Physical Layer

CSC 343·643

Wake Forest University
Department of Computer Science

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Physical Layer

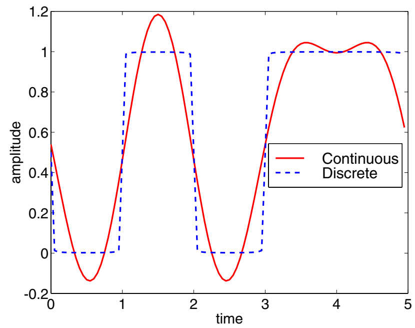
Concerned with moving information in the form of electromagnetic (EM) signals across a transmission medium

- Information - Data, voice, video, etc...
- Sender (transmitter)
  - Converts bits to electromagnetic (EM) waves (digital $\Rightarrow$ analog)
- Receiver
  - Converts EM to bits (analog $\Rightarrow$ digital)
- Communication occurs over some medium
  - Magnetic media
  - Twisted pair
  - Coaxial cable
  - Fiber optics

Analog and Digital

Information can be represented in *analog* or *digital* form

- Analog - Continuous representation, signal intensity changes in a smooth fashion over time
- Digital - Discrete representation, signal intensity maintains a constant level over a period of time, then changes to another level.



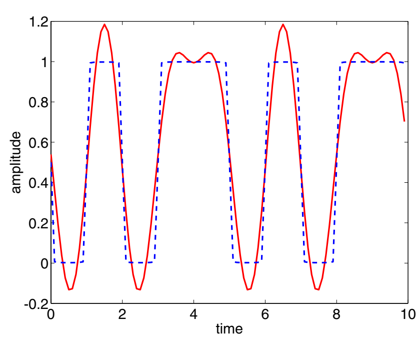
Periodic Waves

Simplest sort of signal (analog or digital) is the *periodic* signal

- Periodic - Pattern repeats over time

$$s(t+T) = s(t), \quad -\infty < t < +\infty$$

T is the *period* of the signal (smallest value solving the equation)

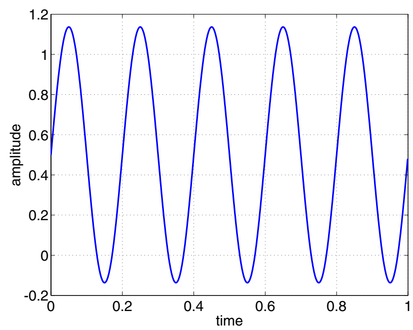


Sine Waves

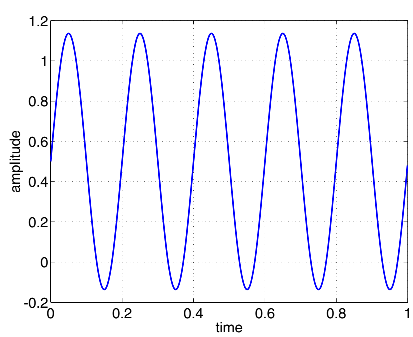
- Sine wave is the most fundamental form of a periodic analog signal
- Three important parameters
  - peak amplitude (A), frequency (f), phase (ϕ)

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

- Amplitude - Height of the signal, for electricity measured in volts



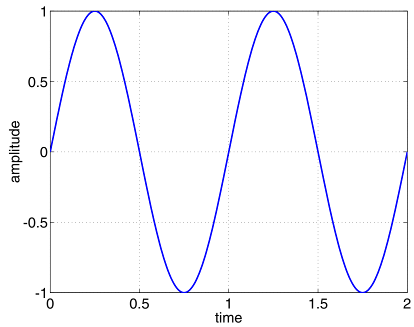
- Frequency - The rate of change over time (number of cycles per second).
  - Period (T) is the time a signal needs to complete a cycle
  - Frequency is the number of periods in a second, $f = \frac{1}{T}$
  - Frequency is expressed in hertz (Hz), where MHz $= 10^6$Hz



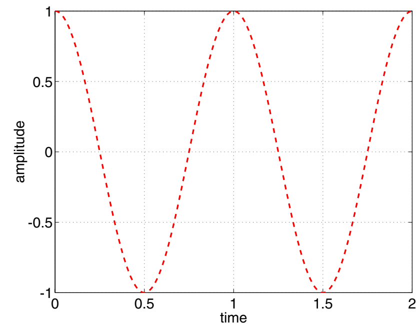
What is the frequency and period of the wave?

– *Frequency extremes* - If a signal does not change over time it has ______ frequency (*dc component*). If a frequency changes instantaneously its frequency is ______.

