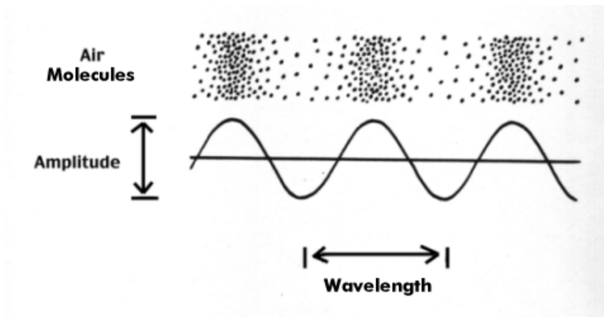
Physical Layer – Transmission Media

Transmission Media

- Two basic formats
  - – Guided media : wires, fiber optics
    - Medium is important
  - – Unguided media : wireless, radio transmission
    - Antenna is important
- Each have tradeoffs over data rate, distance
  - – Attenuation : weakening of signal over distance

Mini Electromagnetic Review

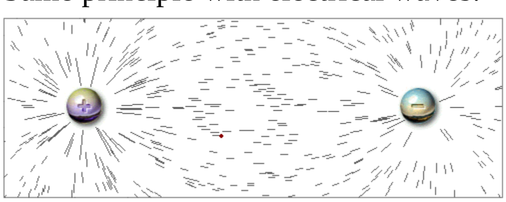
- Take a sound wave…



Frequency (hz) = Number of cycles/second
With a constant wave velocity, frequency = velocity / wavelength
For electromagnetic waves, f = c / w ; c = speed of light

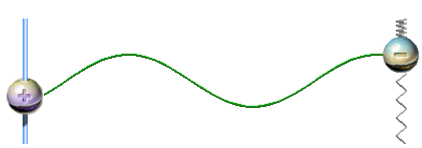
Mini Electromagnetic Review

Same principle with electrical waves:



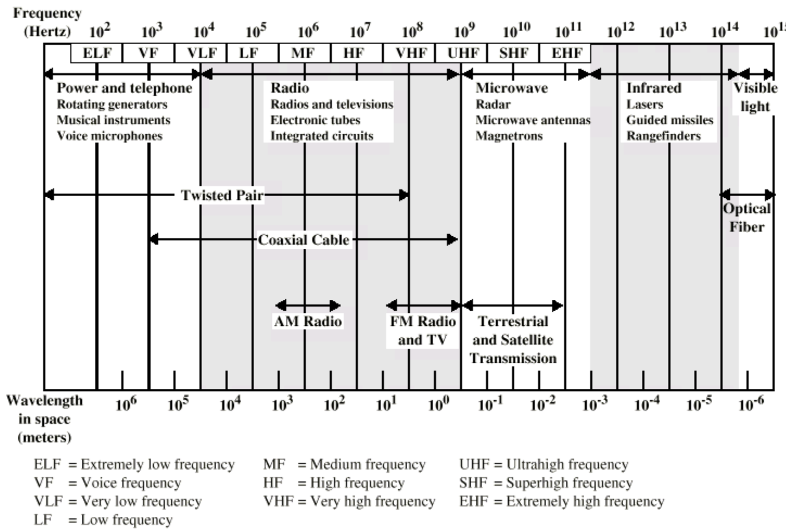
Station at 88.1 FM = 88.1 Mhz

88100000 = 3.0 * 10^8 / w
w = 3.0 * 10^8 / 88100000
= 3.4 meters



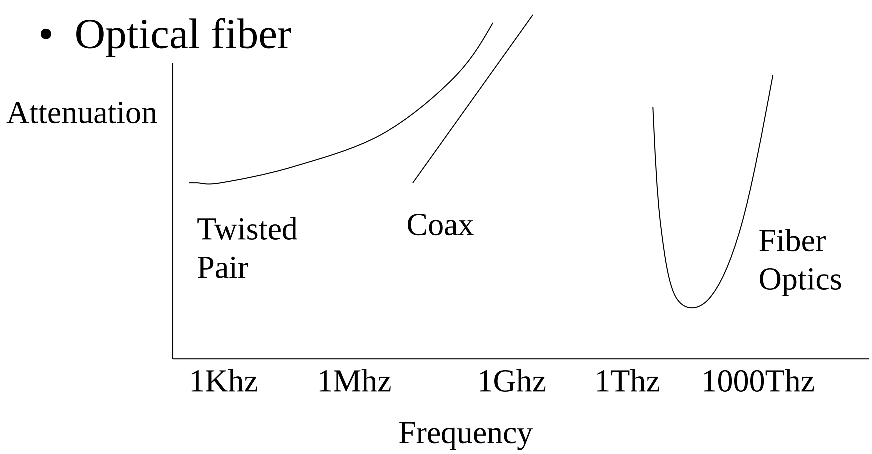
Time to travel this far is 1/f or 0.000000011 seconds

Electromagnetic Spectrum

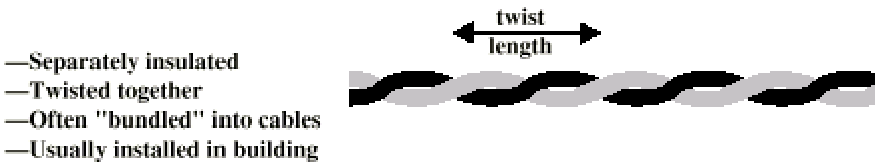


Guided Transmission Media

- Twisted Pair
- Coaxial cable
- Optical fiber



Twisted Pair



(a) Twisted pair

Pair of copper wires constitutes a single communication link.
Twists minimize the effects of electromagnetic interference
- emit less emag energy
- less susceptible to emag energy

Twisted Pair - Applications

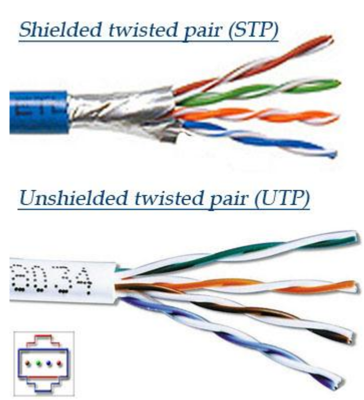
- Most common medium
- Telephone network
  - POTS
  - Between house and local exchange (subscriber loop), also called the end office. From the end office to Central Office (CO) class 4 → CO class 1 via Public Switched Telephone Network (PSTN)
- Within buildings
  - To private branch exchange (PBX)
- For local area networks (LAN)
  - 10Mbps or 100Mbps
  - Possible to rev up to 1Gbps – Gigabit Ethernet

Twisted Pair - Pros and Cons

- Cheap
- Easy to work with
  - Can use as digital or analog
- Limited bandwidth/data rate
  - Generally 1Mhz and 100Mbps but up to 1 Ghz
- Short range
  - 2km for digital, 5km for analog
- Direct relationship between data rate and range
  - Gigabit Ethernet
    - 1000Mbps over 4 Cat5 UTP up to 100 meters
      - IEEE 802.3ab standard in 1999
    - 1000Mbps over 1 Cat5 UTP up to 24 meters

Unshielded and Shielded TP

- Unshielded Twisted Pair (UTP)
  - Ordinary telephone wire
  - Cheapest
  - Easiest to install
  - Suffers from external EM interference
- Shielded Twisted Pair (STP)
  - Metal braid or sheathing that reduces interference
  - More expensive
  - Harder to handle (thick, heavy)



