

18-345 – Fall 08

## Lecture 4 Digital Transmission Fundamentals

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reading: Chapter 3

## Outline Physical Layer Lectures

- Digital representation of information
  - Digital representation of analog signals
- Analog versus digital transmission
- Basic properties of dig. transmission
- Fundamental limits of dig. transmission
- Line coding, modulation
  - Amplitude, frequency, and phase modulation
- Properties of transmission media
- Synchronization
- Error detection and error correction

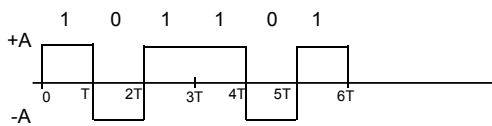
## Outline

- Properties digital transmission
- Limits digital transmission
- Line coding
- Modulation

## Properties and Limits of Digital Transmission Systems

Reading: Sections 3.2.2 and 3.5

## Digital Binary Signal



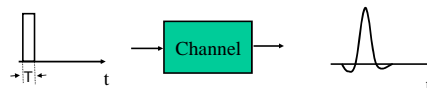
Here, Bit Rate = 1 bit / T seconds

For a given communications medium:

- How do we increase the bit rate (speed) ?
- How do we achieve reliable communications?
- Are there limits to speed and reliability?

## Pulse Transmission Rate

- Objective: Maximize pulse rate through a channel, that is, make T as small as possible



- If input is a narrow pulse, then typical output is a spread-out pulse with ringing
- Question: How frequently can these pulses be transmitted without interfering with each other?
- $2W_c$  pulses/sec with binary amplitude encoding where  $W_c$  is the bandwidth of the channel

## Bandwidth of a Channel

$X(t) = a \cos(2\pi ft) \rightarrow$  Channel  $\rightarrow Y(t) = A(f) a \cos(2\pi ft)$

- If input is sinusoid of frequency  $f$ , then
  - output is a sinusoid of same frequency  $f$
  - Output is attenuated by an amount  $A(f)$  that depends on  $f$
  - $A(f) \approx 1$ , then input signal passes readily
  - $A(f) \approx 0$ , then input signal is blocked
- Bandwidth  $W_c$  is range of frequencies passed by channel

Ideal lowpass channel

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## Multi-level Pulse Transmission

- Assume channel of bandwidth  $W_c$ , and transmit  $2W_c$  pulses/sec (without interference)
- If pulses' amplitudes are either  $-A$  or  $+A$ , then each pulse conveys 1 bit, so
 

**Bit Rate = 1 bit/pulse x  $2W_c$  pulses/sec =  $2W_c$  bps**
- If amplitudes are from  $\{-A, -A/3, +A/3, +A\}$ , then bit rate is  $2 \times 2W_c$  bps
- By going to  $M=2^m$  amplitude levels, we achieve
 

**Bit Rate =  $m$  bits/pulse x  $2W_c$  pulses/sec =  $2mW_c$  bps**

In the absence of noise,  
the bit rate can be increased without limit by increasing  $m$

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## Noise & Reliable Communications

- All physical systems have noise
  - Electrons always vibrate at non-zero temperature
  - Motion of electrons induces noise
- Presence of noise limits accuracy of measurement of received signal amplitude
- Errors occur if digital signal separation is comparable to noise level
- Thus, noise places a limit on how many amplitude levels can be used in pulse transmission
- Bit Error Rate (BER) increases with decreasing signal-to-noise ratio

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## Signal-to-Noise Ratio (SNR)

High SNR

No errors

Low SNR

error

$$SNR = \frac{\text{Average signal power}}{\text{Average noise power}}$$

$$SNR \text{ (dB)} = 10 \log_{10} SNR$$

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## Shannon's Channel Capacity Theorem

$$C = W_c \log_2(1 + SNR) \text{ bps}$$

- $C$ : maximum capacity of the channel (bps)
- $W_c$ : channel bandwidth (Hz)
- SNR: signal to noise ratio of the channel