- Phase - Position of the wave form relative to time zero
  – Measured in radians (360 degrees $= 2\pi$ radians)



$sin(2\pi t)$

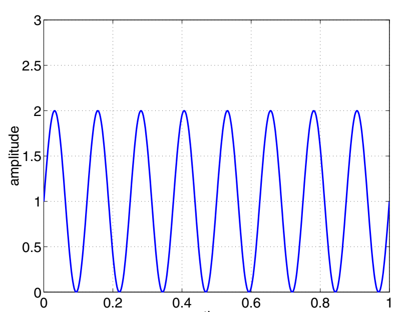


$sin(2\pi t + \frac{\pi}{2}) =$ ______

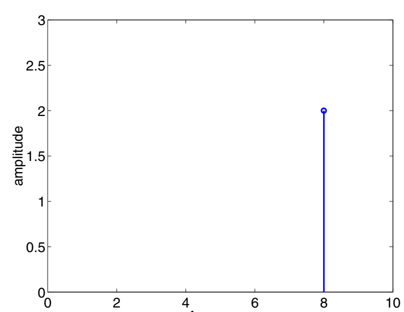
Time and Frequency Domains

We have been displaying sine waves using a *time-domain plot*.

- Time-domain plot - Shows changes in amplitude with respect to time (frequency and phase are not explicitly measured)
- Frequency-domain plot - Shows the maximum amplitude with respect to frequency

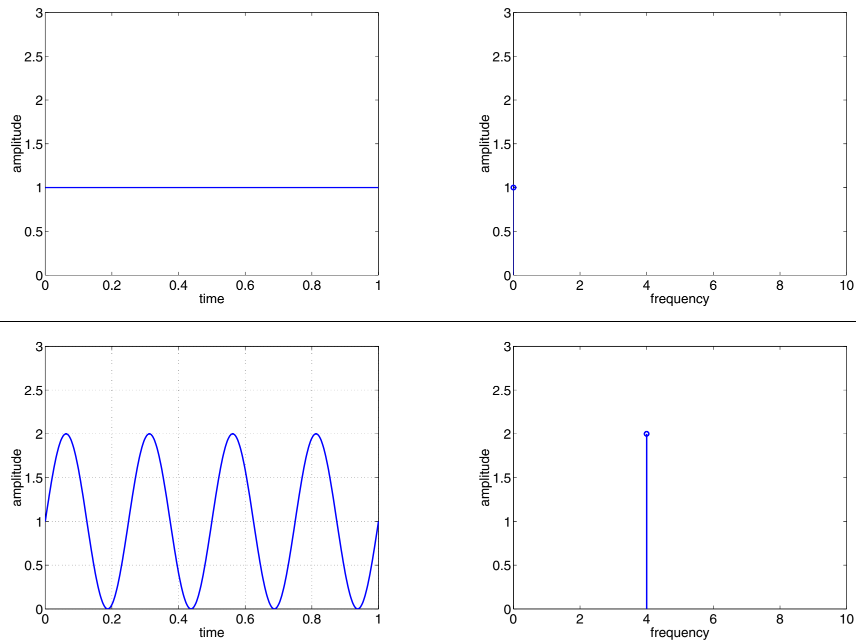


time-domain



frequency-domain

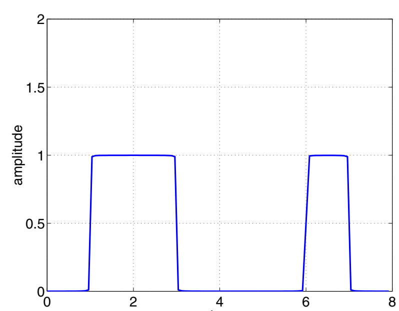
time-domain | frequency-domain



Composite Signals

We have focused on simple periodic waves. What about periodic signals that are not (do not look like) sine waves?

- Want to represent more complex waves
  - Consider transmitting the bit pattern [01100010] ASCII `‘b’`



- Can we represent this (discrete) wave continuously? Using sine waves? (digital $\Rightarrow$ analog)

Fourier Analysis

In the 19th Century, Jean-Baptiste Fourier proved that any reasonably behaved periodic function $g(t)$, with period T, can be constructed by summing a number of sines and cosines.

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

Where $f = \frac{1}{T}$ is the fundamental frequency and, a_n and b_n are the sine and cosine amplitudes of the nth terms (harmonics).

$$c = \frac{2}{T}\int_0^T g(t)dt \tag{2}$$

$$a_n = \frac{2}{T}\int_0^T g(t)\sin(2\pi n f t)dt \tag{3}$$

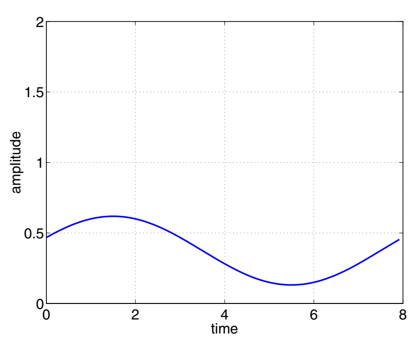
$$b_n = \frac{2}{T}\int_0^T g(t)\cos(2\pi n f t)dt \tag{4}$$

