Note: We will start at 12:53 pm ET

Course Summary:

Date	Details	
Mon Feb 1, 2021	18-441/741 Lecture 1	12:50pm to 2:50pm
Wed Feb 3, 2021	18-441/741 Lecture 2	12:50pm to 2:50pm
Mon Feb 8, 2021	18-441/741 Lecture 3	12:50pm to 2:50pm
→ Wed Feb 10, 2021	18-441/741 Lecture 4	12:50pm to 2:50pm
Fri Feb 12, 2021	18-441/741 Recitation 1 (Hybrid) -- Project-1 Intro -- Zoom / In-person (A-L)	12:50pm to 1:40pm
Sun Feb 14, 2021	Quiz 1	due by 11:59pm
Mon Feb 15, 2021	18-441/741 Lecture 5	12:50pm to 2:50pm
Wed Feb 17, 2021	18-441/741 Lecture 6	12:50pm to 2:50pm
Mon Feb 22, 2021	18-441/741 Lecture 7	12:50pm to 2:50pm
Wed Feb 24, 2021	18-441/741 Lecture 8	12:50pm to 2:50pm
Fri Feb 26, 2021	18-441/741 Recitation 2 (Hybrid) -- Project 2 Intro -- Zoom / In-person (M-Z)	12:50pm to 1:40pm
Sun Feb 28, 2021	Quiz 2	due by 11:59pm
	Project 1	due by 11:59pm

18-441/741: Computer Networks

Lectures 4: Physical Layer II

Swarun Kumar

Physical Layer: Outline

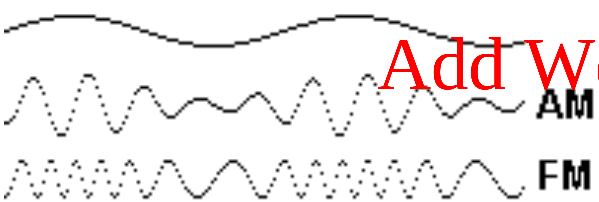
- Digital networks
- Modulation Fundamentals
- Characterization of Communication Channels
- Fundamental Limits in Digital Transmission
- Digital Modulation
- Line Coding
- Properties of Media and Digital Transmission Systems
- Error Detection and Correction

Transferring Information

- Information transfer is a physical process
- In this class, we generally care about
  - Electrical signals (on a wire or wireless)
  - Optical signals (in a fiber)
  - More broadly, EM waves
- Information carriers can be very diverse:
  - Sound waves, quantum states, proteins, ink & paper, etc.
- Quote (usually attributed to Einstein):
  - You see, wire telegraph is a kind of a very, very long cat. You pull his tail in New York and his head is meowing in Los Angeles.

Modulation

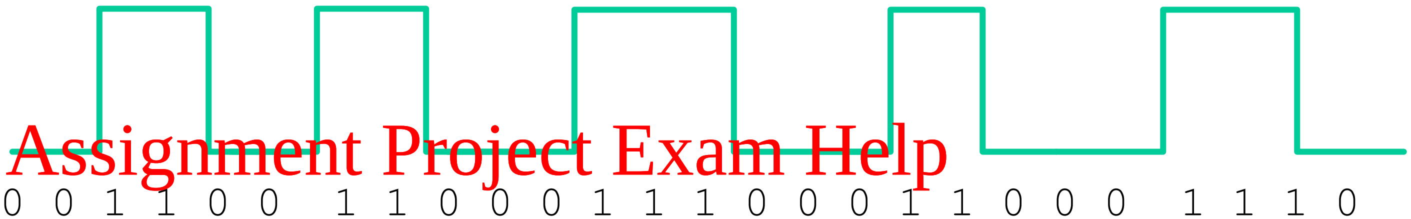
- Changing a signal to convey information
- Ways to modulate a sinusoidal wave
  - Amplitude Modulation (AM)
  - Frequency Modulation (FM)
  - Phase Modulation (PM)



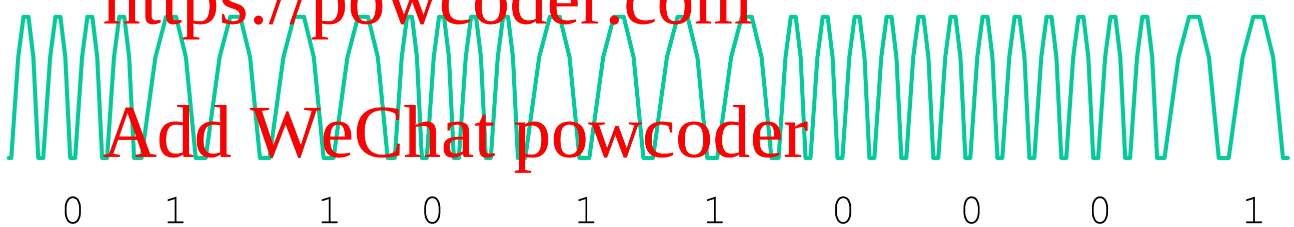
- In our case, modulate signal to encode a 0 or a 1. (multi-valued signals sometimes)
  - Analog is the same – value just changes continuously

Modulation Examples

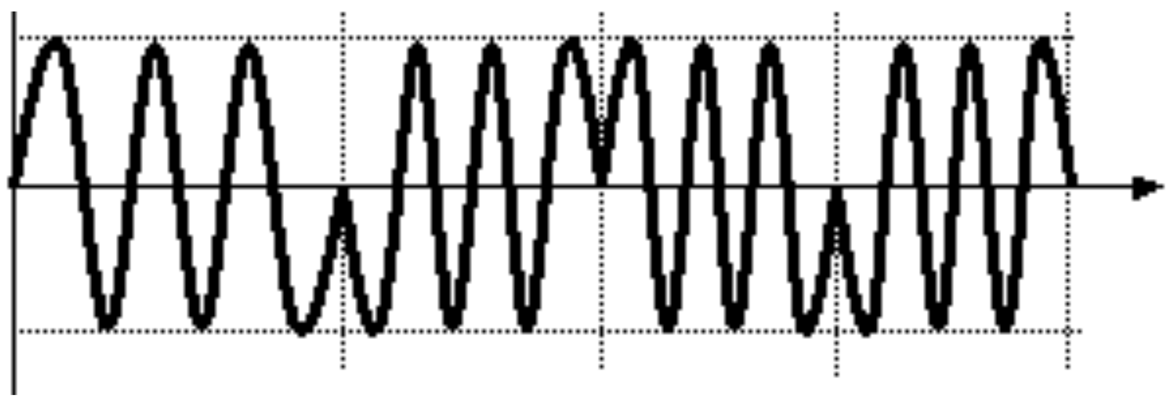
Amplitude



Frequency



Phase



Electrical & Computer ENGINEERING

Why Different Modulation Methods?

- Offers choices with different tradeoffs:
  - Transmitter/Receiver complexity
  - Power requirements
  - Bandwidth
  - Medium (air, copper, fiber, …)
  - Noise immunity
  - Range
  - Multiplexing

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Questions of Interest

- How long will it take to transmit a message?
  - How many bits are in the message (text, image)?
  - How fast does the network/system transfer information?
- Can a network/system handle a voice (video) call?
  - How many bits/second does voice/video require? At what quality?
- How long will it take to transmit a message without errors?
  - How are errors introduced?
  - How are errors detected and corrected?
- What transmission speed is possible over radio, copper cables, fiber, infrared, …?

A Communications System

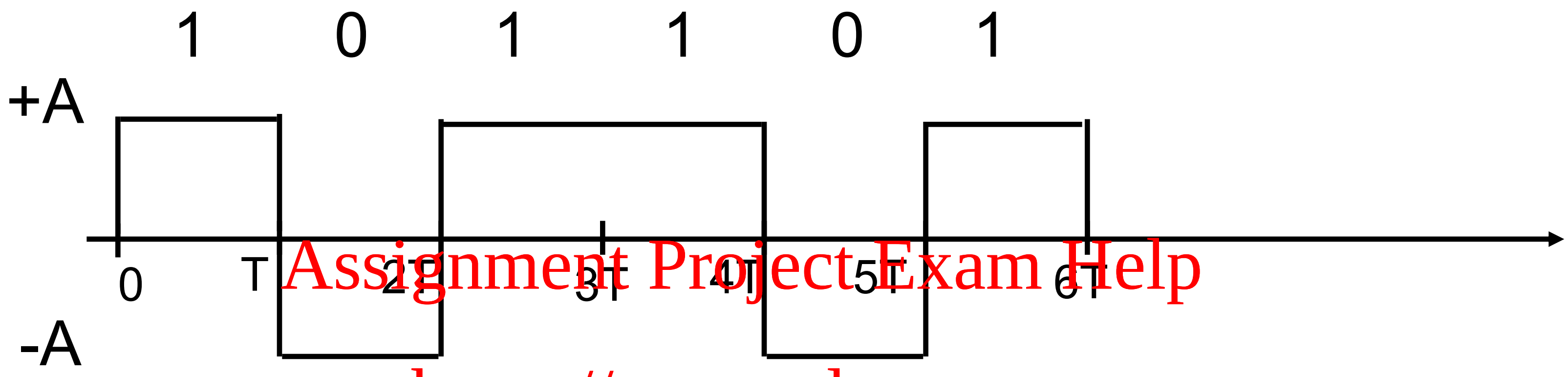
Transmitter

- Converts information into *a signal* suitable for transmission
- Injects energy into communications medium or channel
  - Telephone converts voice into electric current
  - Wireless LAN card converts bits into electromagnetic waves

Receiver

- Receives energy from medium
- Converts received signal into a form suitable for delivery to user
  - Telephone converts current into voice
  - Wireless LAN card converts electromagnetic waves into bits