UTP Categories

- Cat 1
  - Used for audio frequencies, speaker wire, etc. Not for networking.
- Cat 2
  - Up to 1.5Mhz, used for analog phones, not for networking
- Cat 3
  - EIA 568-A Spec from here on up
  - up to 16MHz
  - Voice grade once common in offices, 10 Mb networks
  - Twist length of 7.5 cm to 10 cm
- Cat 4
  - up to 20 MHz
  - Not frequently used today, was used for Token Ring

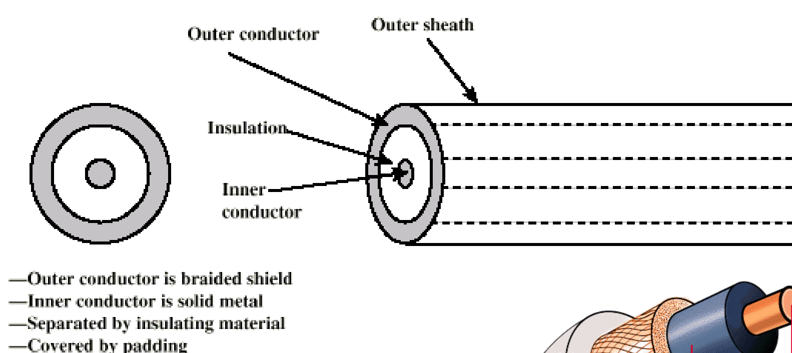
UTP Categories Cont.

- Cat 5
  - up to 100MHz
  - Twist length 0.6 cm to 0.85 cm
  - Commonly pre-installed in new office buildings
- Cat 5e "Enhanced"
  - Up to 100Mhz
  - Specifies minimum characteristics for NEXT (Near End Crosstalk) and ELFEXT (Equal level far end crosstalk)
    - Coupling of signal from one pair to another
    - Coupling takes place when transmit signal entering the link couples back to receiving pair, i.e. near transmitted signal is picked up by near receiving pair
- Cat 6
  - Standard up to 250Mhz; heavier, up to 100 meters
- Cat 6a
  - Standard up to 500Mhz

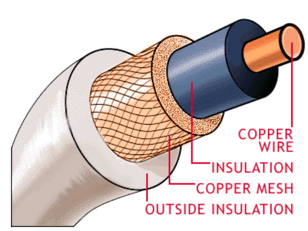
Typical Usage of Twisted Pair

Name	**Type**	**Mbps**	**m**	**In…**
Cat 1	UTP	1	90	
Cat 2	UTP	4	90	Tkn Ring/Phone
Cat 3	UTP	10	100	10BaseT
Cat 4	STP	16	100	TRing 16
Cat 5	S/UTP	100 to 1000	200	100BaseT & 1000BaseT
Cat 6	S/UTP	10 Gbps	100	10 GBaseT

Coaxial Cable



Shielded, less susceptible to noise and attenuation than Twisted Pair.



Coaxial Cable Applications

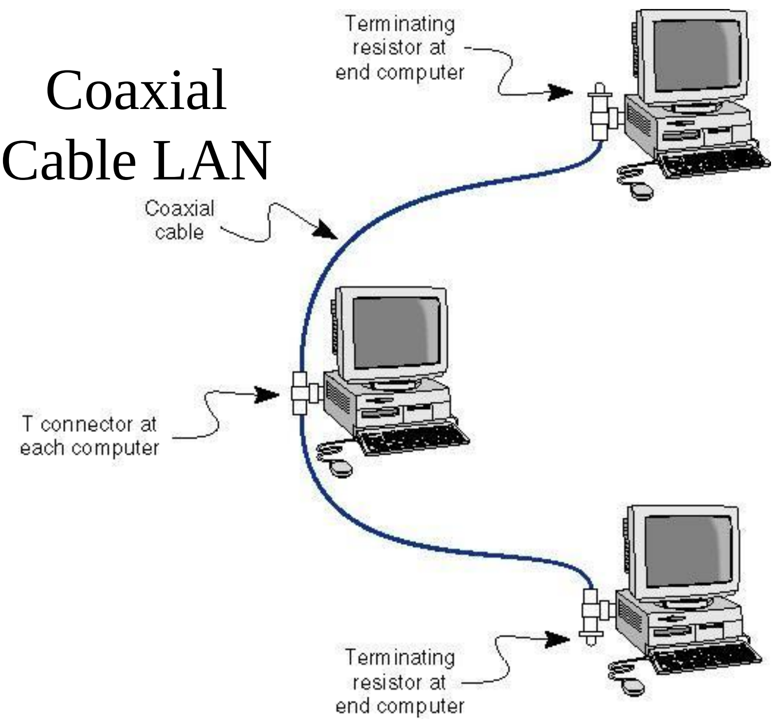
- Most versatile medium
- Television distribution
  - Cable TV
- Long distance telephone transmission
  - Can carry 10,000 voice calls simultaneously
  - Being replaced by fiber optic
- Short distance computer systems links
- Local area networks
  - More expensive than twisted pair, not as popular for LANs

Coaxial Cable Characteristics

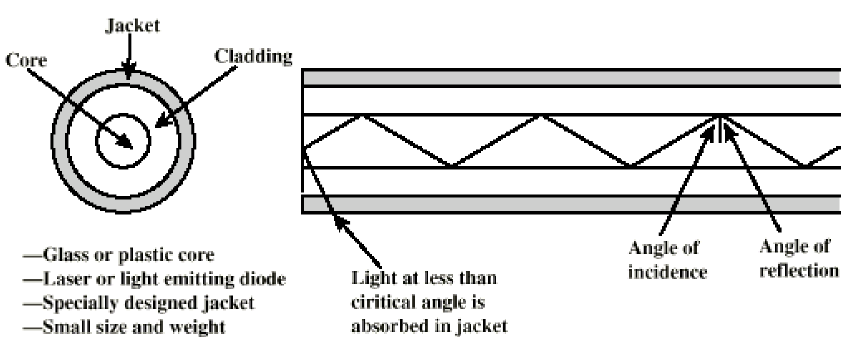
- Analog – Broadband Coaxial Cable
  - Amplifiers every few km, closer if higher frequency
  - Up to 500MHz
  - Cable TV, Cable Modems (~10Mbps)
- Digital – Baseband Coaxial Cable
  - Repeater every 1km
  - Closer for higher data rates

Name	**Type**	**Mbps**	**m**	**In…**
RG-58	Coax	10	185	10Base2, “ThinNet”
RG-8	Coax	10	500	10Base5, “ThickNet”

Coaxial Cable LAN



Optical Fiber



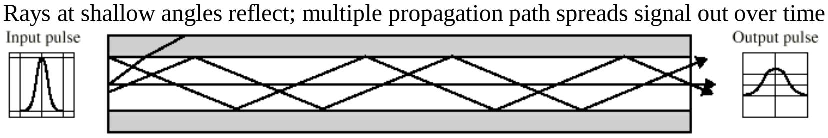
Breakthrough in data transmission systems!
Core: Thin strands of glass
Cladding: Glass with different optical properties than core
Jacket: Plastic/Insulation