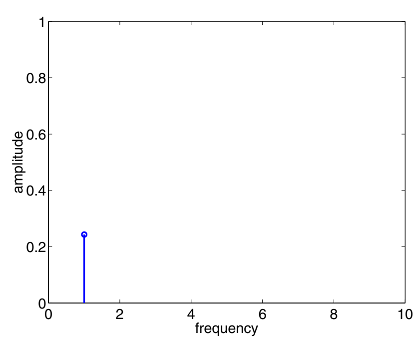
The Fourier analysis of the signal [01100010] yields the coefficients

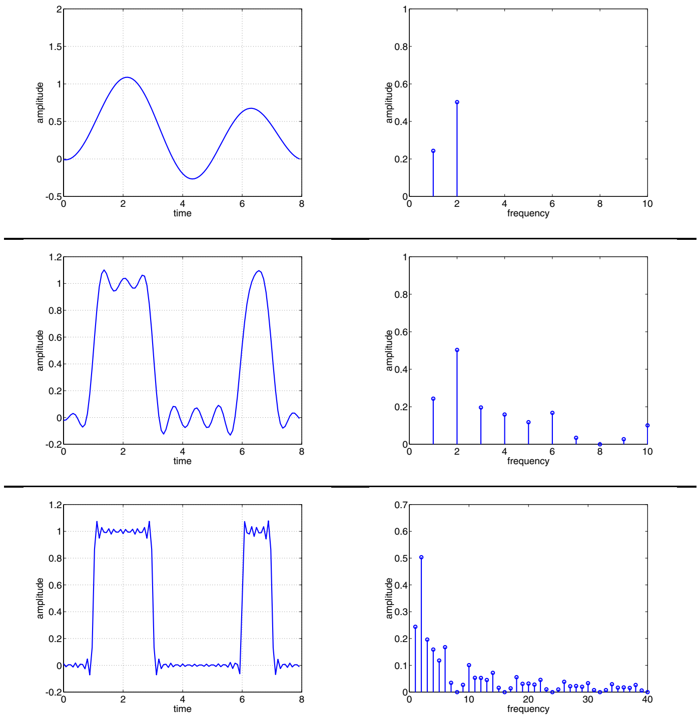
$$c = \frac{3}{4}$$

$$a_n = \frac{1}{\pi n}\left[\cos\left(\frac{\pi n}{4}\right) - \cos\left(\frac{3\pi n}{4}\right) + \cos\left(\frac{6\pi n}{4}\right) - \cos\left(\frac{7\pi n}{4}\right)\right]$$

$$b_n = \frac{1}{\pi n}\left[\sin\left(\frac{3\pi n}{4}\right) - \sin\left(\frac{\pi n}{4}\right) + \sin\left(\frac{7\pi n}{4}\right) - \sin\left(\frac{6\pi n}{4}\right)\right]$$







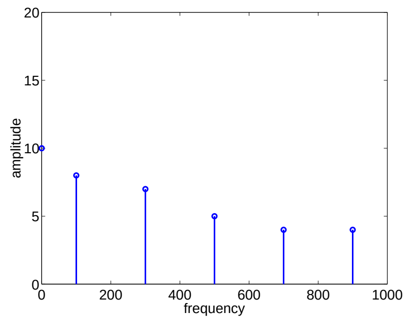
Fourier Analysis

- More harmonics (terms) the better the representation
- The (binary) square wave represents an infinite number of terms
  - Only a finite number of terms are available
  - How many are sufficient?
- Signal Loss/Distortion
  - No transmission medium can transmit signals without losing some power
  - If all the Fourier components diminished equally, then the resulting wave would reduce only in amplitude
  - However, Fourier components diminish at different rates $\Rightarrow$ distorted signal

Frequency Spectrum and Bandwidth

- Frequency Spectrum - The collection of all the component frequencies of a signal
- Bandwidth - The width of the frequency spectrum

If a signal is composed of five sine waves with frequencies 0, 100, 300, 500, 700, and 900 Hz, what is the bandwidth? Draw the frequency spectrum.



If the binary square wave is used, what is its bandwidth?