Digital Binary Signal



Here, Bit Rate = 1 bit / T seconds

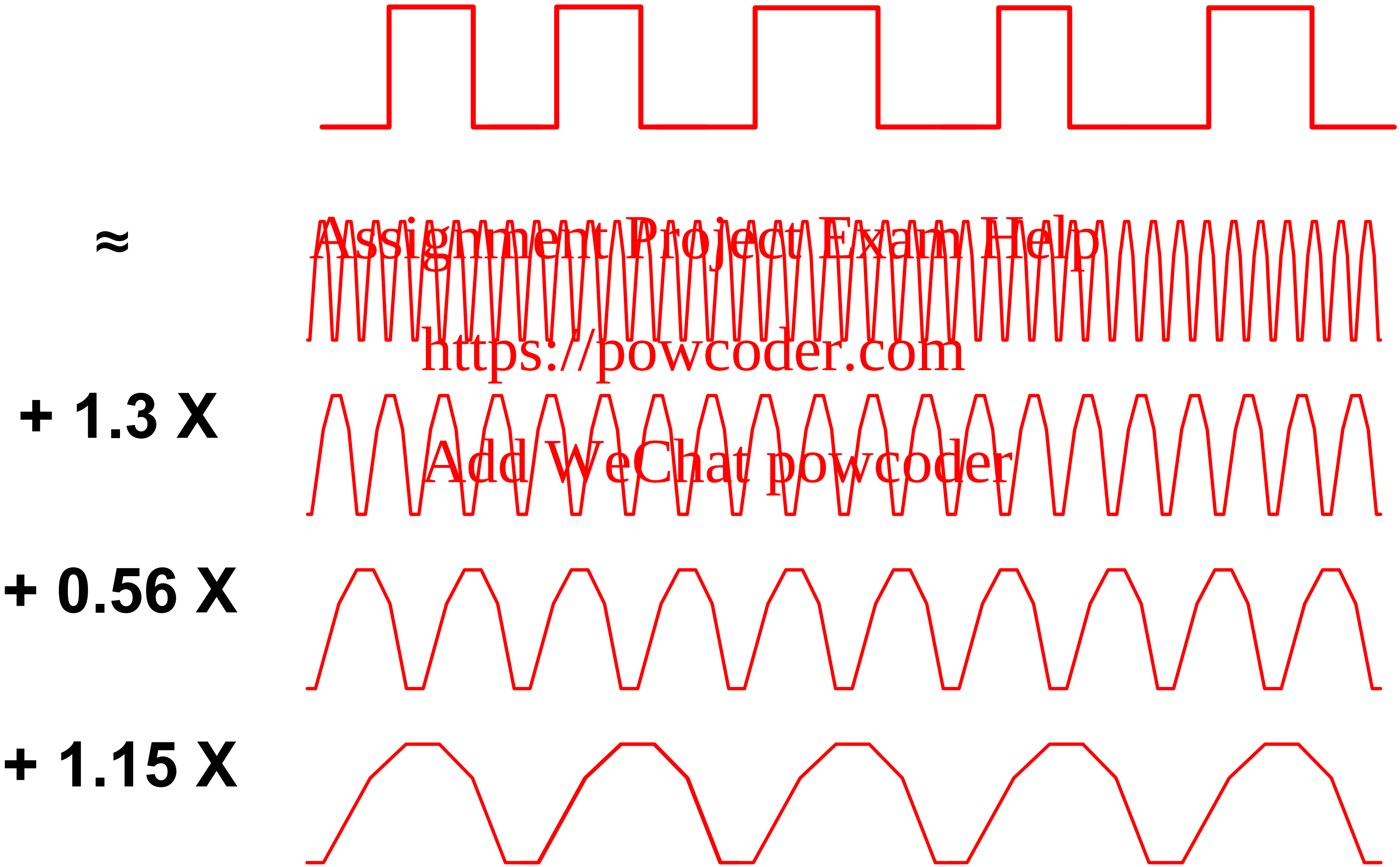
For a given communications medium:

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

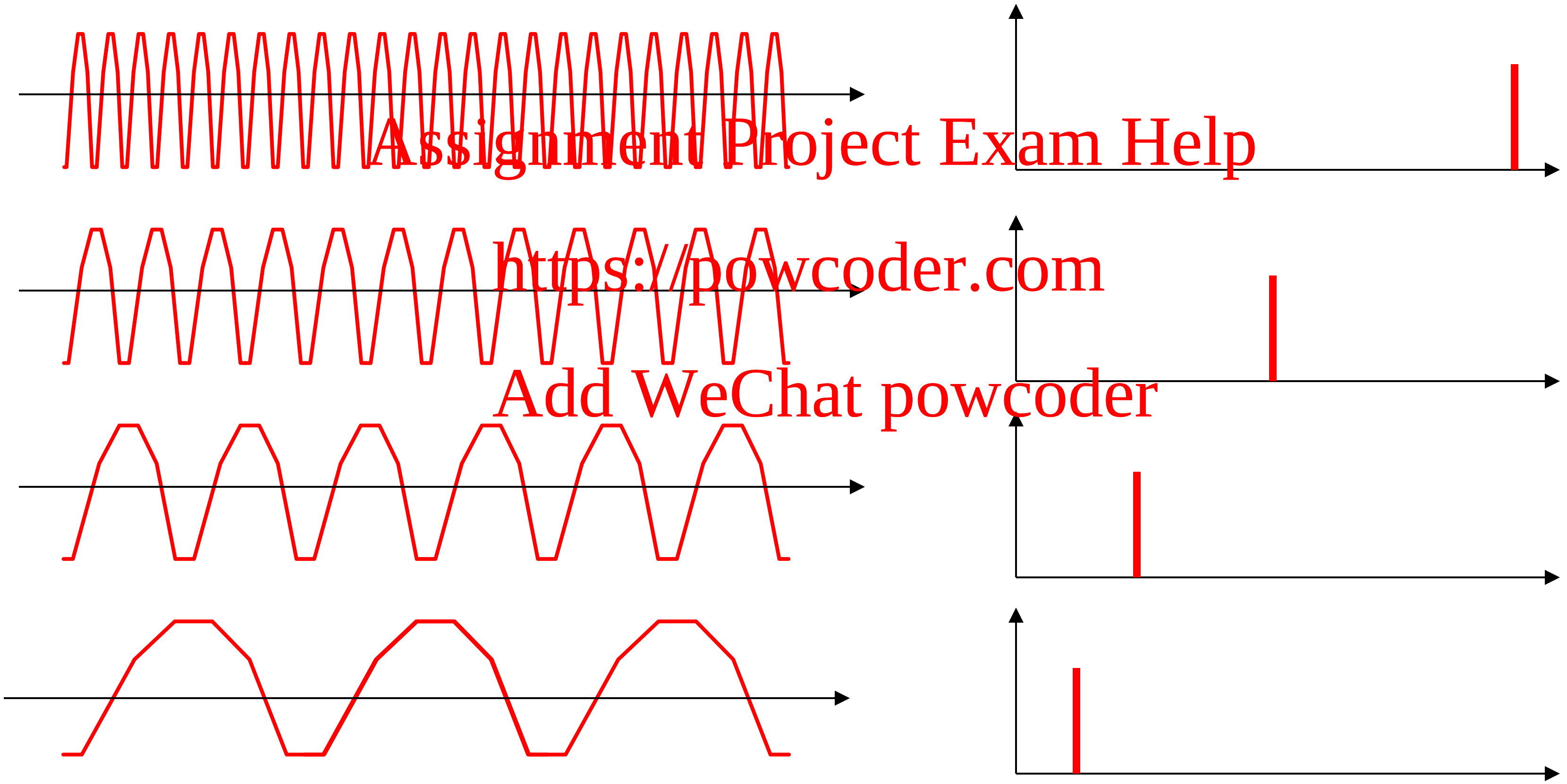
Bandwidth

- Bandwidth is width of the frequency range in which the Fourier transform of the signal is non-zero.
- Sometimes referred to as the channel width
- Or, where it is above some threshold value (Usually, the half power threshold, e.g., -3dB)
- dB - short for decibel
  – Defined as 10 * $\log_{10}(P_1/P_2)$
  – When used for signal to noise: 10 * $\log_{10}(S/N)$
- Also: dBm – power relative to 1 milliwatt
  – Defined as 10 * $\log_{10}(P/1\ \mathrm{mW})$

Signal = Sum of Waves

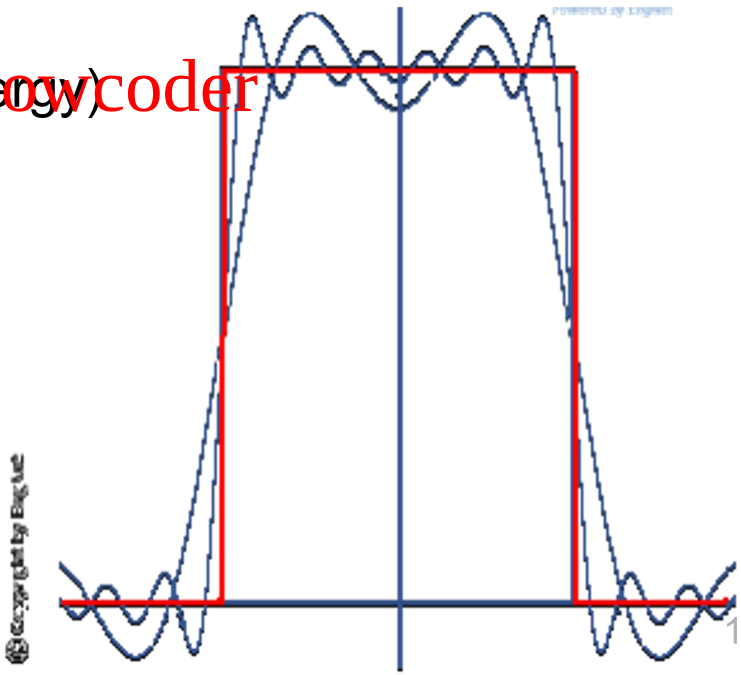


Closer look at waves



The Frequency Domain

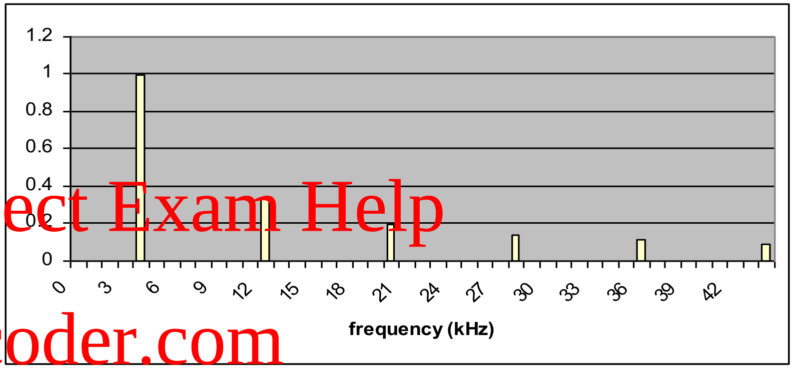
- A (periodic) signal can be viewed as a sum of sine waves of different strengths.
  - Corresponds to energy at a certain frequency
- Every signal has an equivalent representation in the frequency domain.
  - What frequencies are present and what is their strength (energy)
- E.g., radio and TV signals, …