Optical Fiber - Benefits

- Greater capacity
  - Data rates of hundreds of Gbps
  - Tbps demonstrated using WDM
- Smaller size & weight
  - Order of magnitude smaller than TP/Coax
- Lower attenuation
- Electromagnetic isolation
  - Not vulnerable to interference, impulse, crosstalk!
- Greater repeater spacing
  - Often 10’s of kilometers
- Hard to tap

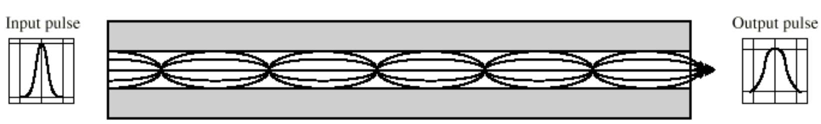
Optical Fiber Transmission Modes

Rays at shallow angles reflect; multiple propagation path spreads signal out over time



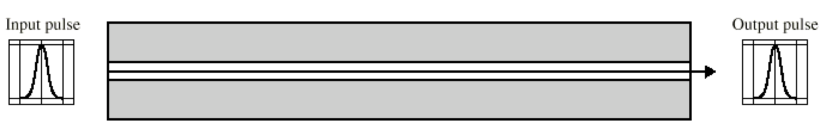
(a) Step-index multimode

Gradient refraction in core allows light to curve helically, more coherent at end



(b) Graded-index multimode

Shrink core to allow only a single angle or mode, light reflect in only one pattern



(c) Single mode

Wireless or Radiated Transmission

- Unguided media
- Transmission and reception via antenna
  - Desirable to make antenna one-quarter or one-half the wavelength
- Directional
  - Focused beam
  - Careful alignment required
- Omnidirectional
  - Signal spreads in all directions
  - Can be received by many antennas

Frequencies

- 2GHz to 40GHz
  - Microwave
  - Highly directional
  - Point to point
  - Satellite
- 30MHz to 1GHz
  - Omnidirectional
  - Broadcast radio
- 3×10^{11} to 2×10^{14}
  - Infrared
  - Local
- Higher frequencies → Higher data rates

Terrestrial Microwave

- Typically parabolic dish, focused beam, line of sight
- Max distance between antenna:

  d=7.14 * Sqrt(hK) ; K=4/3,
  ; h=antenna ht in meters
  ; d=distance in km

  so two 1 meter antenna can be 7.14*Sqrt(4/3)=8.2 km apart
- Applications
  – Long haul telecommunications, television. May need repeaters
  – Short range for BN or closed-circuit TV

Terrestrial Microwave

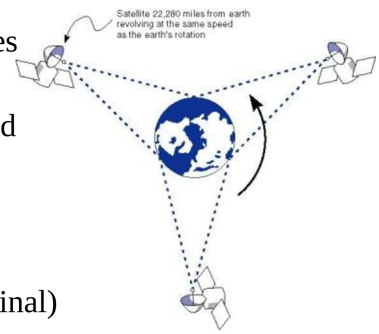
- Data rate increases with frequency
  – 2 Ghz Band → 7 Mhz Bandwidth → 12 Mbps
  – 6 Ghz Band → 30 Mhz Bandwidth → 90 Mbps
  – 11 Ghz Band → 40 Mhz Bandwidth → 135 Mbps
  – 18 Ghz Band → 220 Mhz Bandwidth → 274 Mbps
- Attenuation

$$Loss = 10\log\left(\frac{4\pi d}{\lambda}\right)^2 dB$$

  – Loss varies with the square of the distance
  – TP/Coax: loss varies with log of distance / linear in dB
  – Therefore, we don’t need as many repeaters with microwave
- Interference and Raindrop Attenuation
  – Frequency bands strictly regulated
  – Use lower frequency to avoid raindrop problem

Satellite Microwave

- Satellite is relay station
- Satellite receives on one frequency, amplifies or repeats signal and transmits on another frequency/frequencies (transponder channels)
- Typically geo-stationary orbit
  - Height of 35,784km or 22,236 miles
  - 4 degree spacing in 4/6Ghz Band
  - 3 degree spacing in 12/14 Ghz Band
- Applications
  - TV, telephone
  - Private business networks
  - VSAT (Very Small Aperture Terminal)
    - Large corp. with distributed sites
    - Small receiver to Ku-band satellite to Big earth hub
    - Used by RCA in late 1994 for Direct Broadcast System



Satellite Transmission Characteristics

- Optimum Frequency Range 1-10Ghz
  - Below 1Ghz, natural noise. Above 10Ghz, attenuation from the atmosphere
  - Most applications use the 5.925-6.425 Ghz range uplink, 4.2-4.7Ghz range downlink (4/6 Ghz Band)
- Propagation delay
  - 35784000m / 3.0 * 10^8 m/s → 0.12 seconds one way
  - About quarter second propagation delay round trip, noticeable for phone conversations, problem for two-way communications
    - Error /flow control?
    - Low orbit satellites a solution? (Iridium, Tachyon)

Broadcast Radio

- 30Mhz to 2 Ghz
- Omnidirectional
  - Use loop or wire antenna instead of dish
- Applications
  - Range covers FM radio, UHF and VHF television
  - 802.11b operates in the 2.4Ghz ISM band
- Due to lower frequencies than microwave, less problems with attenuation
- Same equation for antenna distance, attenuation as microwave
- Drawbacks
  - Suffers from multipath interference, Reflections
  - Possible security concerns

Infrared

- Modulate noncoherent infrared light
- Line of sight (or reflection)
- Blocked by walls
- Problems
  - Short range, usually 50-75 feet maximum
  - Low speed, 1-4 Mbps
- e.g. TV remote control, IRD port
  - For networks, not generally used due to the need for direct line-of-sight; was used to connect hubs

Media Selection

Guided Media

Media	Network Type	Cost	Transmission Distance	Security	Error Rates	Speed
Twisted Pair	LAN	Low	Short	Good	Low	Low-high
Coaxial Cable	LAN	Mod.	Short-Mod	Good	Low	Low-high
Fiber Optics	any	High	Mod.-long	V. Good	V.Low	High-V.High

Radiated Media

Media	Network Type	Cost	Transmission Distance	Security	Error Rates	Speed
Radio	LAN	Low	Short	Poor	Mod	Low
Infrared	LAN, BN	Low	Short	Poor	Mod	Low
Microwave	WAN	Mod	Long	Poor	Low-Mod	Mod
Satellite	WAN	Mod	Long	Poor	Low-Mod	Mod

Carriers and Modulation

First, review of digital transmission
of digital data

Baseband Transmission

Digital transmission is the transmission of electrical pulses. Digital information is binary in nature in that it has only two possible states 1 or 0. Sequences of bits encode data (e.g., text characters).

Digital signals are commonly referred to as <u>baseband signals</u>.

In order to successfully send and receive a message, both the sender and receiver have to agree how often the sender can transmit data (<u>data rate</u>).

<u>Data rate</u> often called <u>bandwidth</u> – but there is a different definition of bandwidth referring to the frequency range of a signal!