Review

Digital and Analog Signals

- Analog (continuous), digital (finite number of values)
- Periodic waves repeat over time, amount of time to complete a cycle is the ______
- Frequency is ____________________________
- ________ is the most fundamental periodic wave
  - Can control shape via A, f, and ϕ
- More *complex* wave forms are possible
  - Any periodic wave can be represented via a sum of sine waves (Fourier series)
  - Fundamental frequency $+$ the harmonics
  - The more harmonics, the better the representation

Baud and Bandwidth

Assume we wish to transmit a binary signal

- The time required to transmit characters depends on
  - Encoding method (how bits are represented)
  - Signal speed (number of times per second the signal changes value)
- Modulation rate - Rate at which the signal changes
- Baud - Number of signal changes per second.
  - Baud does not necessarily correspond to the bit rate (bps)
  - Bit-rate/baud-rate relationship depends on the encoding technique

Bandwidth and Bit Rate

- Given a bit rate b (bps), the time required to send the ASCII character [01100010] is $\frac{8}{b}$
- Assume the character repeats over and over (periodic wave)
- The period (T) is $\frac{8}{b} \Rightarrow f = \frac{b}{8}$
- Assume we wish to transmit the character over a phone-line
  - A *voice-grade* phone line cuts any frequency above 3000Hz
  - If we wanted to transmit at 300 bps, what is the frequency of the first harmonic?

$$f = \frac{b}{8} = \frac{300}{8} = 37.5$$

  - How many harmonics are allowed?

$$\frac{3000\text{Hz}}{37.5\text{Hz}} = 80$$

Remember, *harmonics* are multiples of the *fundamental* frequency

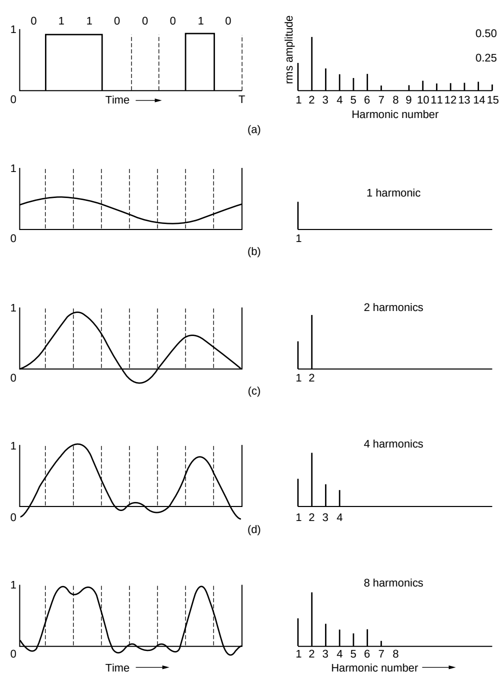
– If we transmit at 19200 bps, what is the first harmonic and how many harmonics are possible?

$$f = \frac{b}{8} = \frac{19200}{8} = 2400$$

Number of harmonics allowed

$$\frac{3000\text{Hz}}{2400\text{Hz}} = 1$$

- NB - The more harmonics present the better the data representation



Bandwidth and Bit Rate

- Now assume we wish to transmit the sequence [01010101]
- Assume the character is repeated over and over
- Given a bit rate b (bps), the period of the bit sequence is ______
- The frequency (f) is ______
- Assume we wish to transmit the sequence over a phone-line
  - A *voice-grade* phone line cuts any frequency above 3000Hz
  - If we wanted to transmit at 300 bps, what is the frequency of the first harmonic?

$$f = \frac{b}{2} = \frac{300}{2} = 150$$

  - How many harmonics are allowed?

$$\frac{3000\text{Hz}}{150\text{Hz}} = 20$$

- NB The sequence [01010101...] generates the highest frequency
  - Has the shortest period $\Rightarrow$ the highest frequency (changes the fastest)
  - Often referred to as the **worst-case sequence**

A binary signal of rate 500bps is to be transmitted over a communication channel. What is the minimum bandwidth requirement for the fundamental and third harmonic?

Maximum Data Rate for a Channel

Nyquist proved that if an arbitrary signal is passed through a low pass filter with bandwidth H, then the filtered signal can be reconstructed by making $2H$ samples per second

- The Nyquist theorem is

$$m = 2H \log_2(v)$$

  Where m is the maximum data rate, H is the bandwidth, and v is the number of values the signal represents

  - What is the maximum data rate of a 3kHz channel sending binary data?

$$m = 2 \cdot 3000 \cdot \log_2(2) = 6000bps$$

  - This equation assumes **no** noise in the channel

If the signal only represents one bit (two values) the Nyquist theorem is

$$m = 2H$$

Is this correct? Have we seen this before?