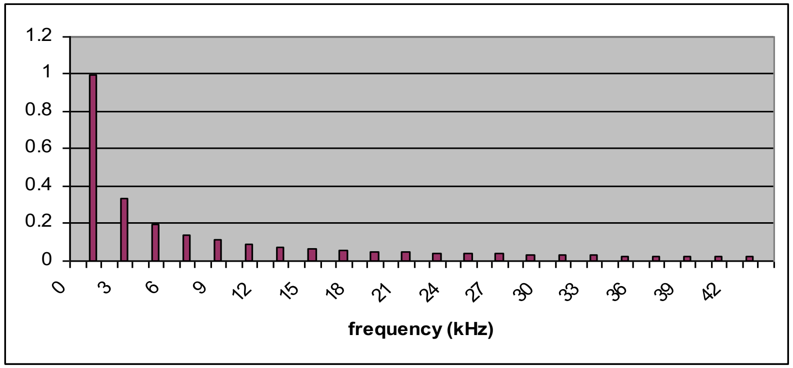
Spectra & Bandwidth

- Spectrum of a signal: measures power of signal as function of frequency
- $x_1(t)$ varies faster in time & has more high frequency content than $x_2(t)$
- Bandwidth W_s is defined as range of frequencies where a signal has non-negligible power, e.g. range of band that contains 99% of total signal power

Spectrum of $x_1(t)$



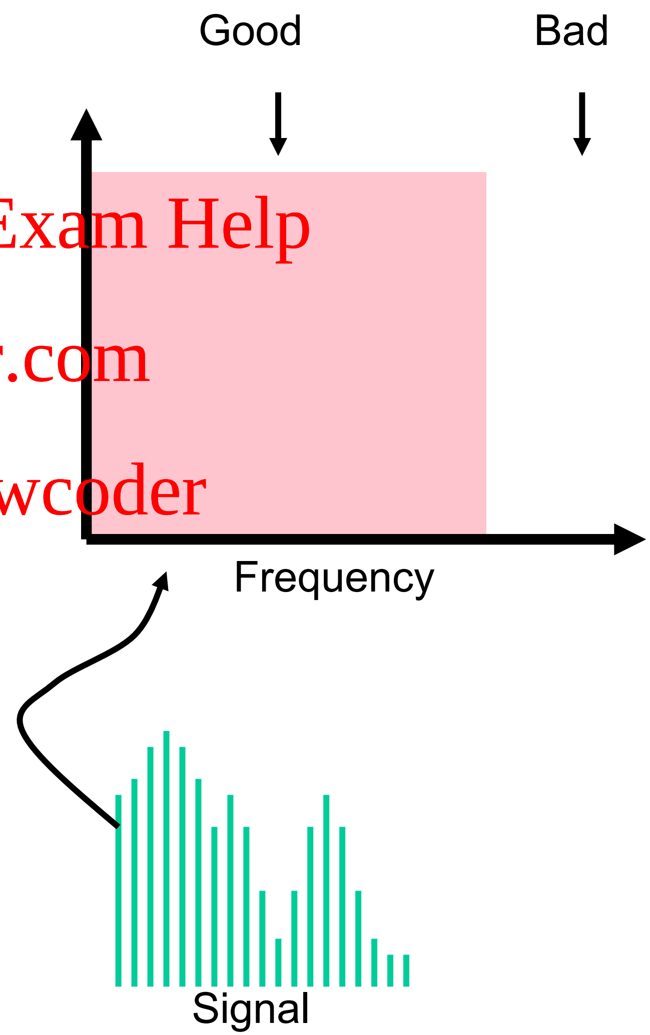
Spectrum of $x_2(t)$



Mini Quiz: Between [A] x_1 and [B] x_2, which has *more* bandwidth?

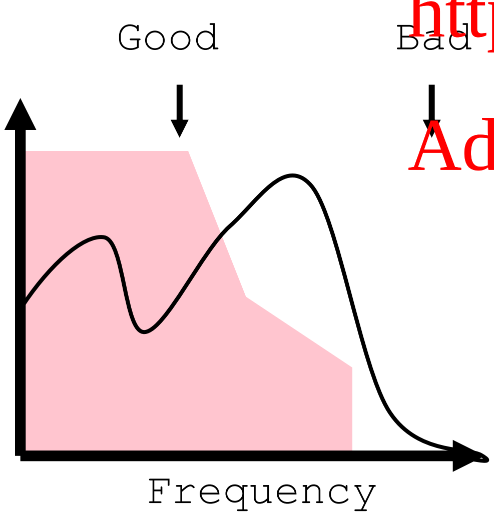
Transmission Channel Considerations

- Every medium supports transmission in a certain frequency range.
  - Outside this range, effects such as attenuation, .. degrade the signal too much
- Transmission and receive hardware will try to maximize the useful bandwidth in this frequency band.
  - Tradeoffs between cost, distance, bit rate
- As technology improves, these parameters change, even for the same wire.



Attenuation & Dispersion

- Not nice low pass filters
- Why do we care?



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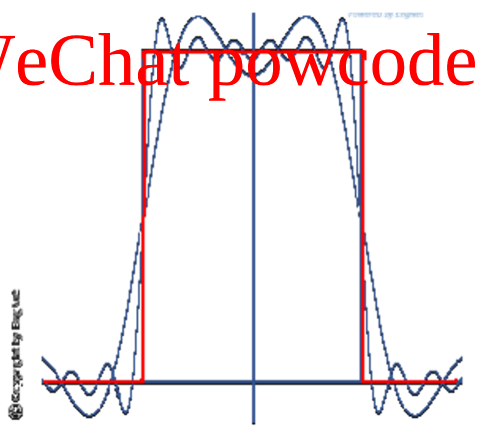


= ???

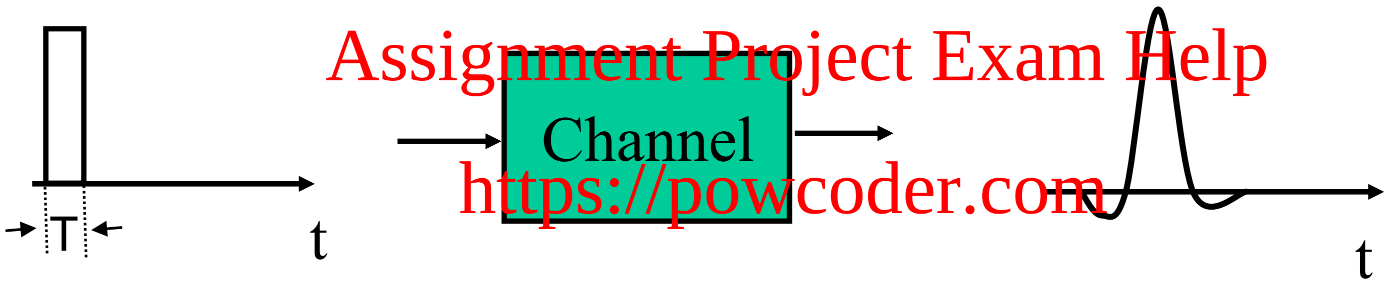
Limits to Speed and Distance

- Noise: "random" energy is added to the signal.
- Attenuation: some of the energy in the signal leaks away.
- Dispersion: attenuation and propagation speed are frequency dependent.
  (Changes the shape of the signal)

- Effects limit the data rate that a channel can sustain.
  - » But affects different technologies in different ways
- Effects become worse with distance.
  - » Tradeoff between data rate and distance

Pulse Transmission Rate

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

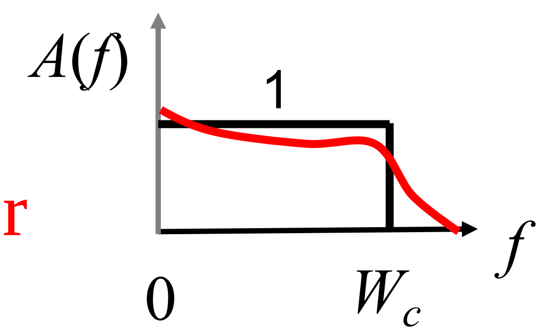


- If input is a narrow pulse, then typical output is a spread-out pulse with ringing
- Question: How frequently can these pulses be transmitted without interfering with each other?
- $2W_c$ pulses/sec with <u>binary amplitude encoding</u> where W_c is the bandwidth of the channel