- Accounts for the effects of noise
- More aggressive encoding can increase the channel bandwidth

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## Shannon's Channel Capacity Theorem

$$C = W_c \log_2(1 + SNR) \text{ bps}$$

- Arbitrarily-reliable communications is possible if the transmission rate  $R < C$
- If  $R > C$ , then arbitrarily-reliable communications is not possible
- "Arbitrarily-reliable" means the BER can be made arbitrarily small through sufficiently complex "coding"
- $C$  can be used as a measure of how close a system design is to the best achievable performance
- Bandwidth  $W_c$  & SNR determine  $C$

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## Example

- Find the Shannon channel capacity for a telephone channel with  $W_c = 3400$  Hz and  $SNR = 40$  dB

$SNR$  (dB) = 40 dB corresponds to  
 $SNR = 10^{(40/10)} = 10000$

$$C = 3400 \log_2 (1 + 10000)$$

$$= 3400 \log_{10} (10001) / \log_{10} 2 = 45200 \text{ bps}$$

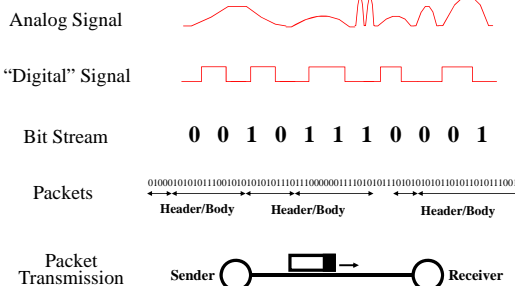
## Bit Rates of Digital Transmission Systems

System	Bit Rate	Observations
Telephone twisted pair	33.6-56 kbps	4 kHz telephone channel
Ethernet twisted pair	10 Mbps, 100 Mbps	100 meters of unshielded twisted copper wire pair
Cable modem	500 kbps-4 Mbps	Shared CATV return channel
ADSL twisted pair	64-640 kbps in, 1.536-6.144 Mbps out	Coexists with analog telephone signal
2.4 GHz radio	2-11 Mbps	IEEE 802.11 wireless LAN
28 GHz radio	1.5-45 Mbps	5 km multipoint radio
Optical fiber	2.5-10 Gbps	1 wavelength optical signal
Optical fiber	>1600 Gbps	Many wavelengths

## Line Coding

Reading: Section 3.6

## From Signals to Packets



## Encoding

- Encoding converts a binary information sequence into a digital signal
- Sender modifies signal in a way that the receiver can recognize
  - Ex. "1" maps to +A square pulse; "0" to -A pulse
- Transmission is synchronous, i.e., a clock is used to sample the signal.
  - Receiver's clock must be synchronized with the sender's clock
- Encoding can be done one bit at a time or in blocks of, e.g., 4 or 8 bits

## Why Do We Need Encoding?

- To meet certain electrical constraints.
  - Many of them! See next slide
- Creates control symbols, besides regular data symbols.
  - E.g. start or end of frame, escape, ...
- Can do error detection or error correction
  - Some codes are illegal so receiver can detect certain classes of errors
  - Minor errors can be corrected by having multiple adjacent signals mapped to the same data symbol

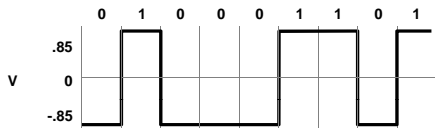
## What System Requirements Must Line Codes Meet?

- *Transmitted power*: Power consumption = \$
- *Bit timing*: Transitions in signal help timing recovery
- *Bandwidth efficiency*: Excessive transitions wastes spectral bandwidth
- *Low frequency content*: Some channels block low frequencies
  - long periods of +A or of -A causes signal to “droop”
  - Waveform should not have low-frequency content
- *Complexity/cost*: Code can be implemented in electronic chip at high speed?