Maximum Data Rate for a Channel with Noise

If *noise* (thermal) is present, the data rate is much lower

- Noise is measured as the ratio of signal power to noise power, called the *signal-to-noise ratio*
- If signal power is s and noise power is n, the ratio is $\frac{s}{n}$; however *decibels* are used measure power instead
- Decibel is a measure in the difference between two powers

$$n_{dB} = 10\log_{10}\left(\frac{s}{n}\right)$$

- Given the noise measurement, the maximum data rate achievable is

$$m = H\log_2\left(1+\frac{s}{n}\right)$$

  The preceding is *Shannon's theorem*

What is the largest bit rate possible given a telephone line (3000Hz) with n_{dB} of 30?

$$30\text{dB} = 10\log_{10}\left(\frac{s}{n}\right) \Rightarrow \frac{s}{n} = 1000$$
$$m = 3000\log_2(1+1000) = 30000\text{bps}$$

This is really an *upper bound*, it does not consider,

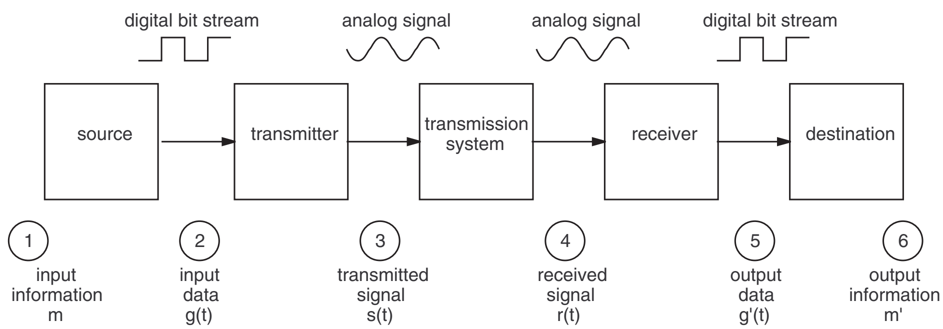
- Attenuation, crosstalk, and impulse noise

What is thermal noise?

- "Thermal agitation of electrons in a conductor"
- Present in all electronic devices and transmission media (cannot be eliminated)
- Uniformly distributed across all frequencies; therefore, it is referred to as ______ noise.

Data Encoding

- To date we made a distinction between digital and analog signals
  - Signals in one form translated into the other (items 2 - 5)
- Given analog/digital data and analog/digital signals we are interested in data $\Rightarrow$ signal translations (encoding, how data is represented, items 1 - 2)



Digital Data and Digital Signals

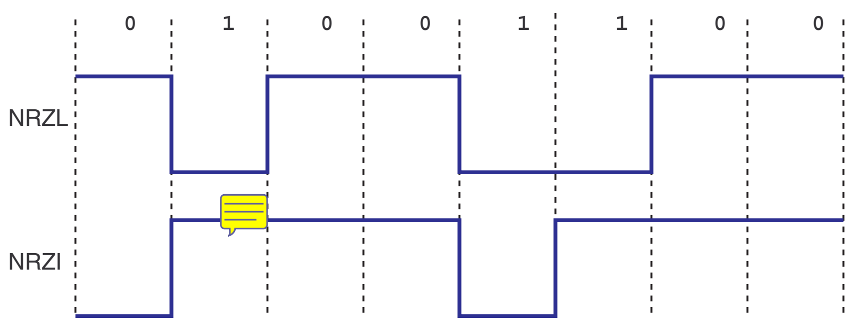
- A digital signal is a series of discrete, discontinuous voltage (light) pulses. (pulse = signal element)
- Binary data is transmitted by *encoding* each bit into signal elements
  - Baud is the number of signaling elements per second
- We used the presence/absence of voltage to represent data
  - Voltage represented a 1, while no voltage represented a 0
  - Other (and better) encoding schemes are available
- Important Definitions
  - Unipolar - All signal elements have the same sign
  - Polar - One logic state is positive, the other is negative

Our voltage/no-voltage encoding method is unipolar or polar?

Nonreturn to Zero (NRZ)

The most common form to transmit digital signals

- Use two different voltages for the two binary values
- Voltage is constant during a bit interval (no return to zero)
- For example, no voltage would represent 0 while a constant positive voltage would represent a 1 (our early encoding scheme)
- Typically a negative voltage represents 1, while a positive voltage represents 0
  - This is a NRZL (nonreturn-to-zero-level) code
- NRZI (nonreturn-to-zero, invert on ones) is another code
  - Maintain a constant voltage for the duration of a bit
  - Data is represented by the presence or absence of a *transition*



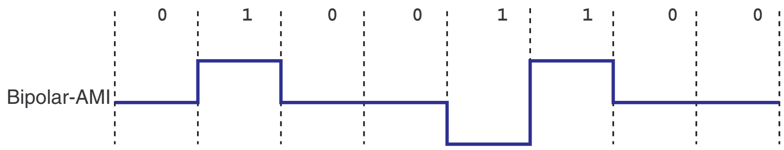
- NRZI is an example of *differential encoding*
- Differential encoding - Signal is decoded by measuring the polarity of the adjacent signal elements

Differential encoding is a better method (than NRZ), why?
What is the disadvantage of NRZ/NRZI encoding? What may happen if [000000000000000000000000001] is sent?