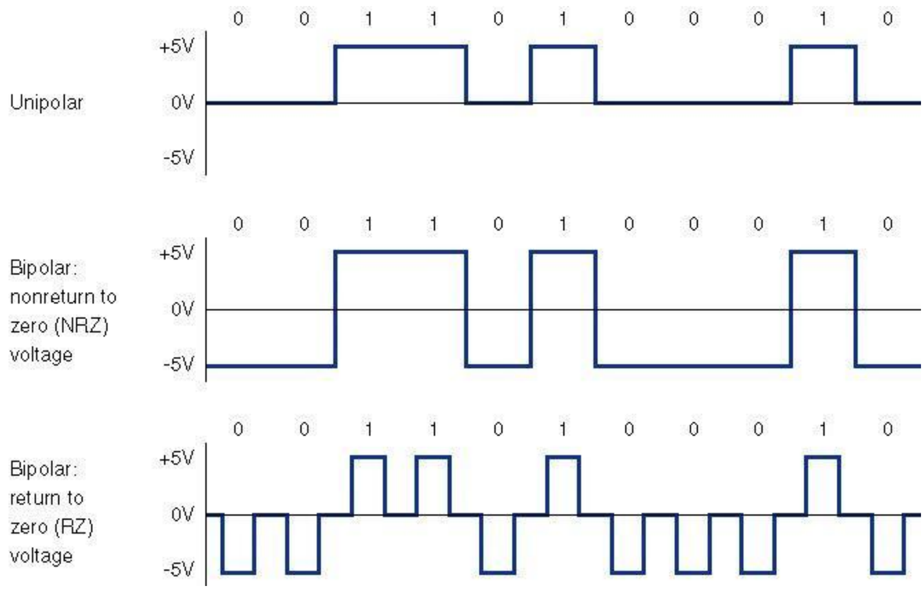
Baseband Transmission

With unipolar signaling techniques, the voltage is always positive or negative (like a dc current).

In bipolar signaling, the 1's and 0's vary from a plus voltage to a minus voltage (like an ac current).

In general, bipolar signaling experiences fewer errors than unipolar signaling because the signals are more distinct.

Baseband Transmission



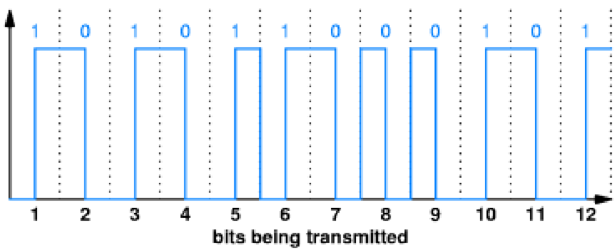
Baseband Transmission

Manchester encoding is a special type of unipolar signaling in which the signal is changed from a high to low (0) or low to high (1) in the middle of the signal.

- More reliable detection of transition rather than level
  - consider perhaps some constant amount of dc noise, transitions still detectable but dc component could throw off NRZ-L scheme
  - Transitions still detectable even if polarity reversed

Manchester encoding is commonly used in local area networks (ethernet, token ring).

Manchester Encoding

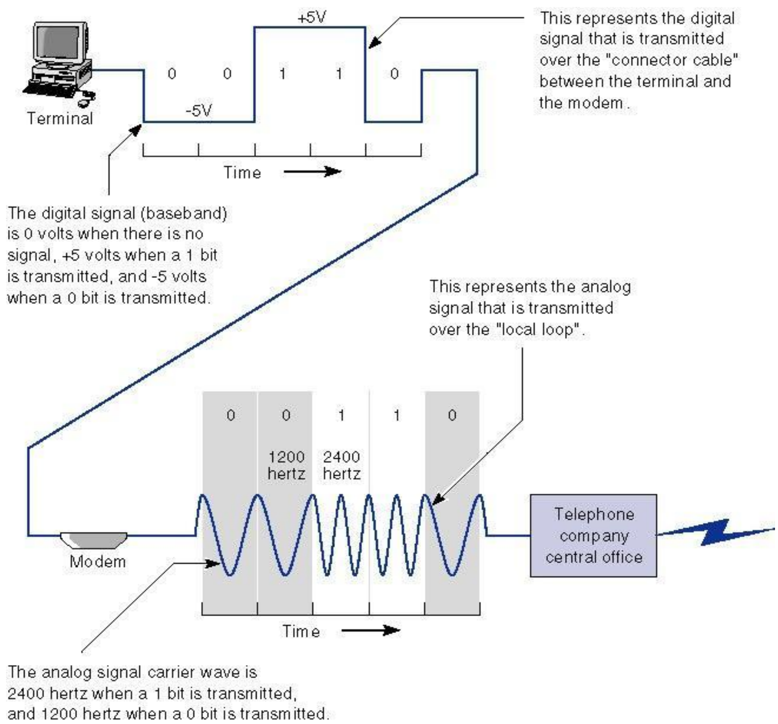


ANALOG TRANSMISSION OF DIGITAL DATA

Analog Transmission occurs when the signal sent over the transmission media continuously varies from one state to another in a wave-like pattern.

e.g. telephone networks, originally built for human speech rather than data.

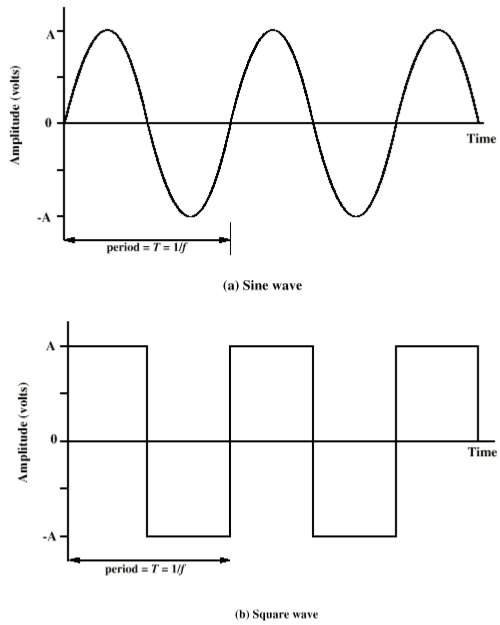
Advantage for long distance communications: much less attenuation for analog carrier than digital



Digital Data to Analog Transmission

Before we get further into Analog to Digital, we need to understand various characteristics of analog transmission.

Periodic Signals

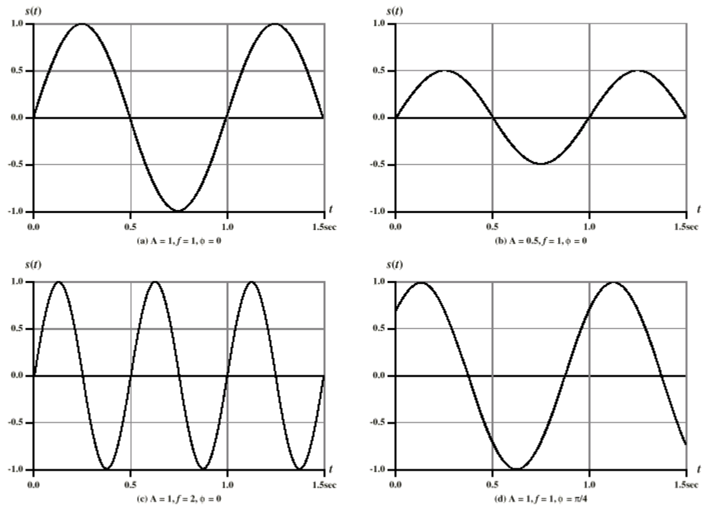


Sine Wave

- Peak Amplitude (A)
  - maximum strength of signal
  - volts
- Frequency (f)
  - Rate of change of signal
  - Hertz (Hz) or cycles per second
  - Period = time for one repetition (T)
  - T = 1/f
- Phase (ϕ)
  - Relative position in time, from 0-2*pi
- General Sine wave