## Baseband versus Carrier Modulation

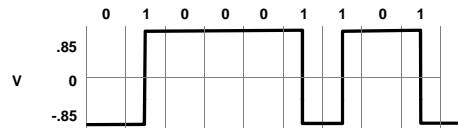
- Baseband modulation: send the “bare” digital signal
  - Channel must be able to transmit low frequencies
  - For example, copper media
- Carrier modulation: use the signal to modulate a higher frequency signal, called a carrier
  - Can send the signal in a particular part of the spectrum
  - Can modulate the amplitude, frequency or phase
  - For example, wireless and optical

## Non-Return to Zero (NRZ)



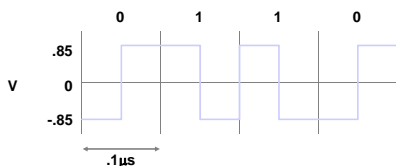
- 1 -> high signal; 0 -> low signal
- Long sequences of 1's or 0's can cause problems:
  - Sensitive to clock skew, i.e. hard to recover clock
  - Difficult to interpret 0's and 1's

## Non-Return to Zero Inverted (NRZI)



- 1 -> make transition; 0 -> signal stays the same
- Solves the problem for long sequences of 1's, but not for 0's.

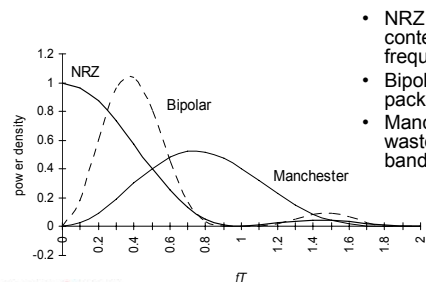
## Ethernet Manchester Encoding



- Positive transition for 0, negative for 1
- Transition every cycle communicates clock (but need 2 transition times per bit)
- DC balance has good electrical properties

## Spectrum of Line codes

- Assume 1's & 0's independent & equiprobable



- NRZ has high content at low frequencies
- Bipolar tightly packed around T/2
- Manchester wasteful of bandwidth

## Unipolar & Polar Non-Return-to-Zero (NRZ)

### Unipolar NRZ

- “1” maps to +A pulse
- “0” maps to no pulse
- High Average Power  
 $0.5 \cdot A^2 + 0.5 \cdot 0^2 = A^2/2$
- Long strings of A or 0
  - Poor timing
  - Low-frequency content
- Simple

### Polar NRZ

- “1” maps to +A/2 pulse
- “0” maps to -A/2 pulse
- Better Average Power  
 $0.5 \cdot (A/2)^2 + 0.5 \cdot (-A/2)^2 = A^2/4$
- Long strings of +A/2 or -A/2
  - Poor timing
  - Low-frequency content
- Simple

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## Bipolar Code

- Three signal levels:  $\{-A, 0, +A\}$
- “1” maps to +A or -A in alternation
- “0” maps to no pulse
  - Every +pulse matched by -pulse so little content at low frequencies
- String of 1’s produces a square wave
  - Spectrum centered at T/2
- Long string of 0’s causes clock to lose synch
- Zero-substitution codes

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## Manchester code & mB/nB codes

- “1” maps into A/2 first T/2, -A/2 last T/2
- “0” maps into -A/2 first T/2, A/2 last T/2
- Every interval has transition in middle
  - Timing recovery easy
  - Uses double the minimum bandwidth
- Simple to implement
- Used in Ethernet & other LAN standards

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## mB/nB Encoding

- m data bits are coded as *symbols* of n line bits
- Example: FDDI uses 4B5B
  - 4 data bits for 5 line bits, so 100 Mbps uses 125 MHz.
  - Uses less frequency than Manchester encoding (1B2B)
- Each valid symbol has at least two 1s: get dense transitions.
- 16 data symbols, 8 control symbols
  - Data symbols: 4 data bits
  - Control symbols: idle, begin frame, etc.
- Also: 8B10B (Gigabit Ethernet, Fiber channel) and 64B66B code (10G Ethernet)