Multilevel Binary

Methods that use more that two signal levels to represent data

- Bipolar-AMI (Alternate Mark Inversion)
  - 0 is represented by no voltage, while a 1 is represented by a positive or negative pulse (must alternate)



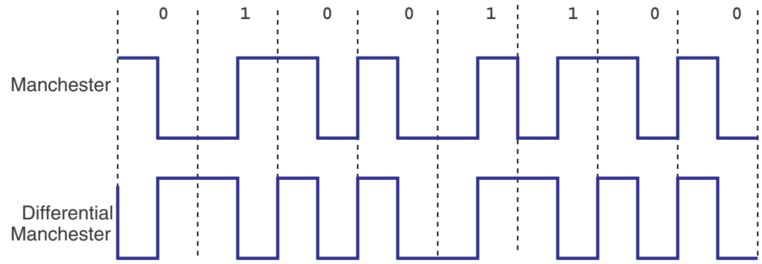
Does this solve the [0000000000000000000000001] problem?

Biphase

Two encoding techniques *Manchester* and *Differential Manchester*

- Manchester
  - Transition in the middle of **each** bit period
  - High-to-low transition represents a 0
  - Low-to-high transition represents a 1
  - Transition serves as a synchronization mechanism
- Differential Manchester
  - 0 represented by the presence of a transition at the **beginning** of a bit period while a 1 is represented by the absence of a transition

  What is the advantage of Differential Manchester?



Biphase methods have several advantages

- Synchronization - Predictable transition during each bit, receiver can resynchronize on the transition (self-clocking code)
- Using + and - voltages reduces interference
- The absence of an expected transition can help in error detection
- Used in IEEE 802.3 (Ethernet) and IEEE802.5 (token ring)

Encoding Methods (Review)

- Interested in representing (encoding) data on a signal
  1. Digital data ⇒ digital signal
  2. Digital data ⇒ analog signal
  3. Analog data ⇒ digital signal
  4. Analog data ⇒ analog signal
- The previous slides concerned digital data and signals
  - Sending signals that *looked* like square waves
  - Also called **baseband** transmission
  - *But, we don't have to send square waves...*

Sending Digital Data with Analog Signals

Sending digital data through the telephone network

- Telephone network was designed to transmit analog signals
  - Most backbone networks are digital, but your local loop...
- Signals are in the voice frequency (300Hz to 3400Hz)
  - As a result DC components are not present
    So what...
- Digital devices are attached to the network via a *modem*
  - Modem is short for *modulator-demodulator*
  - Converts digital data to analog signals (vice versa)

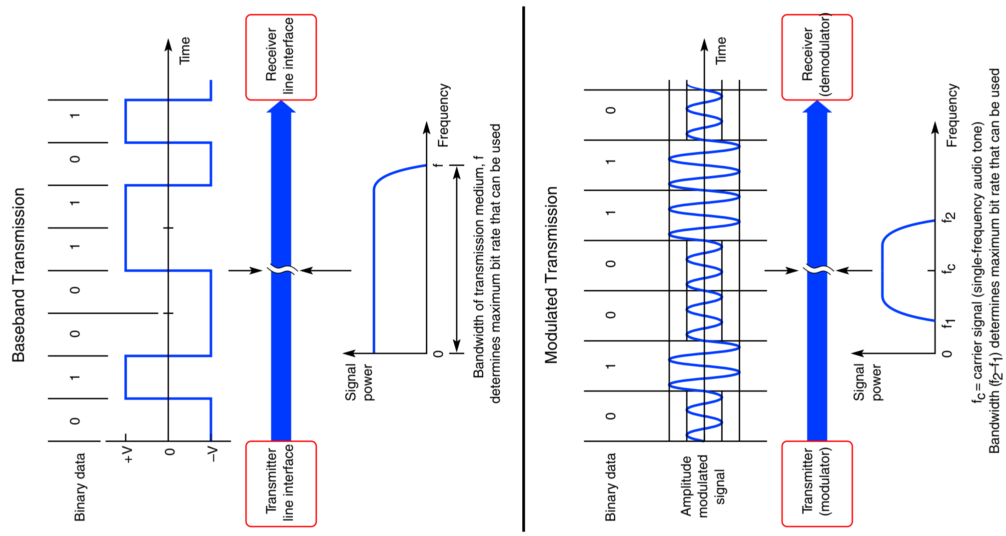
Encoding Techniques

As we have seen, sending *square waves* requires a large bandwidth

- Need a *large* number of harmonics
- Strong attenuation and delay distortions
- Used only for short distances (LAN)

AC (modulated) signaling is used to avoid the *square wave problem*

- Carrier sine wave
  - A continuous tone (1000kHz to 2000kHz)
  - Also called a carrier frequency (typically a center frequency)
- Its *amplitude*, *frequency*, or *phase* can be changed to transmit information



Amplitude-Shift Keying (ASK)

- Binary values represented by two different amplitudes on the carrier frequency
  - Two different voltage levels
- The resulting signal is

$$s(t) = \begin{cases} A \sin(2\pi f_c t + \phi) & \text{binary 1} \\ 0 & \text{binary 0} \end{cases}$$

- On voice-lines can be used up to 1200 bps
- Can be used for fiber

If used for fiber transmission, what are the characteristics of a 1 versus a 0?

