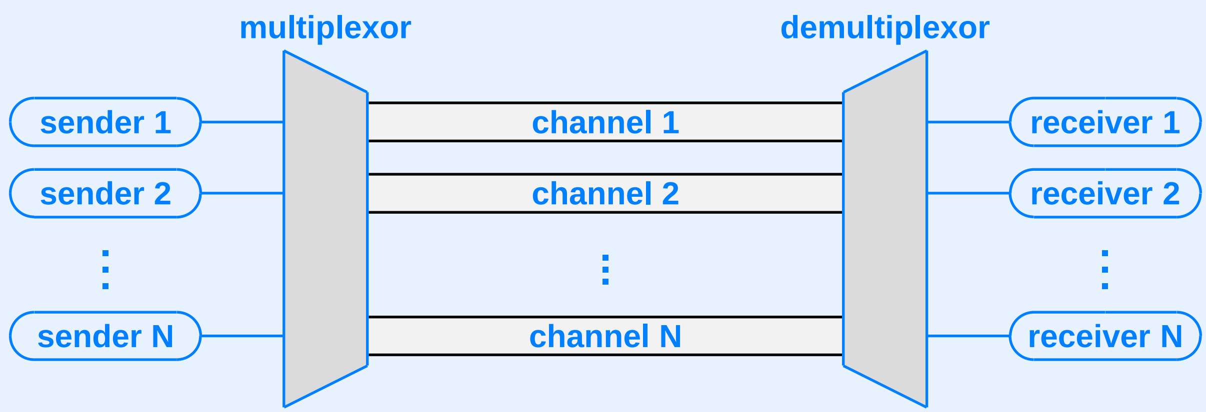
Concept Of Multiplexing And Types



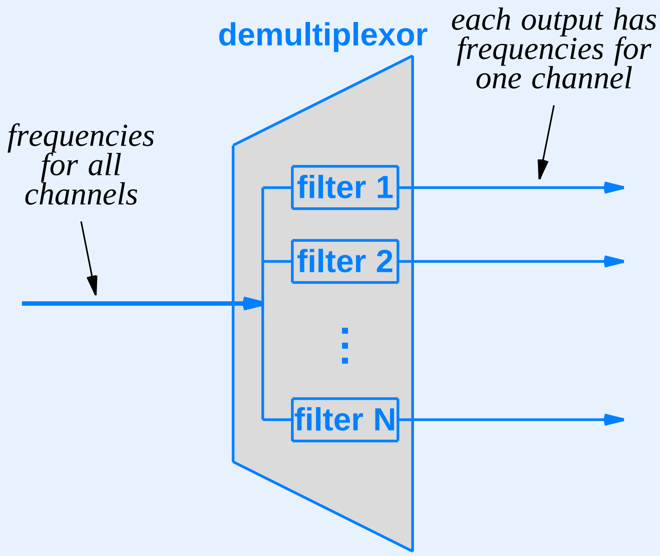
- Types:
  - Frequency division multiplexing
  - Wavelength division multiplexing
  - Time division multiplexing
  - Code division multiplexing

Frequency Division Multiplexing (FDM)