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## 4B/5B Encoding


Data	Code	Data	Code
0000	11110	1000	10010
0001	01001	1001	10011
0010	10100	1010	10110
0011	10101	1011	10111
0100	01010	1100	11010
0101	01011	1101	11011
0110	01110	1110	11100
0111	01111	1111	11101


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## Line coding examples

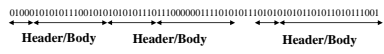
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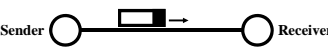
## From Signals to Packets

Analog Signal 

"Digital" Signal 

Bit Stream **0 0 1 0 1 1 1 0 0 0 1**

Packets 

Packet Transmission 

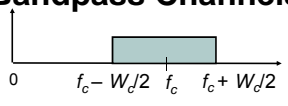
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## Modulation

**Reading: Section 3.7 (light)**

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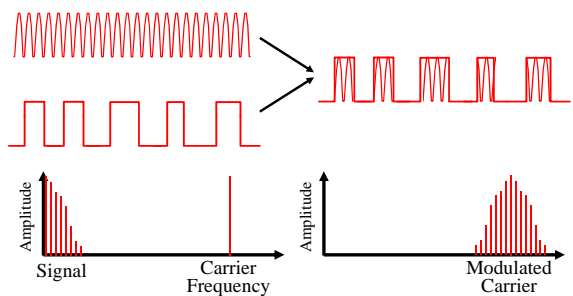
## Bandpass Channels



- Bandpass channels pass a range of frequencies around some center frequency  $f_c$ 
  - Radio channels, telephone & DSL modems
- Digital modulators embed information into waveform with frequencies passed by bandpass channel
- Sinusoid of frequency  $f_c$  is centered in middle of bandpass channel
- Modulators embed information into a sinusoid

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## Amplitude Carrier Modulation

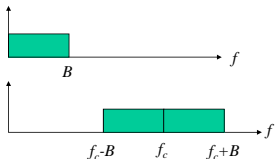


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## Signaling rate and Transmission Bandwidth

- Fact from Transmission Bandwidth

If Baseband signal  $x(t)$  with bandwidth  $B$  Hz then



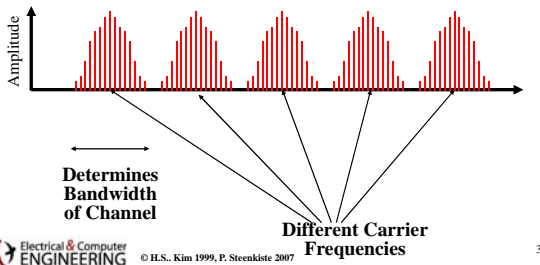
Modulated signal  $x(t)\cos(2\pi f_c t)$  has bandwidth  $2B$  Hz

- If bandpass channel has bandwidth  $W_c$  Hz,
  - Then baseband channel has  $W_c/2$  Hz available, so
  - modulation system supports  $W_c/2 \times 2 = W_c$  pulses/second
  - That is,  $W_c$  pulses/second per  $W_c$  Hz = 1 pulse/Hz

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## Frequency Division Multiplexing: Multiple Channels

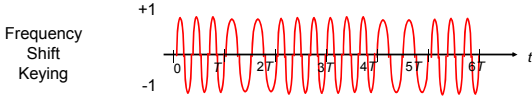
Determines Bandwidth of Link



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## Frequency Modulation

Information: 1 0 1 1 0 1

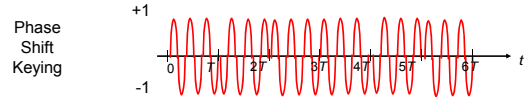
Frequency Shift Keying: 