Frequency-Shift Keying (FSK)

- Binary values represented by two different frequencies (f_1 and f_2 within the carrier frequency)
- The resulting signal is

$$s(t) = \begin{cases} A\sin(2\pi f_1 t + \phi) & \text{binary 1} \\ A\sin(2\pi f_2 t + \phi) & \text{binary 0} \end{cases}$$

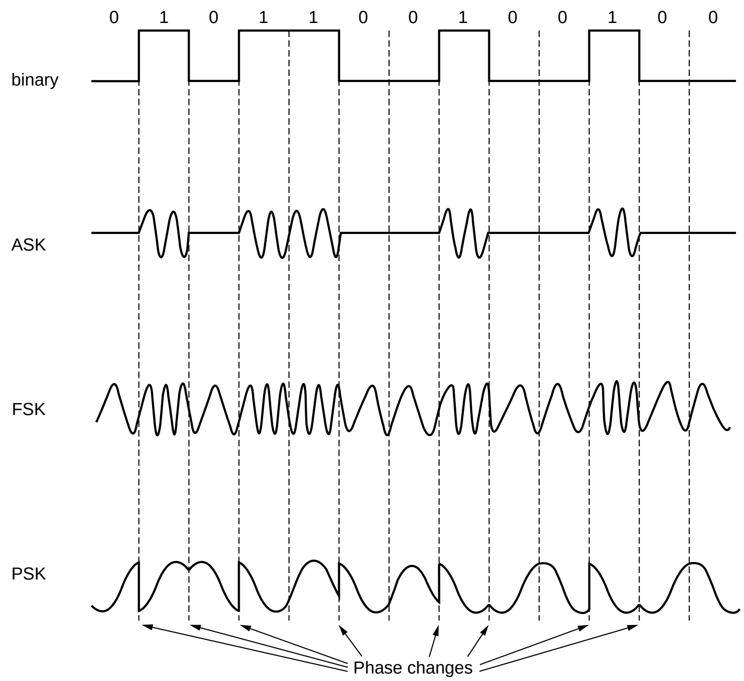
- Example is the Bell System 108 modem
  - Voice is in the range 300Hz to 3400Hz
  - For full duplex the bandwidth is split at 1700Hz
  - One half is for sending, the other half for receiving
  - One one half frequency is shifted by 100Hz for 0 and 1
- Can be used for coaxial cable based LANs

Phase-Shift Keying (PSK)

- Binary values represented by shifting the phase
- Simple example - Two-phase system
  - 0 represented by sending a signal *burst* of the same phase as the previous burst
  - 1 represented by sending a signal burst of opposite phase to the preceding one

    Is this differential?
- The resulting two-phase signal is

$$s(t) = \begin{cases} A\sin(2\pi f_c t + \pi) & \text{binary 1} \\ A\sin(2\pi f_c t) & \text{binary 0} \end{cases}$$



Bandwidth and Data Rate Limits

Nyquist theorem gives an *upper* bound on the possible data rate.

- A perfect 3400Hz telephone-line can achieve only 6800bps
- However current telephone-modems have higher data rates

How can we achieve higher data rates?

Quadrature Phase-Shift Keying (QPSK)

Can make more efficient use of bandwidth if each signaling element can represent more than one bit

- QPSK uses phase shifts of multiples of 90 degrees
- The resulting signal is

$$s(t) = \begin{cases} A\sin(2\pi f_c t + 45^\circ) & 11 \\ A\sin(2\pi f_c t + 135^\circ) & 10 \\ A\sin(2\pi f_c t + 225^\circ) & 00 \\ A\sin(2\pi f_c t + 315^\circ) & 01 \end{cases}$$

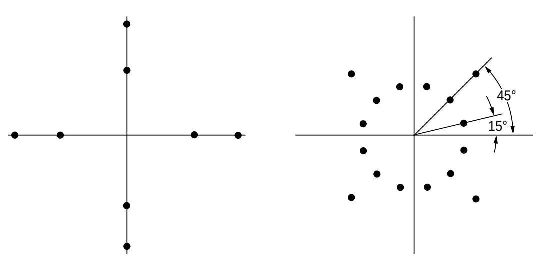
  Therefore each signal element represents 2 bits instead of one

How many phase angles are required to represent 3 bits per signaling element?