Bandwidth of a Channel

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

- 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

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

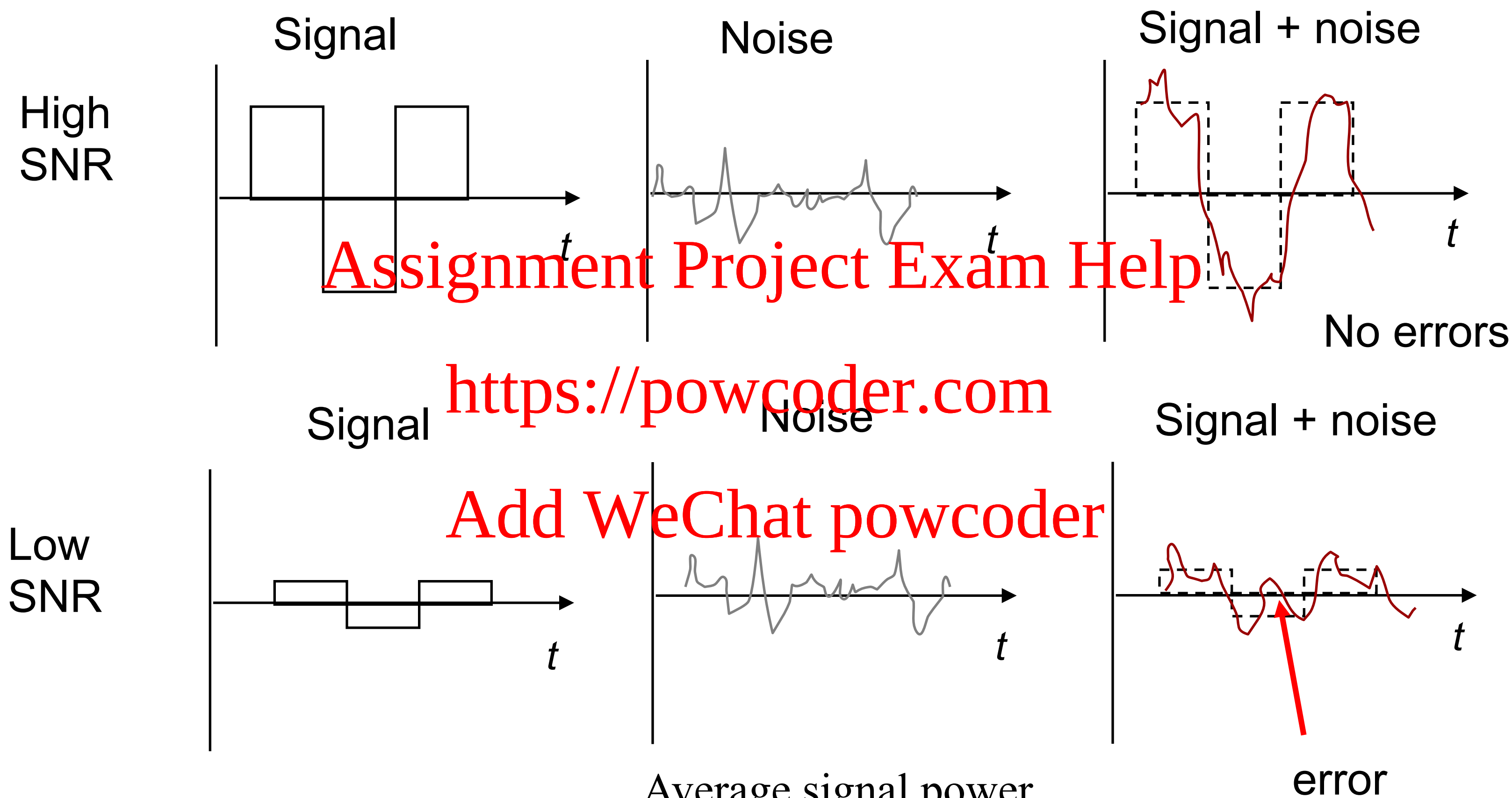
In the absence of noise,

the bit rate can be increased without limit by increasing m

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

Signal-to-Noise Ratio (SNR)



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

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

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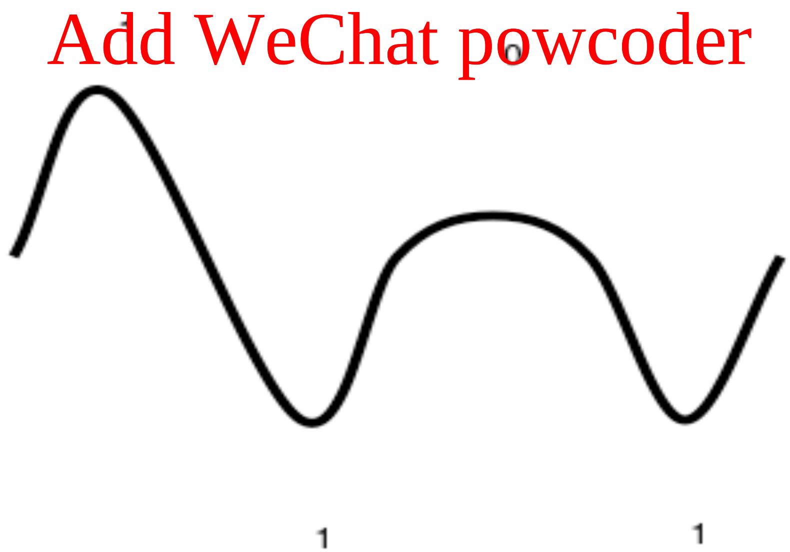
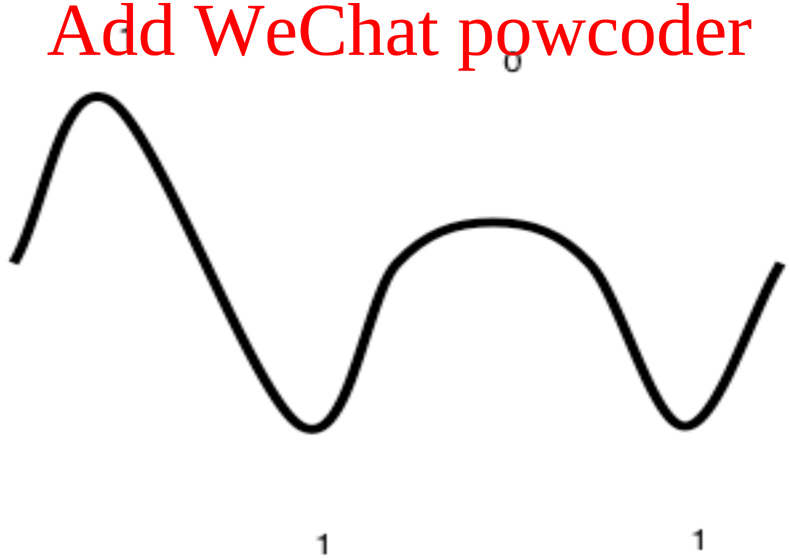
The Nyquist Limit

- A noiseless channel of width H can at most transmit a binary signal at a rate 2 x H.
  – Assumes binary amplitude encoding



The Nyquist Limit

- A noiseless channel of width H can at most transmit a binary signal at a rate 2 x H.
  - Assumes binary amplitude encoding
  - E.g. a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second

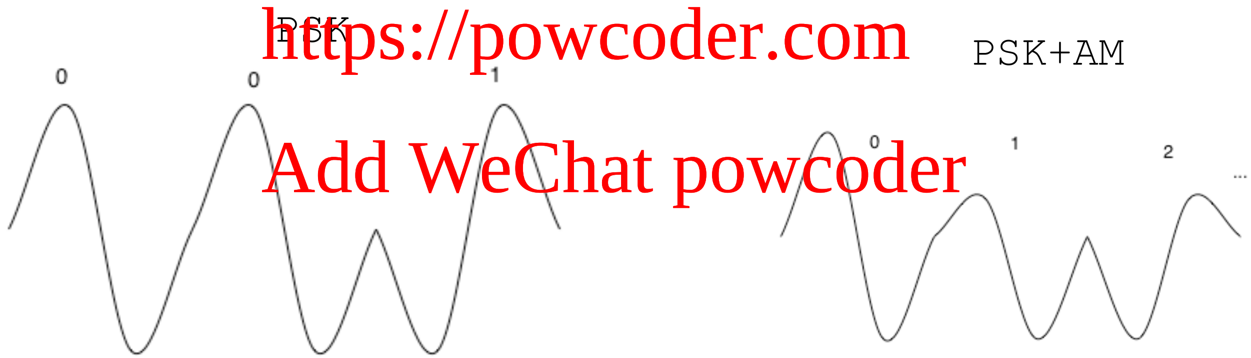


Sample Quiz Question

- **[True / False]** The bandwidth of Wi-Fi (802.11ac, first-gen) is 80 MHz. So by Nyquist theorem, it's max speed is 160 Mbps

