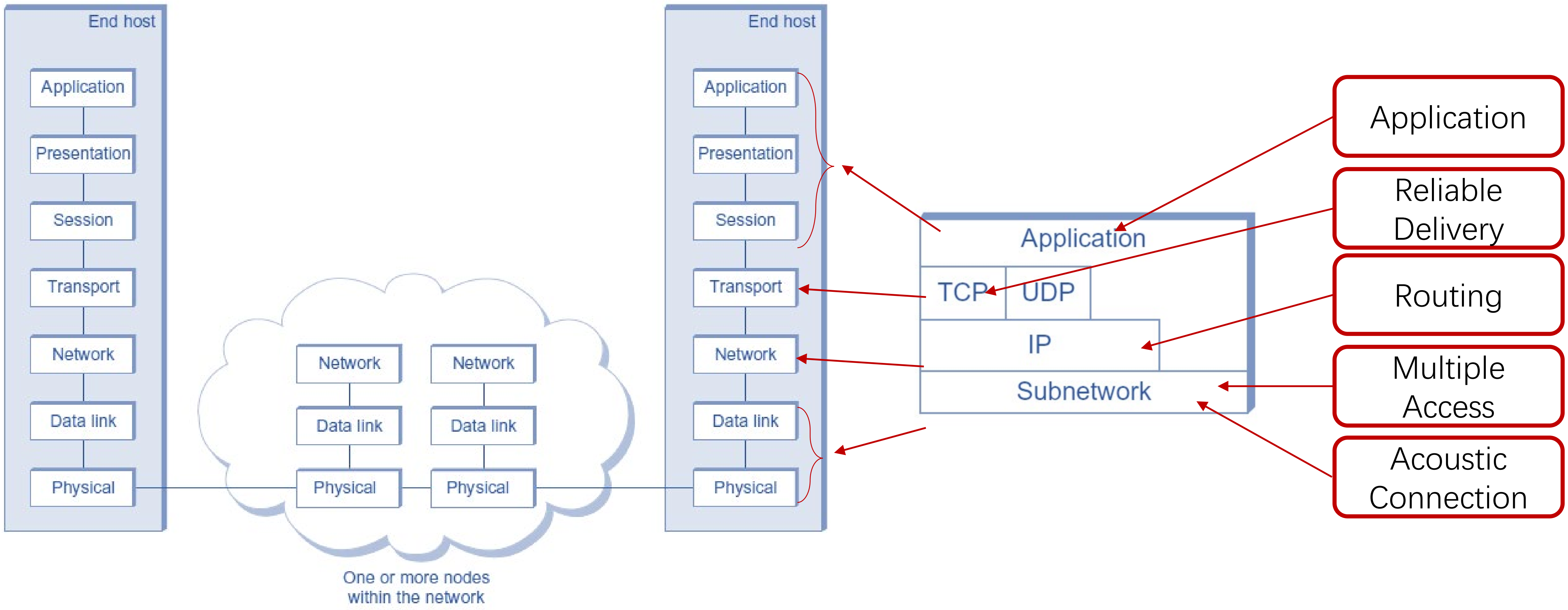
CS120: Computer Networks

Lecture 3. Physical Links

Zhice Yang

Network Layers



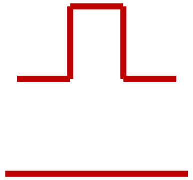
Outline

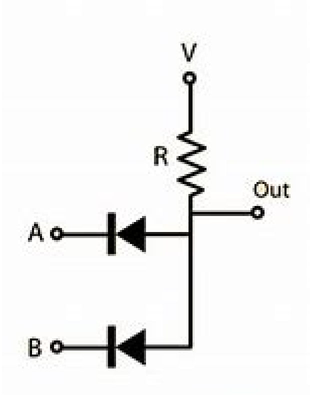
- Communication Basics
    - Communication Medium
        - Carrier
    - Modulation
- Upper Bound of Throughput
- Transmission Method

How to Transmit a Bit in Physical World ?

- Bits in the physical world

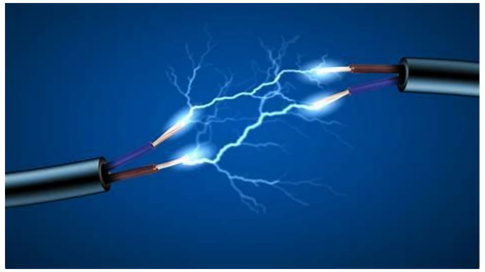
```
a = 1 & 0;
```



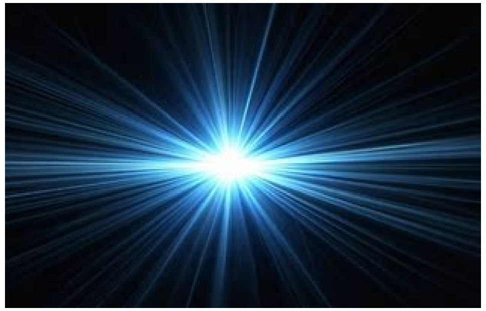


Bits are conveyed by physical medium (eg. electrical signal)