- Used in broadcast radio and cable TV



- Demultiplexing implemented with sets of filters

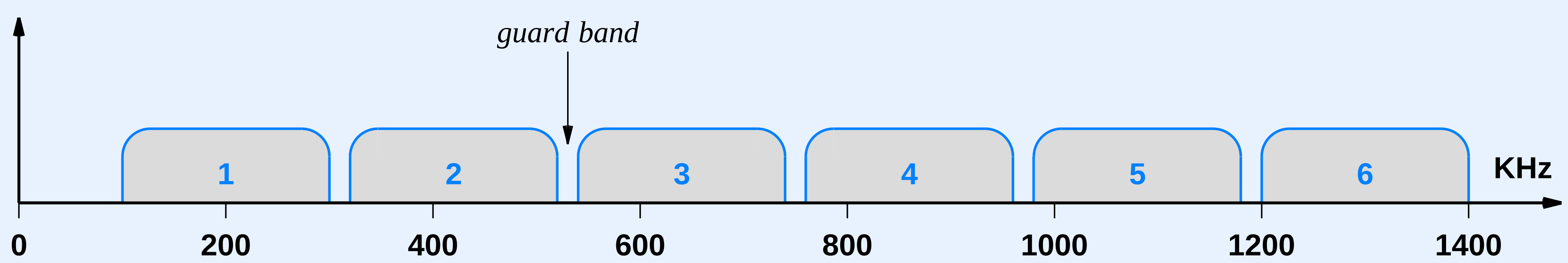


FDM In Practice

- Each channel assigned a range of frequencies

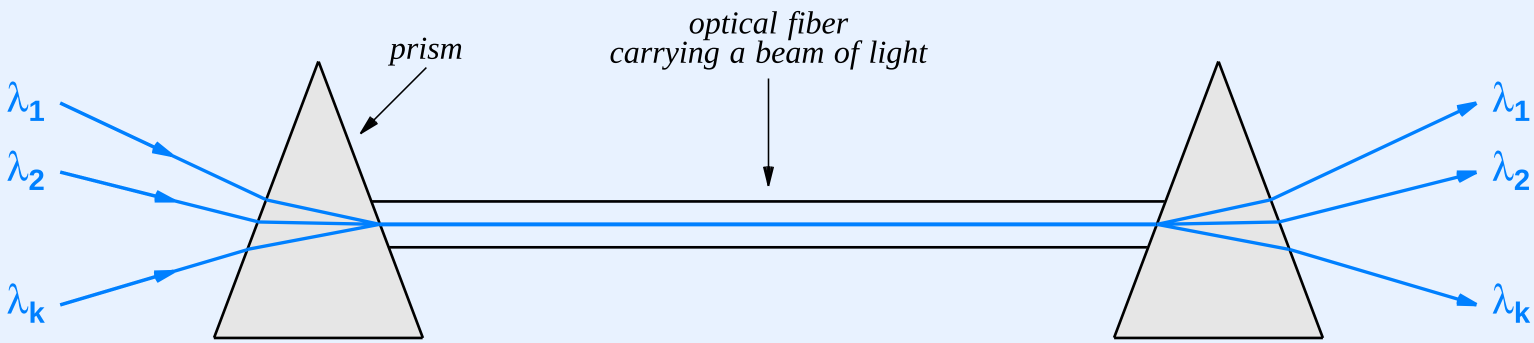
Channel	Frequencies Used
1	100 KHz - 300 KHz
2	320 KHz - 520 KHz
3	540 KHz - 740 KHz
4	760 KHz - 960 KHz
5	980 KHz - 1180 KHz
6	1200 KHz - 1400 KHz

- A *guard band* separates adjacent channels



Wavelength Division Multiplexing (WDM)

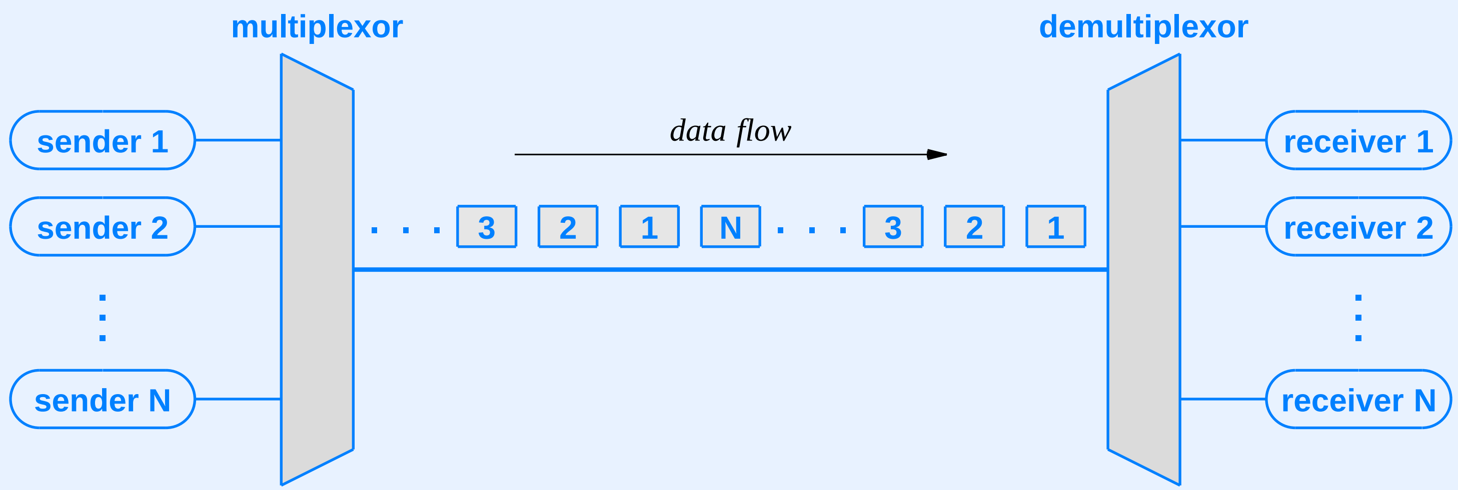
- Form of FDM used with light (i.e., on an optical fiber)
- Separate frequencies called *colors* or *lambdas*
- Prisms used to separate frequencies



- Current technology is *Dense WDM* (*DWDM*); an individual channel can provide 10 Gbps

Time Division Multiplexing

- Senders take turns transmitting



- Synchronous TDM
  - Each sender assigned a slot (typically round-robin)
  - Used by the telephone company
- Statistical TDM
  - Sender only transmits when ready (e.g., Ethernet)

Code Division Multiplexing

- Mathematical form of multiplexing used with cell phones
- Algorithm
  - Each sender/receiver pair is assigned a unique number called a *chip sequence*
  - Senders multiply the data value by their chip sequence (orthogonal vector spaces)
  - Transmitted value is a sum of all senders
  - Each receiver multiplies incoming value by its chip sequence to extract data
- Advantage over statistical TDM: lower delay when network loaded

Hierarchical Multiplexing

- Hierarchies used with FDM and TDM to combine multiple lower-capacity channels
- Example of TDM hierarchy used by the phone system