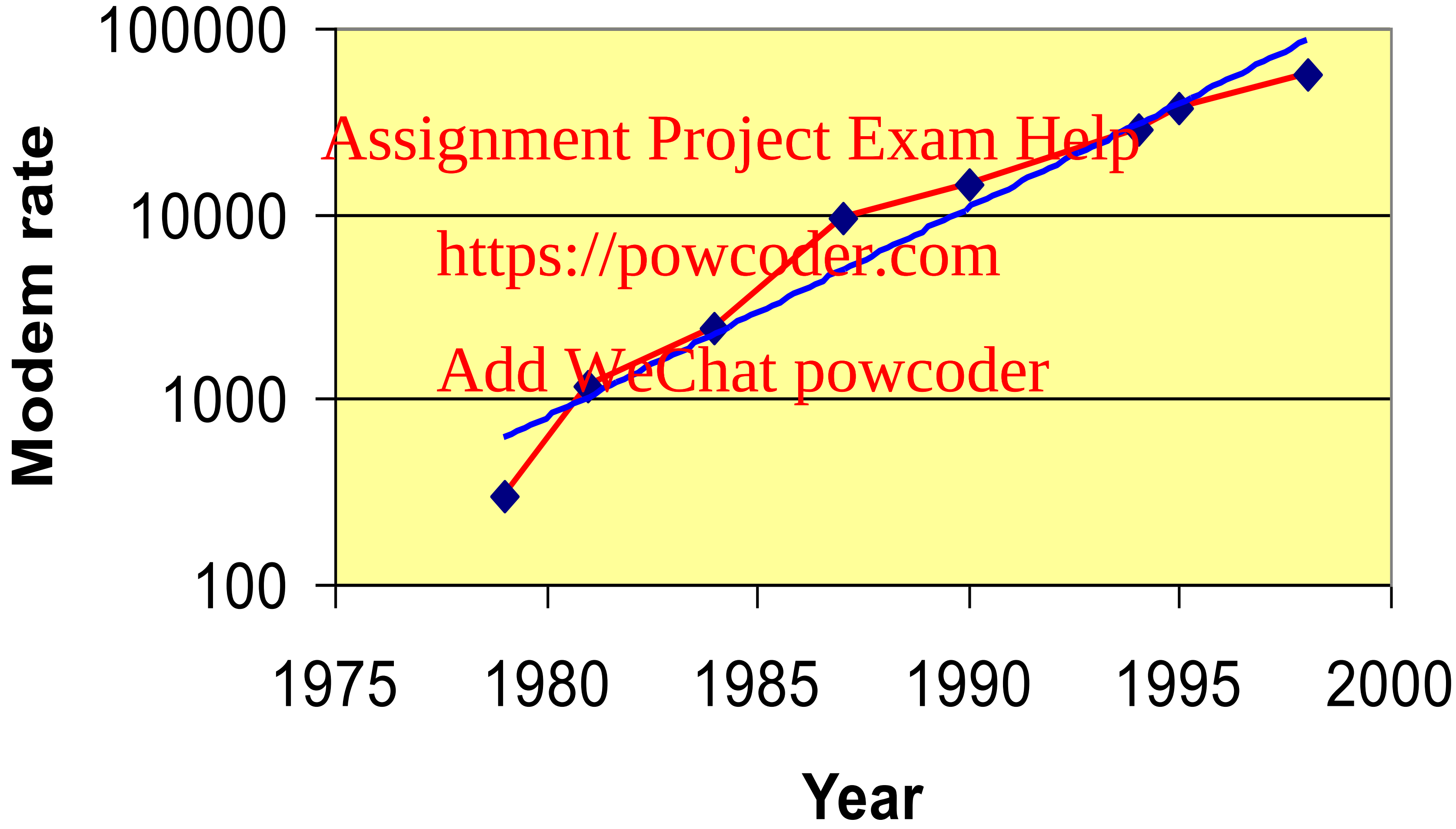
Past the Nyquist Limit

- More aggressive encoding can increase the bandwidth
- Example: modulate multi-valued symbols
  - Modulate blocks of “digital signal” bits, e.g, 3 bits = 8 values
  - Often combine multiple modulation techniques



- Problem? Noise!
  - The signals representing two symbols are less distinct
  - Noise can prevent receiver from decoding them correctly

Example: Modem Rates



Capacity of a Noisy Channel

- Places upper bound on channel capacity, while considering noise
- Shannon's theorem:

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

  - C: maximum capacity (bps)

  - B: channel bandwidth (Hz)
  - S/N: signal to noise ratio of the channel
    Often expressed in decibels (db) ::= 10 log(S/N)

- Example:

  - Local loop bandwidth: 3200 Hz (old school dialup)
  - Typical S/N: 1000 (30db)
  - What is the upper limit on capacity?

$$C = 3200 \times \log_2(1 + 1000) = 31.9 \text{ Kbps}$$

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

Sample Quiz Question

- Find the Shannon channel capacity for a WiFi channel with W_c = 80 MHz and SNR = 40 dB

SNR (dB) = 40 dB corresponds to

SNR = 10^(40/10) = 10000

$C = 80 \log_2 (1 + 10000)$ Mbps

$= 80 \log_{10} (10001)/\log_{10}2 = 1063$ Mbps

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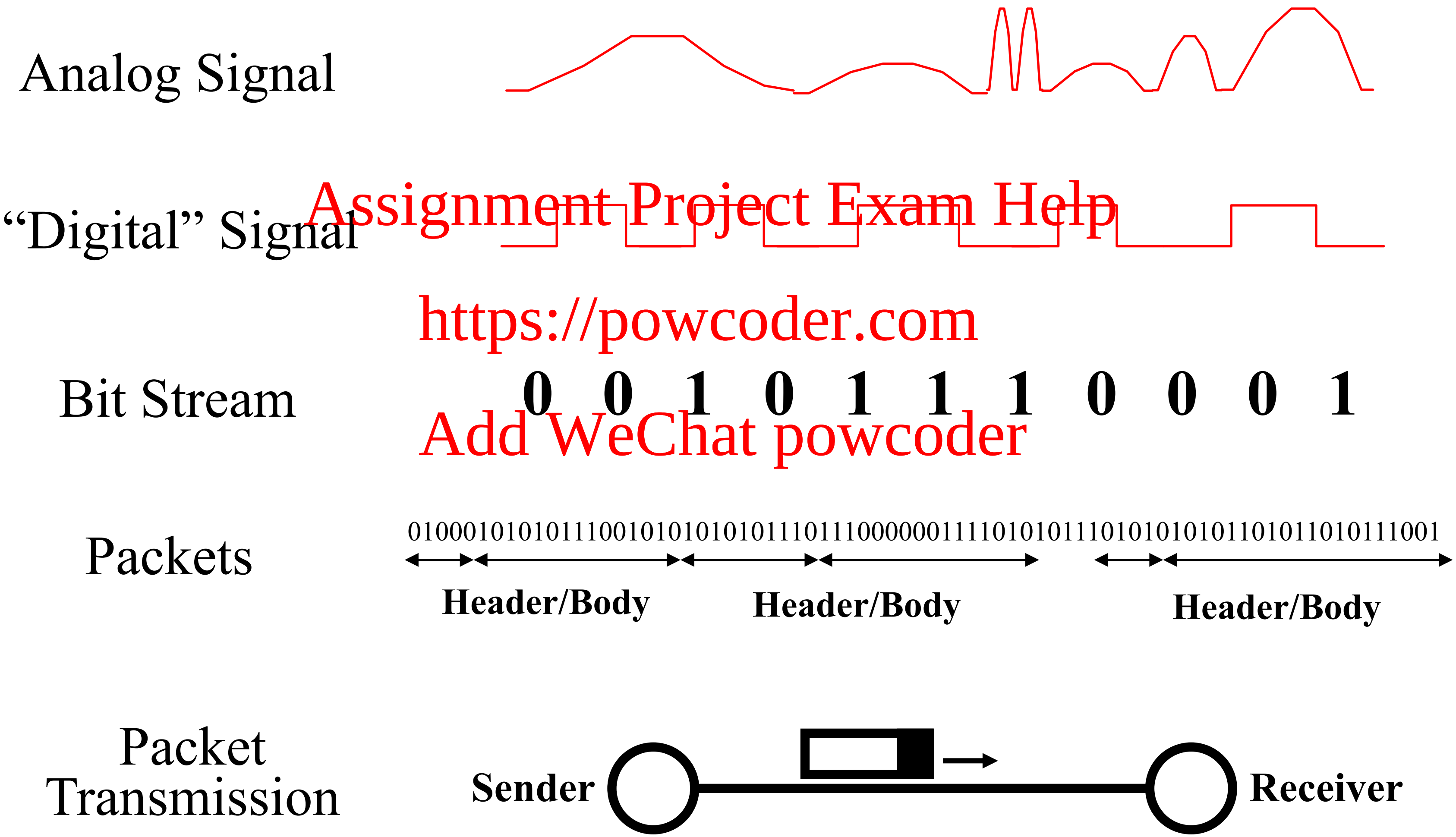
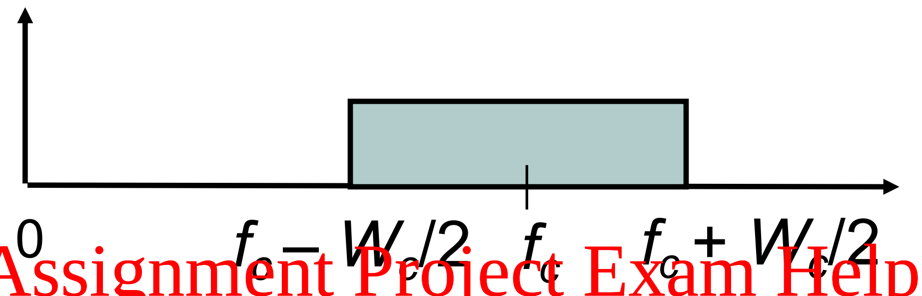
From Signals to Packets



Baseband versus Carrier Modulation

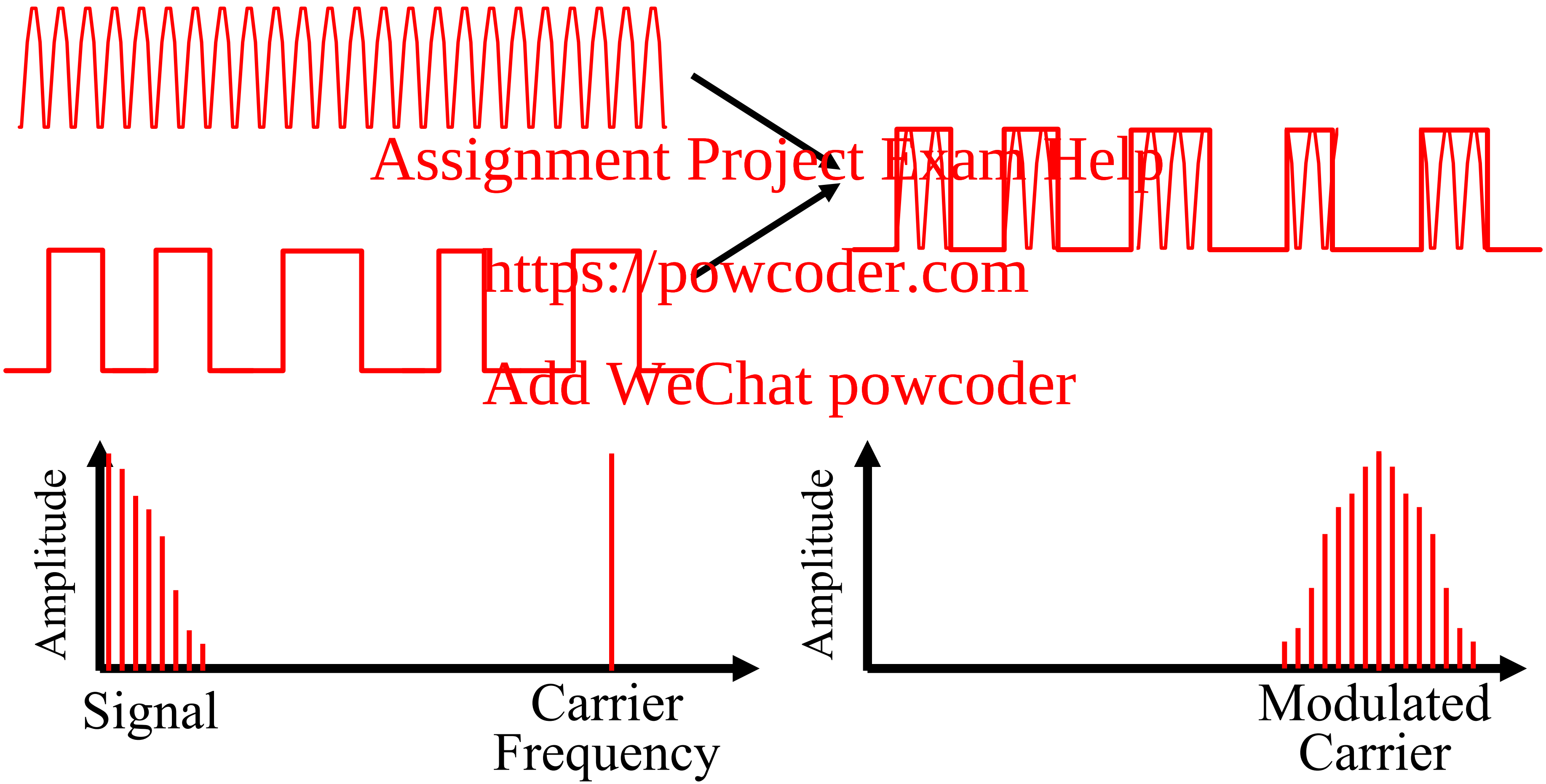
- Baseband modulation: send the “bare” digital signal
  - Channel must be able to transmit low frequencies
  - For example, copper media
- Carrier modulation: use the signal to modulate a higher frequency signal, called a carrier
  - Can send the signal in a particular part of the spectrum
  - Can modulate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