Basic Components of Communication



Electrical Signal



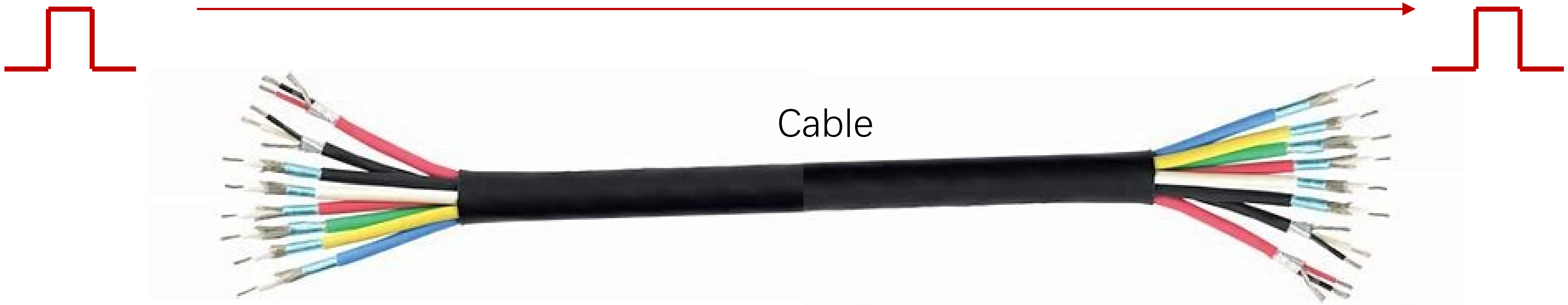
Light

Sound

Medium + Modulation

Change/Manipulate the Physical Medium

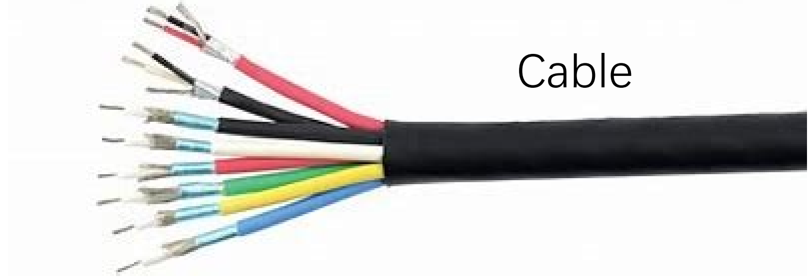
Communication Medium

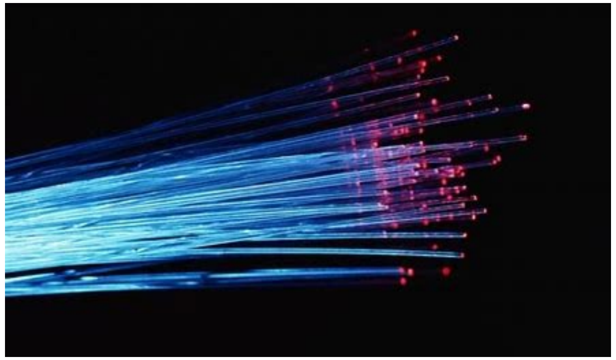


Communication Medium

- Problems of directly conveying bits in cables
  - Distance, distortion, mobility, etc.

?