$$s(t) = A \sin(2\pi f t + \phi)$$

Varying Sine Waves



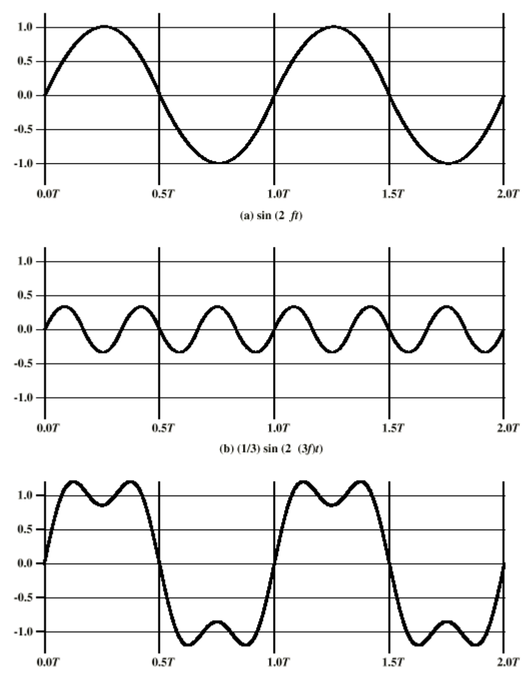
Wavelength

- Distance occupied by one cycle
- Distance between two points of corresponding phase in two consecutive cycles
- λ = Wavelength
- Assuming signal velocity *v*
  - $\lambda = vT$
  - $\lambda f = v$
  - c = $3*10^8$ ms^{-1} (speed of light in free space)

Frequency Domain Concepts

- Signal usually made up of many frequencies
- Components are sine (or cosine) waves
- Can be shown (Fourier analysis) that any continuous signal is made up of component sine waves
- Can plot frequency domain functions

Addition of Frequency Components



Notes:

2nd freq a multiple of 1st
1st called fundamental freq
Others called harmonics

Period of combined =
Period of the fundamental

Fundamental = carrier freq

Frequency Domain

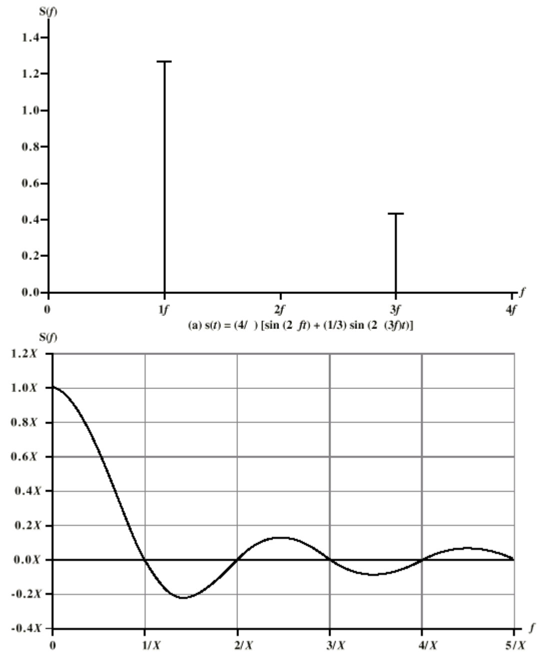
Discrete Freq Rep:

$s(t) = 4/\pi[\sin(2\pi ft) + 1/3\sin(2\pi(3f)t)]$

Any continuous signal can be represented as the sum of sine waves! (May need an infinite number..)

Discrete signals result in Continuous, Infinite Frequency Rep:

s(t)=1 from –X/2 to X/2



(a) s(t) = (4/) [sin (2 ft) + (1/3) sin (2 (3f)t)]

(b) s(t) = 1 –X/2 t X/2

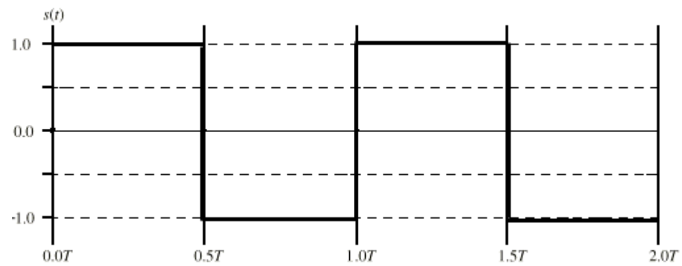
Data Rate and Bandwidth

- Any transmission system has a limited band of frequencies
- This limits the data rate that can be carried

- Spectrum
  - range of frequencies contained in signal
- Absolute bandwidth
  - width of spectrum
- Effective bandwidth
  - Often just *bandwidth*
  - Narrow band of frequencies containing most of the energy

Example of Data Rate/Bandwidth

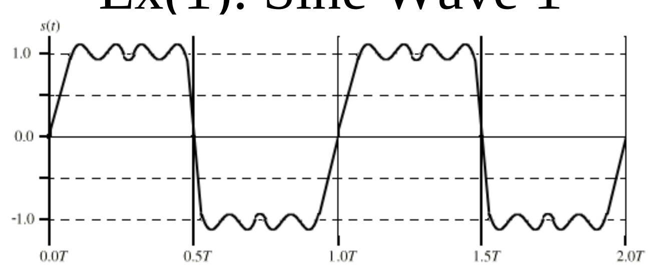
Want to transmit:



Let's say that f=1Mhz or 10^6 cycles/second, so T= 1microsecond

Let's approximate the square wave with a few sine waves:

Ex(1): Sine Wave 1

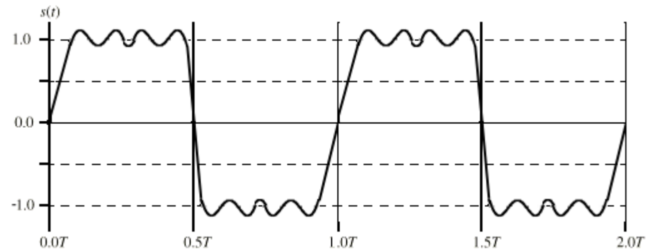


$s(t) = 4/\pi[\sin(2\pi ft) + 1/3\sin(2\pi(3f)t) + (1/5)\sin(2\pi(5f)t)]$

Bandwidth=5f-f =4f
If f=1Mhz, then the bandwidth = 4Mhz

T=1 microsecond; we can send two bits per microsecond so the data rate = 2 * 10^6 = 2Mbps

Ex(2): Sine Wave 1, Higher freq



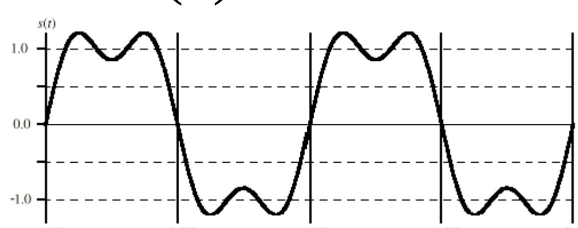
$$s(t) = 4/\pi[\sin(2\pi ft) + 1/3\sin(2\pi(3f)t) + (1/5)\sin(2\pi(5f)t)]$$

Bandwidth=5f-f =4f
If f=2Mhz, then the bandwidth = 8Mhz

T=0.5 microsecond; we can send two bits per 0.5 microseconds or 4 bits per microsecond, so the data rate = 4 * 10^6 = 4Mbps

Double the bandwidth, double the data rate!