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

Amplitude Carrier Modulation



Signaling rate and Transmission Bandwidth

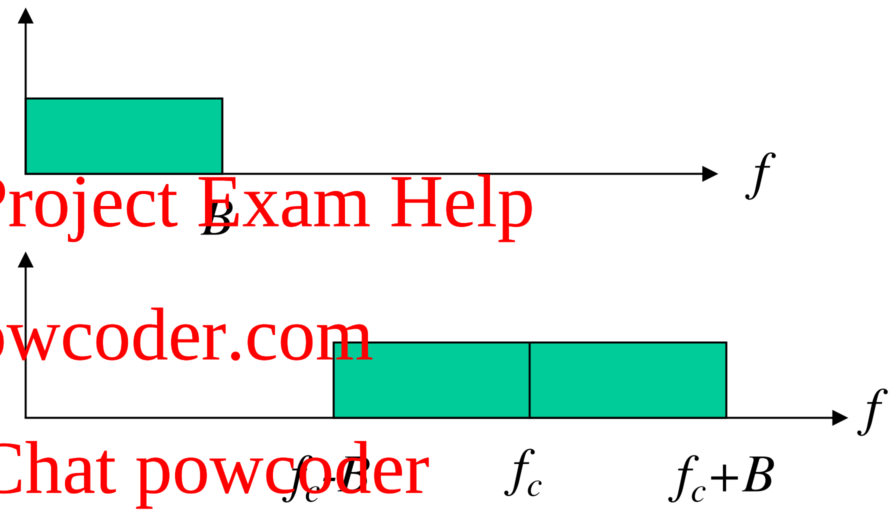
- From modulation theory:

If

Baseband signal *x(t)* with bandwidth *B* Hz

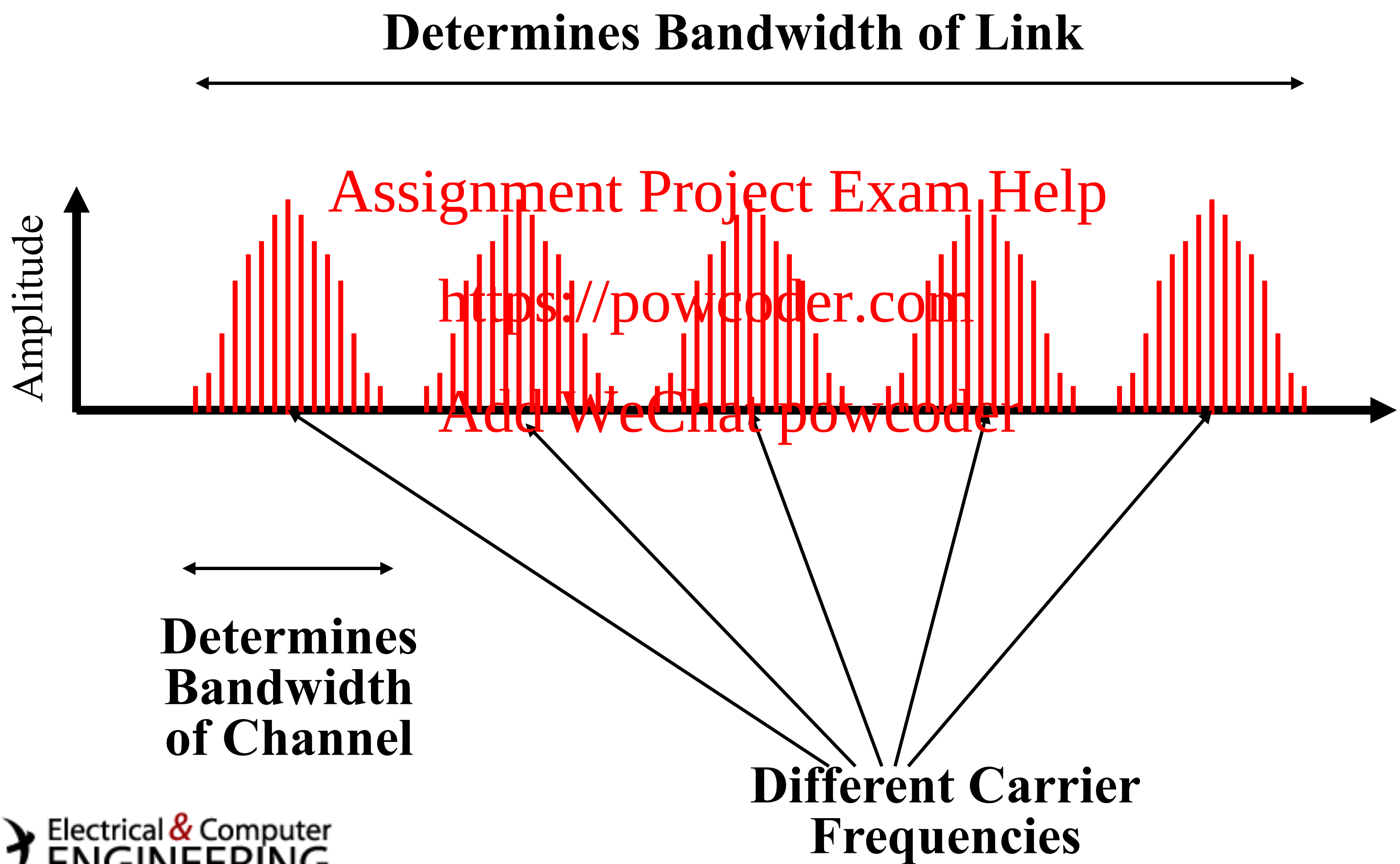
then

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

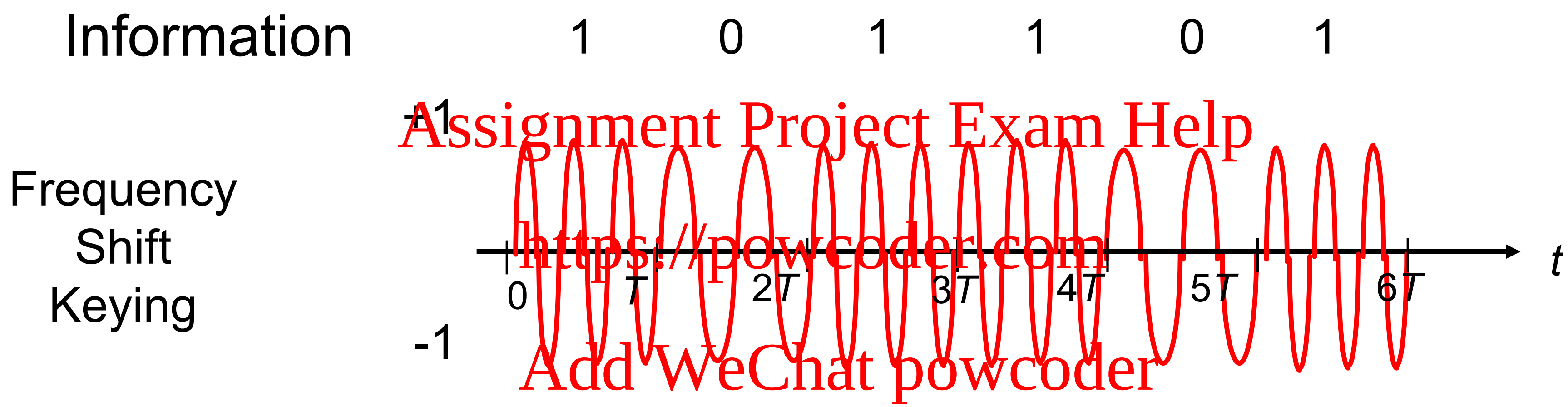


- If bandpass channel has bandwidth W_c Hz,
  - Then baseband channel has $W_c/2$ Hz available, so
  - modulation system supports $W_c/2$ x 2 = W_c pulses/second
  - That is, W_c pulses/second per W_c Hz = 1 pulse/Hz
  - Recall baseband transmission system supports 2 pulses/Hz