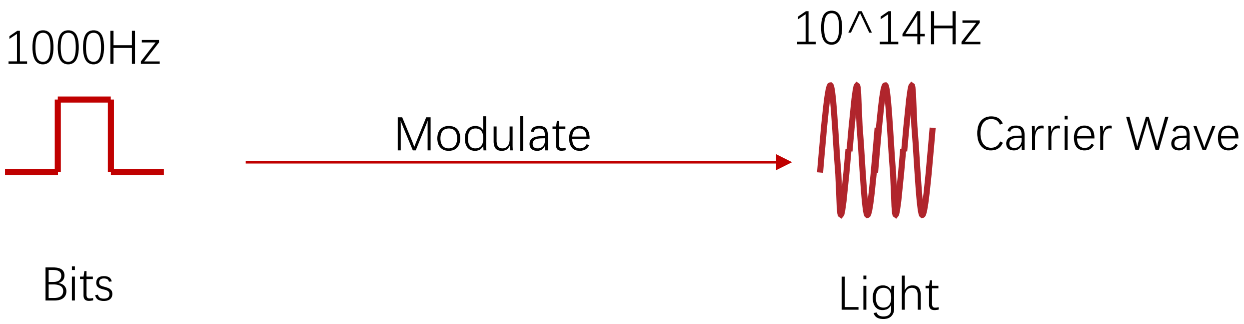




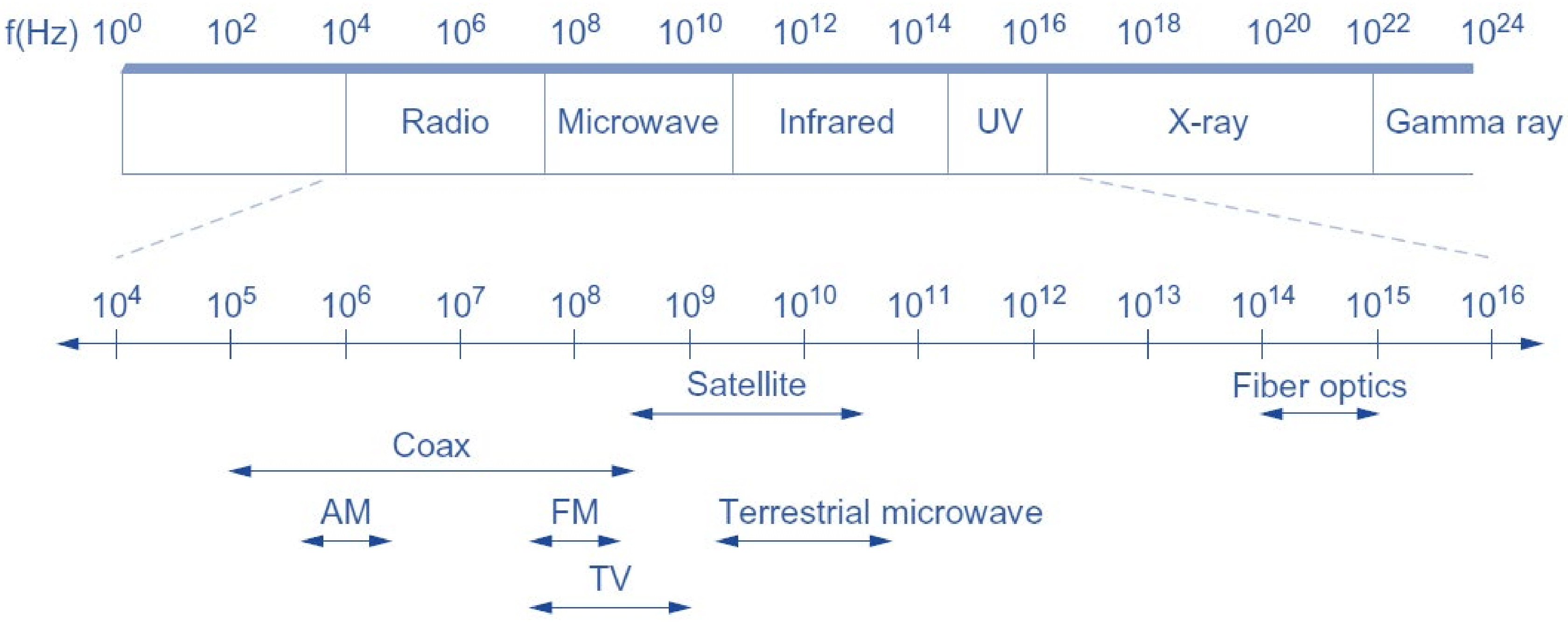
Fiber:
Light Wave

Free Space:
Radio Wave,
Acoustic Wave,
etc.