Ex(3): Sine Wave 2



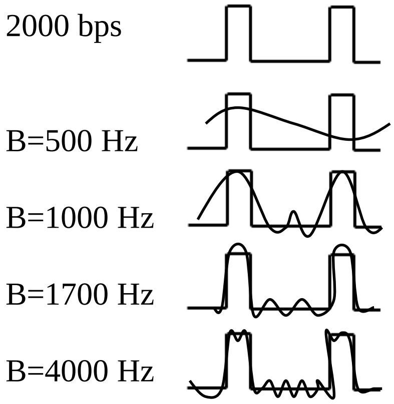
$$s(t) = 4/\pi[\sin(2\pi ft) + 1/3\sin(2\pi(3f)t)]$$

Bandwidth=3f-f =2f
If f=2Mhz, then the bandwidth = 4Mhz

T=0.5 microsecond; we can send two bits per 0.5 microseconds or 4 bits per microsecond, so the data rate = 4 * 10^6 = 4Mbps

Still possible to get 4Mbps with the “lower” bandwidth, but our receiver must be able to discriminate from more distortion!

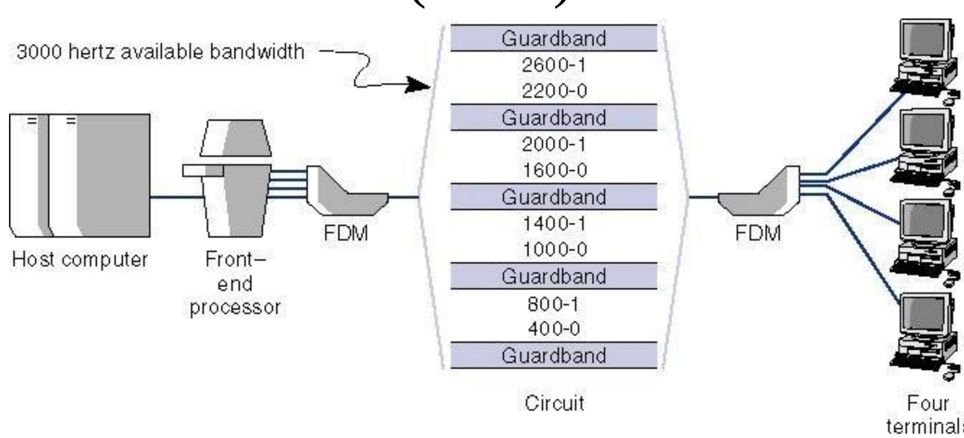
Bandwidth / Representation



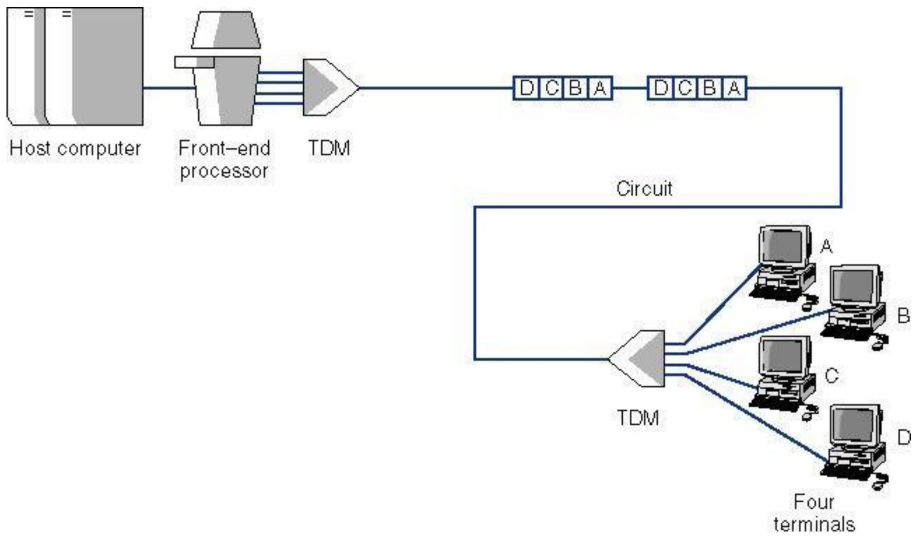
Increasing bandwidth improves the representation of the data signal.

500Hz too low to reproduce the signal. Want to maximize the capacity of the available bandwidth.

Frequency Division Multiplexing (FDM)



Time Division Multiplexing (TDM)



Transmission Impairments

- Signal received may differ from signal transmitted
- Analog - degradation of signal quality
- Digital - bit errors
- Caused by
  - Attenuation and attenuation distortion
  - Delay distortion
  - Noise

Attenuation

- Signal strength falls off with distance
- Depends on medium
- Received signal strength:
  - must be enough to be detected
  - must be sufficiently higher than noise to be received without error
- Attenuation is an increasing function of frequency; higher frequencies suffer from more attenuation. Can distort the signal.

- Solution: Equalization. Boost higher frequency components.

Delay Distortion

- Only in guided media
- Propagation velocity varies with frequency
  - Velocity highest near center frequency
  - Results in phase shift at different frequencies
  - “Overlapping” bits

- Solution: Equalization

Noise (1)

- Additional signals inserted between transmitter and receiver
- Thermal
  - Due to thermal agitation of electrons
  - Uniformly distributed
  - White noise
- Intermodulation
  - Signals that are the sum and difference of original frequencies sharing a medium

Noise (2)

- Crosstalk
  - A signal from one line is picked up by another
- Impulse
  - Irregular pulses or spikes
  - e.g. External electromagnetic interference
  - Short duration
  - High amplitude

What Causes Errors?

Summary of Errors and Noise:

Source of Error	What Causes It	How to Prevent It.
Line Outages	Storms, Accidents	
White Noise	Movement of electrons	Increase signal strength
Impulse Noise	Sudden increases in electricity (e.g. lightning)	Shield or move the wires
Cross-Talk	Multiplexer guardbands too small, or wires too close together	Increase the guardbands, or move or shield the wires
Echo	Poor connections	Fix the connections, or tune equipment
Attenuation	Graduate decrease in signal over distance	Use repeaters or amps
Intermodulation Noise	Signals from several circuits combine	Move or shield the wires
Jitter	Analog signals change phase	Tune equipment
Harmonic Distortion	Amplifier changes phase	Tune equipment

Error Prevention

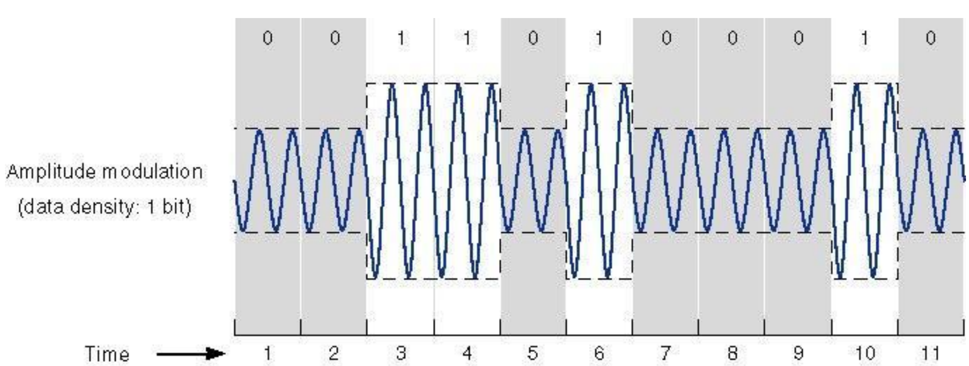
There are many ways to prevent errors:

- Shielding (adding insulation)
- Moving cables away from noise sources
- Changing multiplexing type (FDM$\rightarrow$TDM)
- Tuning transmission equipment and improving connection quality
- Using amplifiers and repeaters
- Equalization

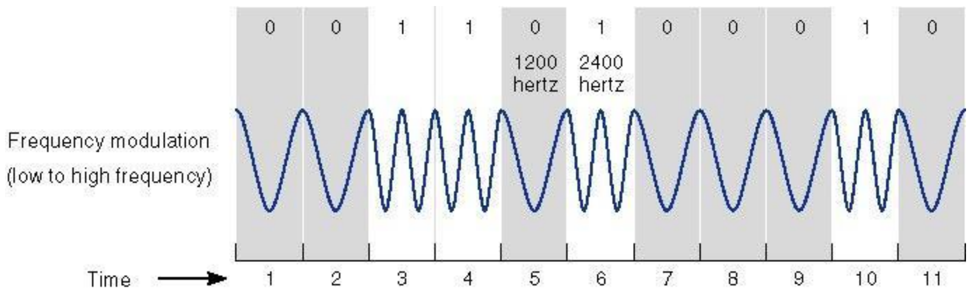
Modulation - Digital Data, Analog Signal

- Public telephone system
  - 300Hz to 3400Hz
    - Guardband from 0-300, 3400-4000Hz
  - Use modem (modulator-demodulator)
- Amplitude shift keying (ASK)
- Frequency shift keying (FSK)
- Phase shift keying (PSK)

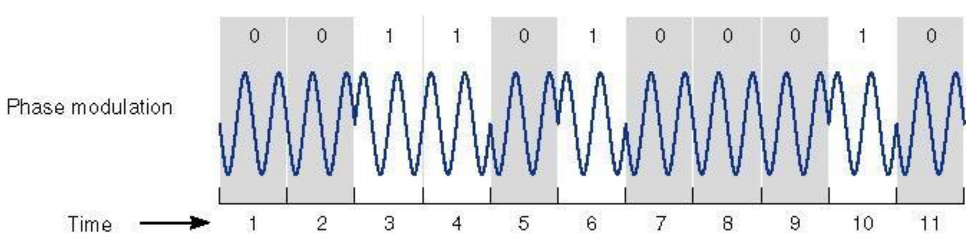
Amplitude Modulation and ASK



Frequency Modulation and FSK



Phase Modulation and PSK



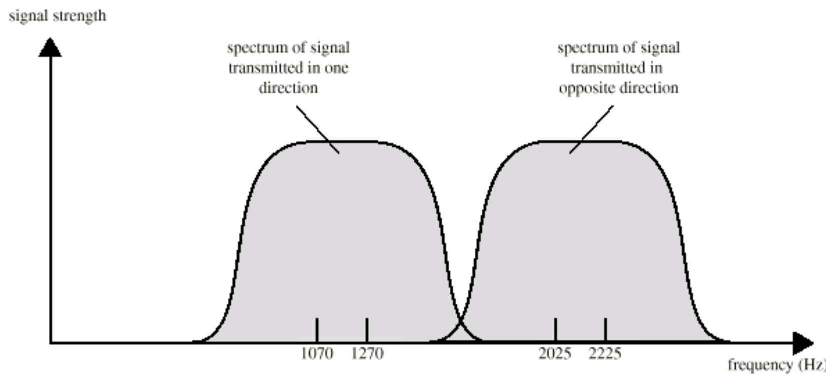
Amplitude Shift Keying

- Values represented by different amplitudes of carrier
- Usually, one amplitude is zero
  - i.e. presence and absence of carrier is used
- Susceptible to sudden gain changes
- Inefficient
- Typically used up to 1200bps on voice grade lines
- Used over optical fiber

Frequency Shift Keying

- Values represented by different frequencies (near carrier)
- Less susceptible to error than ASK
- Typically used up to 1200bps on voice grade lines
- High frequency radio
- Even higher frequency on LANs using co-ax

FSK on Voice Grade Line



Bell Systems 108 modem

Figure 5.8 Full-Duplex FSK Transmission on a Voice-Grade Line

Phase Shift Keying

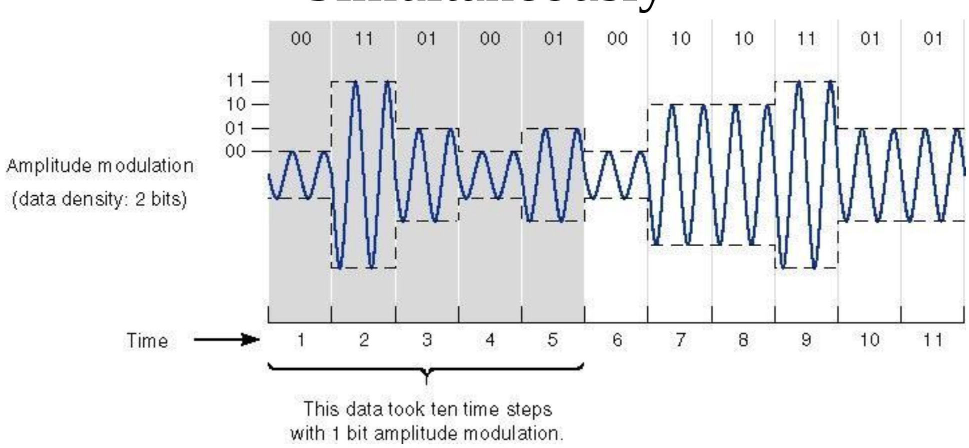
- Phase of carrier signal is shifted to represent data
- Differential PSK
  - Phase shifted relative to previous transmission rather than some reference signal

Sending Multiple Bits Simultaneously

Each of the three modulation techniques can be refined to send more than one bit at a time. It is possible to send two bits on one wave by defining four different amplitudes.

This technique could be further refined to send three bits at the same time by defining 8 different amplitude levels or four bits by defining 16, etc. The same approach can be used for frequency and phase modulation.

Sending Multiple Bits Simultaneously

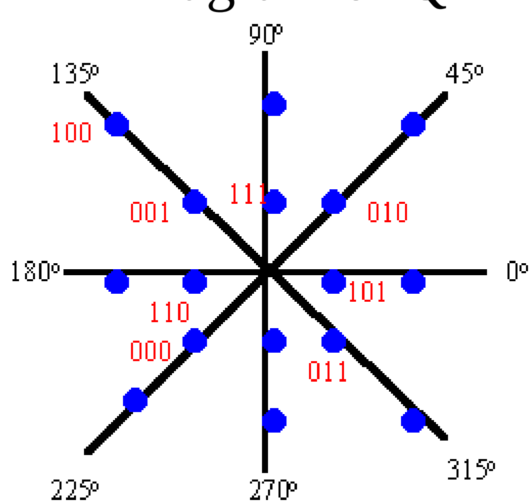


Sending Multiple Bits Simultaneously

In practice, the maximum number of bits that can be sent with any one of these techniques is about five bits. The solution is to combine modulation techniques.