Frequency Division Multiplexing: Multiple Channels



Frequency Modulation

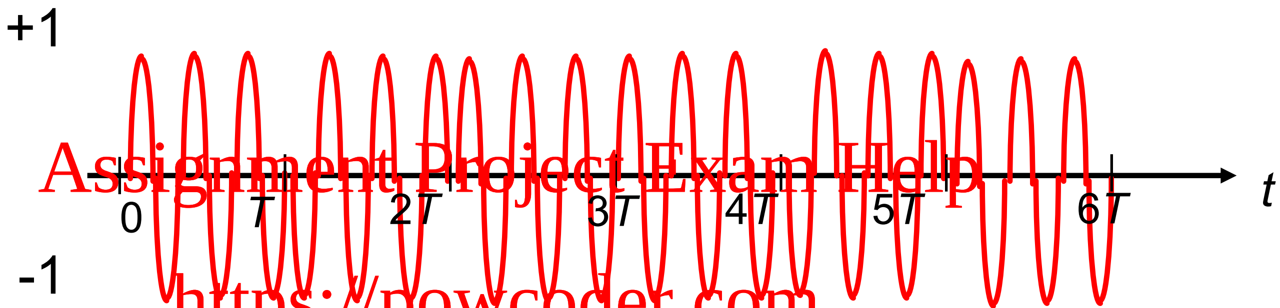


- Use two frequencies to represent bits
  - "1" send frequency *fc* + d
  - "0" send frequency *fc* – d
- Demodulator looks for power around *fc* + d or *fc* - d

Phase Modulation

Information 1 0 1 1 0 1

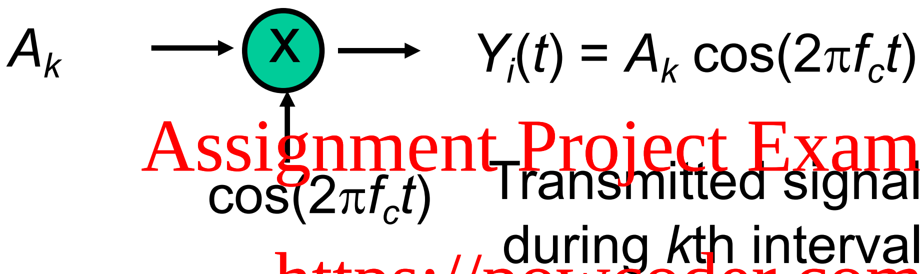
Phase Shift Keying



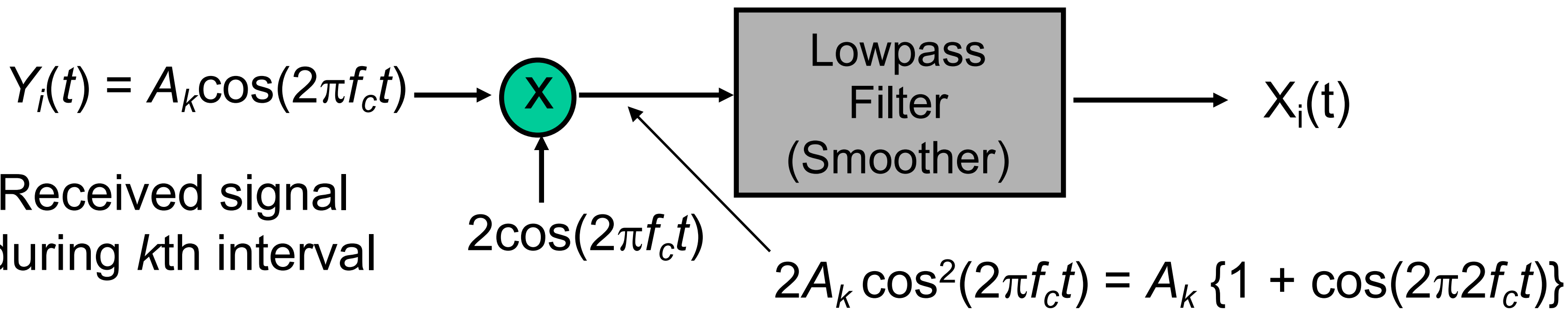
- Map bits into phase of sinusoid:
  - "1" send A cos($2\pi ft$) , i.e. phase is 0
  - "0" send A cos($2\pi ft+\pi$) , i.e. phase is π
- Equivalent to multiplying cos($2\pi ft$) by +A or -A
  - "1" send A cos($2\pi ft$) - multiply by 1
  - "0" send A cos($2\pi ft+\pi$) = - A cos($2\pi ft$) - multiply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

Modulator & Demodulator

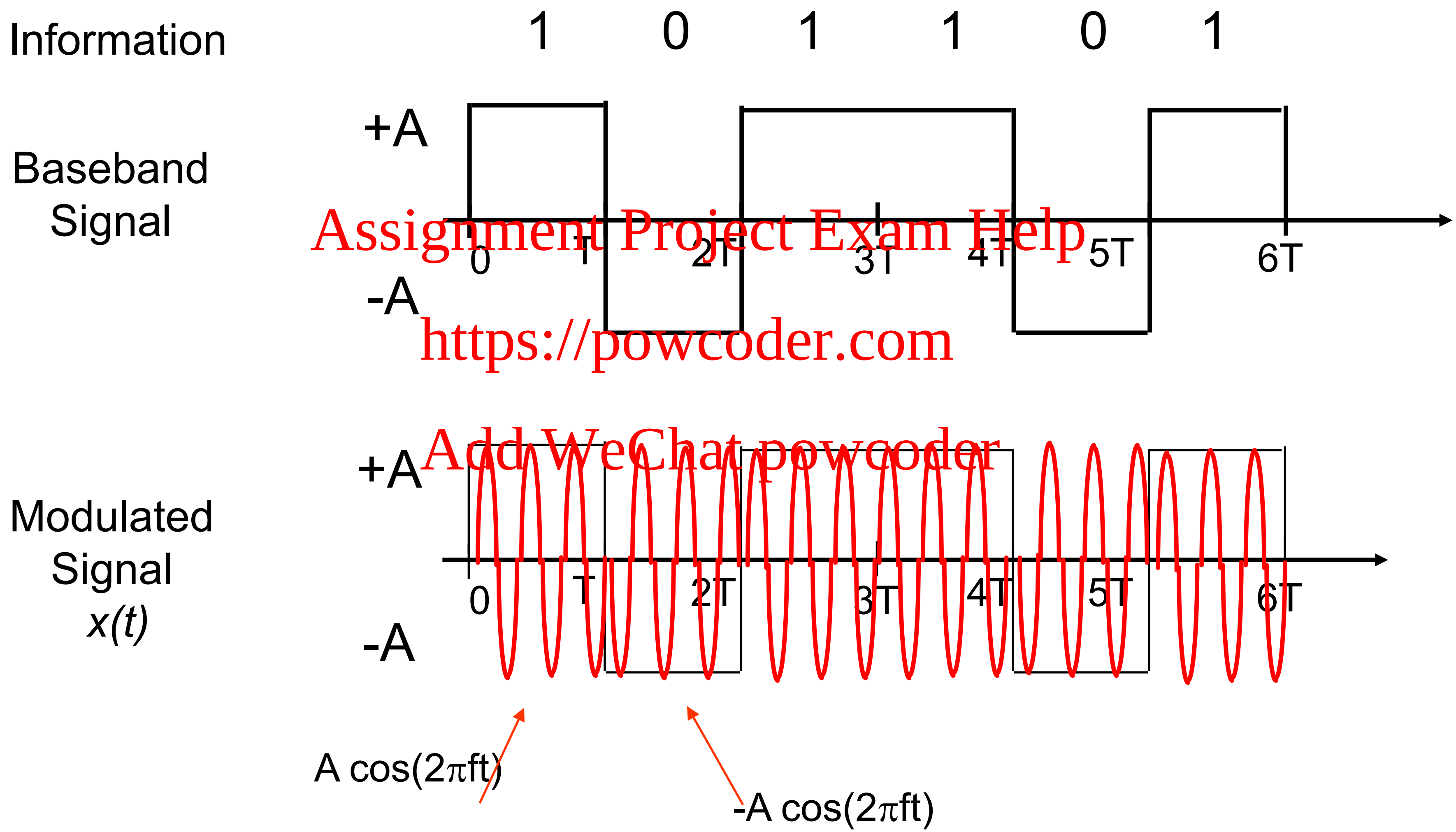
Modulate $\cos(2\pi f_c t)$ by multiplying by A_k for T seconds:



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



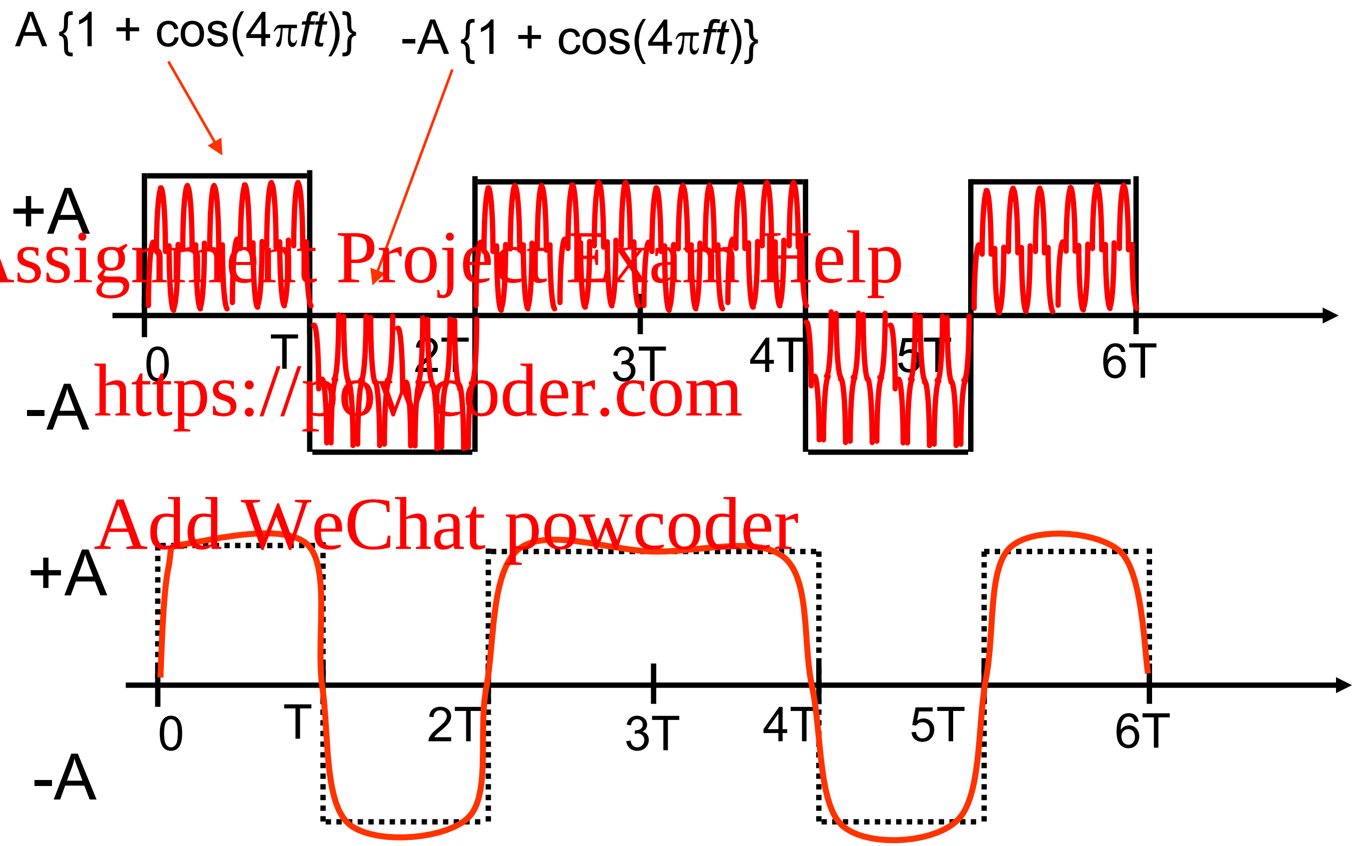
Example of Phase Modulation



Example of Phase Demodulation

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

Baseband signal discernable after smoothing

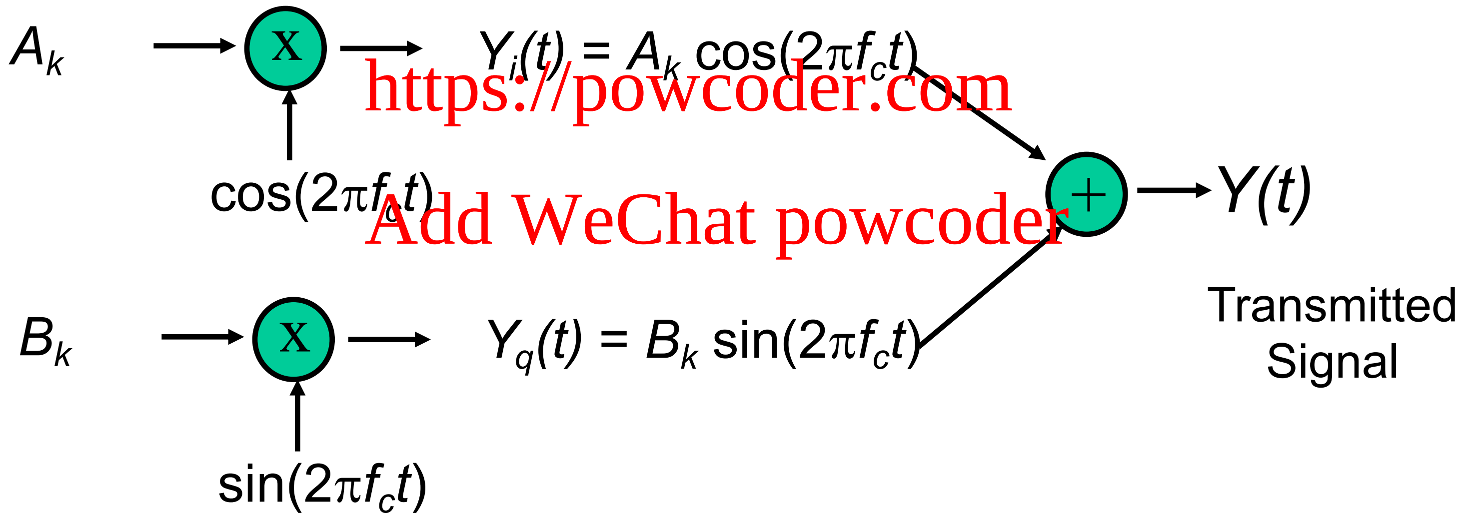


Recovered Information

1 0 1 1 0 1

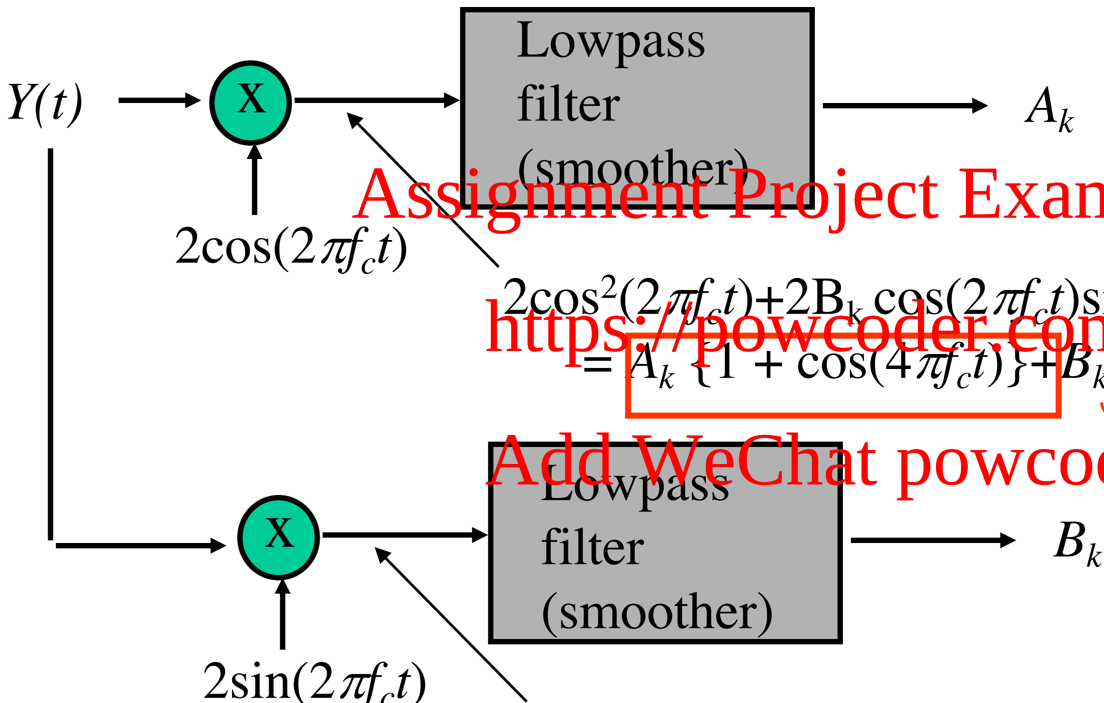
Quadrature Amplitude Modulation (QAM)

- 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



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

QAM Demodulation



$$2\cos^2(2\pi f_c t)+2B_k \cos(2\pi f_c t)\sin(2\pi f_c t)$$

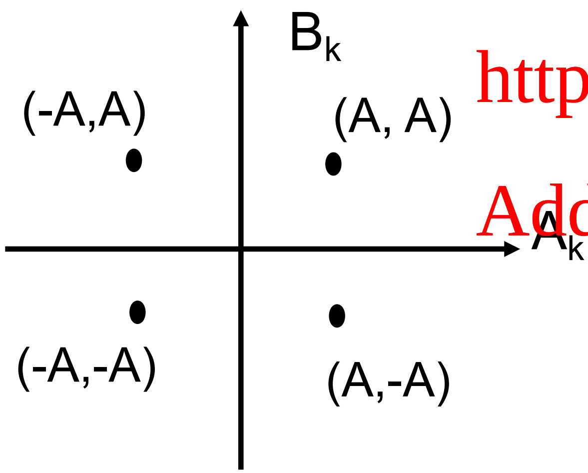
$$= A_k \boxed{\{1 + \cos(4\pi f_c t)\}} + \underbrace{B_k \{0 + \sin(4\pi f_c t)\}}_{\text{smoothed to zero}}$$

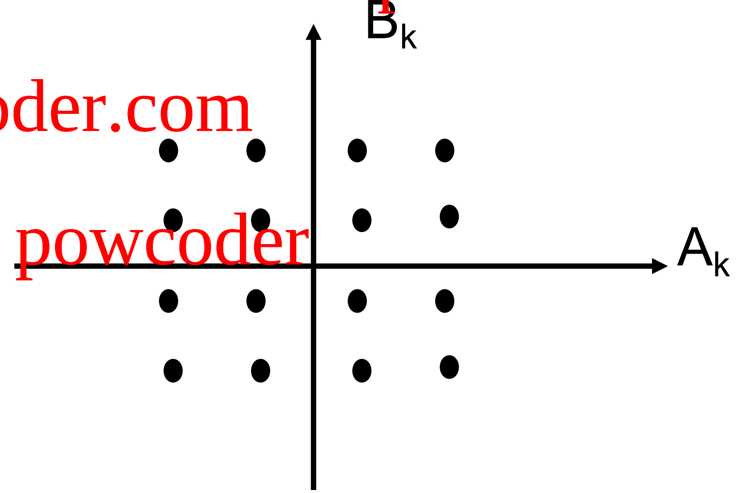
$$2B_k \sin^2(2\pi f_c t)+2A_k \cos(2\pi f_c t)\sin(2\pi f_c t)$$

$$= B_k \boxed{\{1 - \cos(4\pi f_c t)\}} + \underbrace{A_k \{0 + \sin(4\pi f_c t)\}}_{\text{smoothed to zero}}$$

Signal Constellations

- Each pair (A_k, B_k) defines a point in the plane
- *Signal constellation* set of signaling points





4 possible points per *T* sec.
2 bits / pulse

16 possible points per *T* sec.
4 bits / pulse

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- Line Coding (next lecture)
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