- Use two frequencies to represent bits
  - "1" send frequency  $fc + d$
  - "0" send frequency  $fc - d$
- Demodulator looks for power around  $fc + d$  or  $fc - d$

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## Phase Modulation

Information: 1 0 1 1 0 1

Phase Shift Keying: 

- Map bits into phase of sinusoid:
  - "1" send  $A \cos(2\pi ft)$ , i.e. phase is 0
  - "0" send  $A \cos(2\pi ft + \pi)$ , i.e. phase is  $\pi$
- Equivalent to multiplying  $\cos(2\pi ft)$  by +A or -A
  - "1" send  $A \cos(2\pi ft)$  - multiply by 1
  - "0" send  $A \cos(2\pi ft + \pi) = -A \cos(2\pi ft)$  - multiply by -1

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## Modulator & Demodulator

Modulate  $\cos(2\pi f_c t)$  by multiplying by  $A_k$  for  $T$  seconds:

$A_k \rightarrow \text{Multiplier} \rightarrow Y(t) = A_k \cos(2\pi f_c t)$   
Transmitted signal during kth interval

Demodulate (recover  $A_k$ ) by multiplying by  $2\cos(2\pi f_c t)$  for  $T$  seconds and lowpass filtering (smoothing):

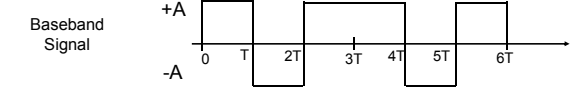
$Y(t) = A_k \cos(2\pi f_c t) \rightarrow \text{Multiplier} \rightarrow 2A_k \cos^2(2\pi f_c t) = A_k \{1 + \cos(2\pi f_c t)\}$   
Received signal during kth interval

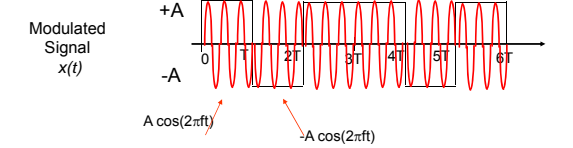
$\rightarrow \text{Lowpass Filter (Smoother)} \rightarrow X_k(t)$

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## Example of Phase Modulation

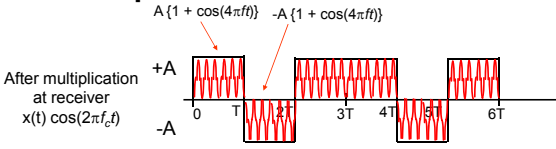
Information: 1 0 1 1 0 1

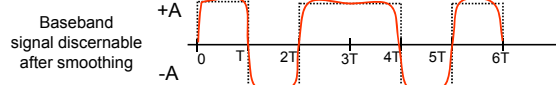
Baseband Signal: 

Modulated Signal  $x(t)$ : 

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## Example of Phase Demodulation

After multiplication at receiver  $x(t) \cos(2\pi f_c t)$ : 

Baseband signal discernable after smoothing: 

Recovered Information: 1 0 1 1 0 1

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## Quadrature Amplitude Modulation (QAM)

- QAM uses two-dimensional signaling
  - $A_k$  modulates in-phase  $\cos(2\pi f_c t)$
  - $B_k$  modulates quadrature phase  $\sin(2\pi f_c t)$
  - Transmit sum of inphase & quadrature phase components

$A_k \rightarrow \text{Multiplier} \rightarrow Y_i(t) = A_k \cos(2\pi f_c t)$

$B_k \rightarrow \text{Multiplier} \rightarrow Y_q(t) = B_k \sin(2\pi f_c t)$

$Y_i(t) + Y_q(t) \rightarrow \text{Adder} \rightarrow Y(t)$   
Transmitted Signal

- $Y_i(t)$  and  $Y_q(t)$  both occupy the bandpass channel
- QAM sends 2 pulses/Hz

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