One popular technique is quadrature amplitude modulation (QAM) involves splitting the signal into eight different phases, and two different amplitude for a total of 16 different possible values, giving us lg(16) or 4 bits per value.

2-D Diagram of QAM



Sending Multiple Bits Simultaneously

Trellis coded modulation (TCM) is an enhancement of QAM that combines phase modulation and amplitude modulation.

The problem with high speed modulation techniques such as TCM is that they are more sensitive to imperfections in the communications circuit.

Bits Rate Versus Baud Rate Versus Symbol Rate

The terms bit rate (the number of bits per second) and baud rate are used incorrectly much of the time. They are not the same.

A bit is a unit of information, a baud is a unit of signaling speed, the number of times a signal on a communications circuit changes. ITU-T now recommends the term baud rate be replaced by the term symbol rate.

Bits Rate Versus Baud Rate Versus Symbol Rate

The bit rate and the symbol rate (or baud rate) are the same only when one bit is sent on each symbol. If we use QAM or TCM, the bit rate would be several times the baud rate.

Typically we use compression techniques on top of the modulation technique

Analog Data, Digital Signal

- Digitization
  - Conversion of analog data into digital data
  - Digital data can then be transmitted using digital signaling (e.g. Manchester)
  - Or, digital data can then be converted to analog signal
  - Analog to digital conversion done using a codec (coder/decoder)
  - Two techniques to convert analog to digital
    - Pulse code modulation / Pulse amplitude modulation
    - Delta modulation

Pulse Amplitude Modulation

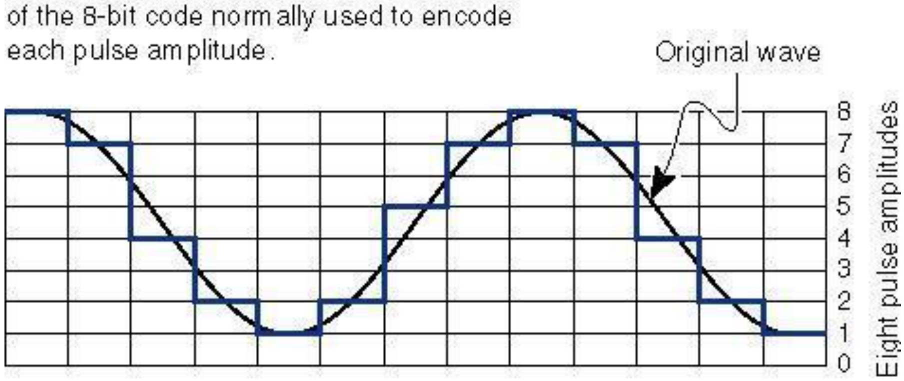
Analog voice data must be translated into a series of binary digits before they can be transmitted.

With Pulse Amplitude Modulation, the amplitude of the sound wave is sampled at regular intervals and translated into a binary number.

The difference between the original analog signal and the translated digital signal is called quantizing error.

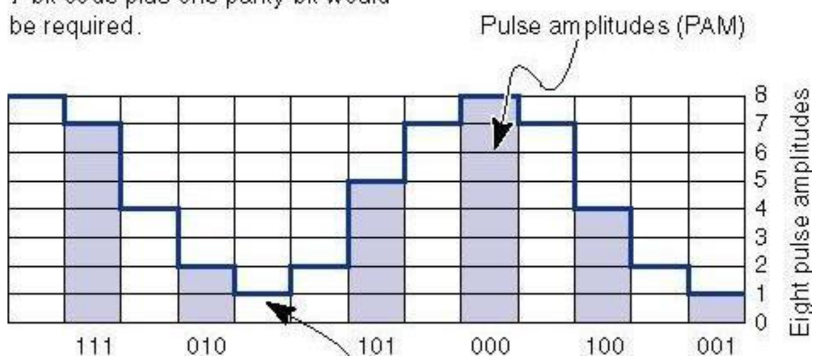
Pulse Amplitude Modulation

The signal (original wave) is quantized into 128 pulse amplitudes (PAM). In this example we have used only eight pulse amplitudes for simplicity. These eight amplitudes can be depicted by using only a 3-bit code instead of the 8-bit code normally used to encode each pulse amplitude.

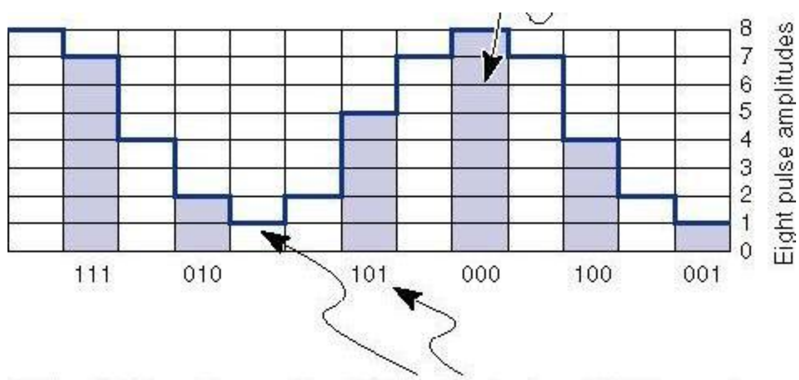


Pulse Amplitude Modulation

After quantizing, samples are taken at specific points to produce amplitude modulated pulses. These pulses are then coded. Because we used eight pulse levels, we only need three binary positions to code each pulse.[1] If we had used 128 pulse amplitudes, then a 7-bit code plus one parity bit would be required.



Pulse Amplitude Modulation



[1] 001 = PAM level 1
010 = PAM level 2
011 = PAM level 3
100 = PAM level 4
101 = PAM level 5
110 = PAM level 6
111 = PAM level 7
000 = PAM level 8

For digitizing a voice signal, 8,000 samples per second are taken. These 8,000 samples are then transmitted as a serial stream of 0s and 1s. In our case 8,000 samples times 3 bits per sample would require a 24,000 bps transmission rate. In reality, 8 bits per sample times 8,000 samples requires a 64,000 bps transmission rate.

Pulse Amplitude Modulation

For standard voice grade circuits, the sampling of 3300 Hz at an average of 2 samples/second would result in a sample rate of 6600 times per second.

There are two ways to reduce quantizing error and improve the quality of the PAM signal.

- Increase the number of amplitude levels
- Sample more frequently (oversampling).

Pulse Code Modulation

Pulse Code Modulation is the most commonly used technique in the PAM family and uses a sampling rate of 8000 samples per second.

Each sample is an 8 bit sample resulting in a digital rate of 64,000 bps (8 x 8000).

Sampling Theorem: If a signal is sampled at a rate higher than twice the highest signal frequency, then the samples contain all the information of the original signal.

E.g.: For voice capped at 4Khz, can sample at 8000 times per second to regenerate the original signal.

Performance of A/D techniques

- Good voice reproduction via PCM
  - PCM - 128 levels (7 bit)
  - Voice bandwidth 4khz
  - Should be 8000 x 7 = 56kbps for PCM
    - (Actually 8000 x 8 with control bit)
- Data compression can improve on this
  - e.g. Interframe coding techniques for video
- Why digital?
  - Repeaters instead of amplifiers; don’t amplify noise
  - Allows efficient and flexible Time Division Multiplexing over Frequency Division Multiplexing
  - Conversion to digital allows use of more efficient digital switching techniques