Quadrature Amplitude Modulation (QAM)

Combine multiple modulation techniques to transmit multiple bits per signaling element

- Change amplitude and phase, consider the two constellations



(a) (b)

- In (a) points are located at 0°, 90°, 180°, and 270° with two amplitude levels per phase
  – Amplitude is measured as the distance from the origin

- (a) has 8 points total, which can represent 3 bits each
  How many bits are represented per point in (b)?

- ITU has defined a set of standards (constellations) known as the V series modems
  - V.x modem can connect with another V.x modem of different manufacturers
  - The ITU V.32 9600bps modem uses the (b) constellation and can achieve 9600bps
  - V.32 bis achieves 14.4kbps using 6 bits per sample
    How many points are in its constellation?

We are achieving higher data rates using QAM, but what is the disadvantage?

Analog Data and Digital Signals

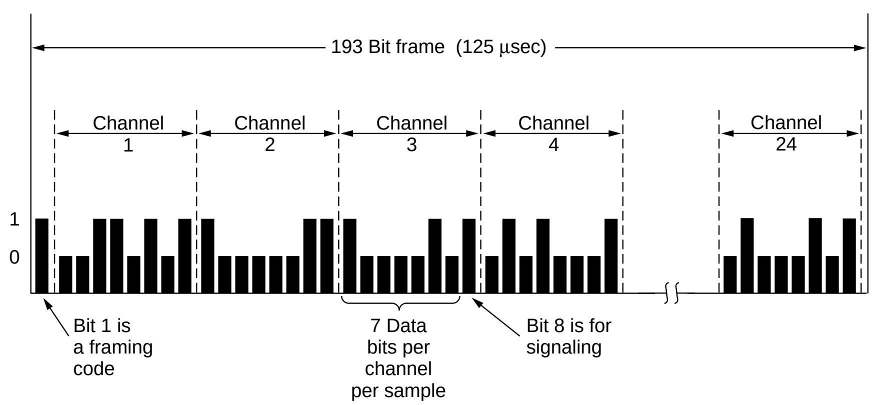
Also called *digitization*, converting analog data into digital signal

- Pulse Code Modulation (PCM)
  - Samples (measurements) of the analog signal are taken at discrete periods of time
  - Nyquist theorem gives the appropriate sampling time: *Number of samples required is equal to twice the highest significant signal frequency*
- If voice data is limited to 4000Hz, then 8000 samples per second would suffice to characterize the signal
  - *These are analog*, PAM (Pulse Amplitude Modulation) values
  - To produce digital data, these samples are then digitized

- To produce PCM data, each PAM sample is approximated using an n bit integer *How does n impact the approximation?*

- Telephone system example
  - Analog signals are digitized at the end office using a *codec* producing a 7 (US and Japan) or 8 (Europe) bit number.
    What are the implications of the existence of 7 and 8 bit systems?
  - 8000 samples are taken per second (due to Nyquist)
  - Time per sample is ______, as a result all time intervals in the telephone system are multiples of this number
    What is the bit rate for a US voice channel? (an additional bit/sample is used for control)

- A T1 (US) carrier is commonly used for transmitting 24 *voice channels* at once (yielding 1.54Mbps)

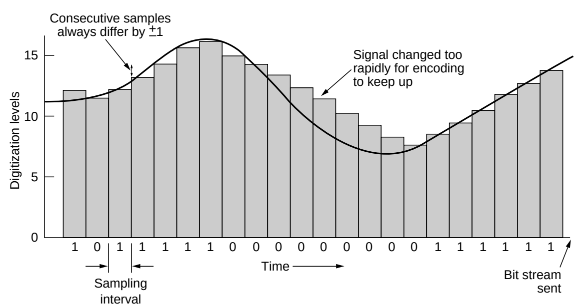


This is a form of *time division multiplexing*, we will discuss later...

- Differential Pulse Code Modulation
  - Digitizing the *difference between the consecutive samples*, not the amplitude
  - The number of bits n indicates the possible range between levels.
- A variation is *Delta Modulation*
  - Analog wave is approximated by a staircase function
  - The function moves up or down by one level, at each sampling interval (*quantization level* δ)
  - Therefore the range only has two values δ and $-\delta$

    What are some possible problems associated with delta modulation?

- Issues include, what happens if the signal changes too rapidly?



Analog Data Analog Signals

What is an example of analog data analog signal conversion?

Two principle reasons for analog data analog signal conversion

- Higher frequency may be required for transmission
  - Voice is 300Hz to 3000Hz, but radio frequencies are higher
- Modulation permits frequency division multiplexing (discuss later)

Modulation techniques include

- Amplitude Modulation (AM)
- Frequency Modulation (FM)