Carrier Wave – the wave for carrying information

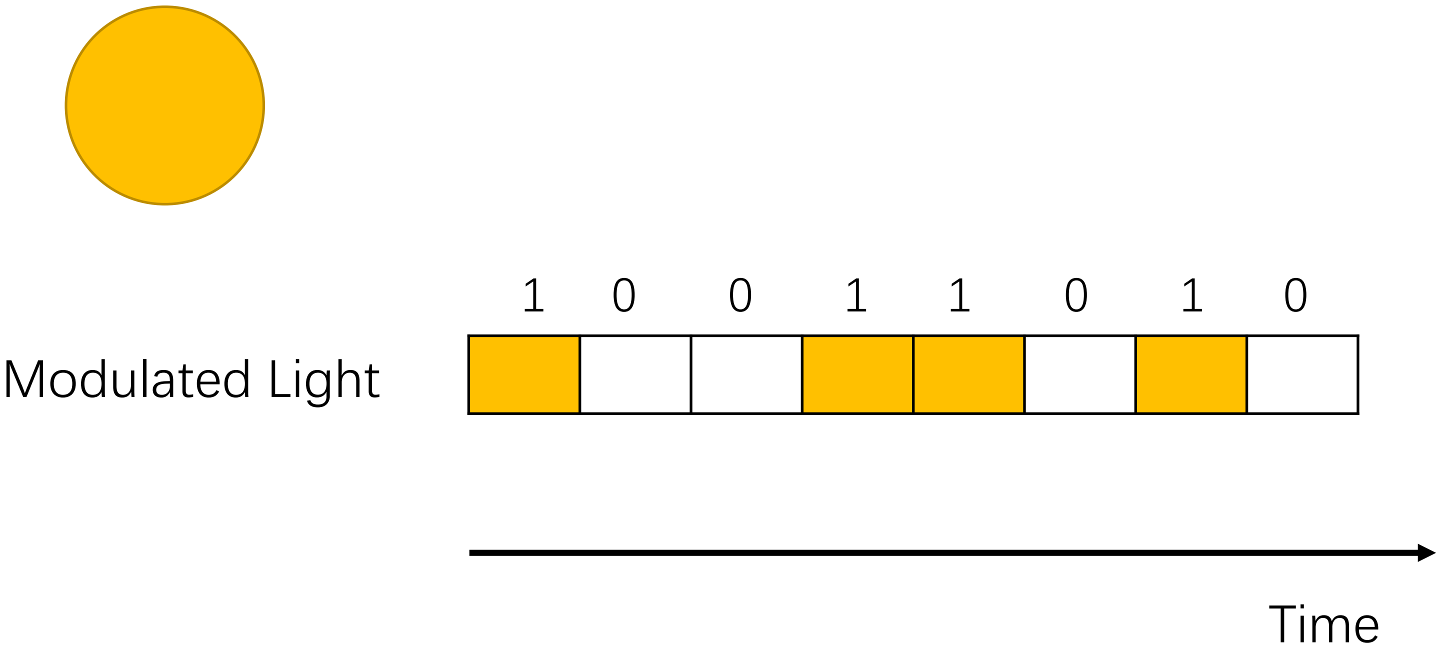


Radio Spectrum:



Modulation

- Modulation: the process of varying one or more properties of the carrier wave to transmit the information
  - Signal containing information is called modulated signal
- Example: On-Off Modulation



Demo: On-Off Modulation

```
%%
clear all;
t=linspace(0,1,44100);
one=sin(2*pi*1000*t);
zero=zeros(1,length(one));
transmit=([one,zero,zero,one,one,zero,one,zero]);
figure;
plot(transmit);
sound(transmit,44100);
```

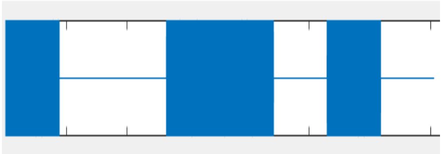
1 0 0 1 1 0 1 0

How Fast can We Achieve ?

1 0 0 1 1 0 1 0

1bps

2bps



Outline

- Communication Basics
  - Communication Medium
    - Carrier
  - Modulation
- ➢Upper Bound of Throughput
- Transmission Method

Shannon-Hartley Theorem

- The theoretical throughput upper bound:

Bandwidth

Signal Power

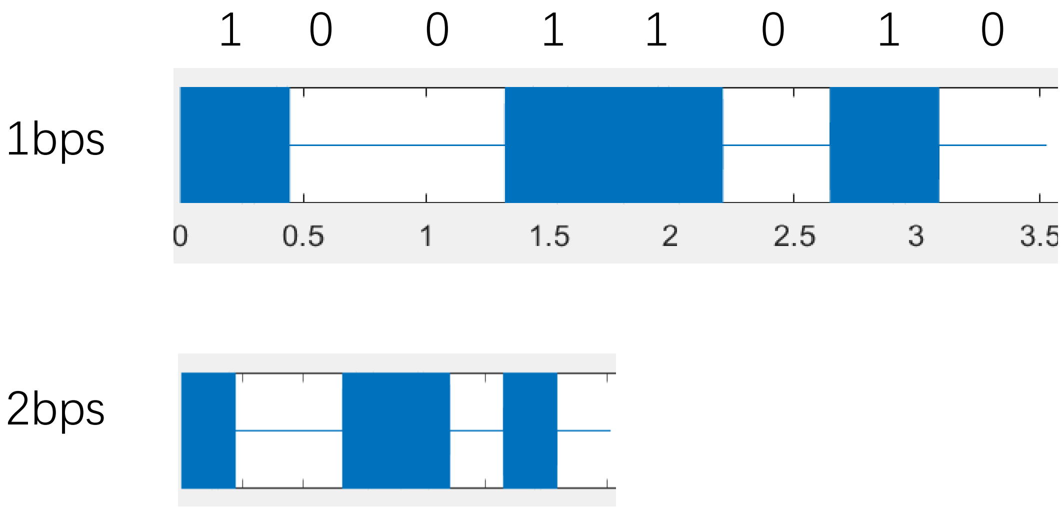
$$C = B\log_2(1 + \frac{S}{N})$$

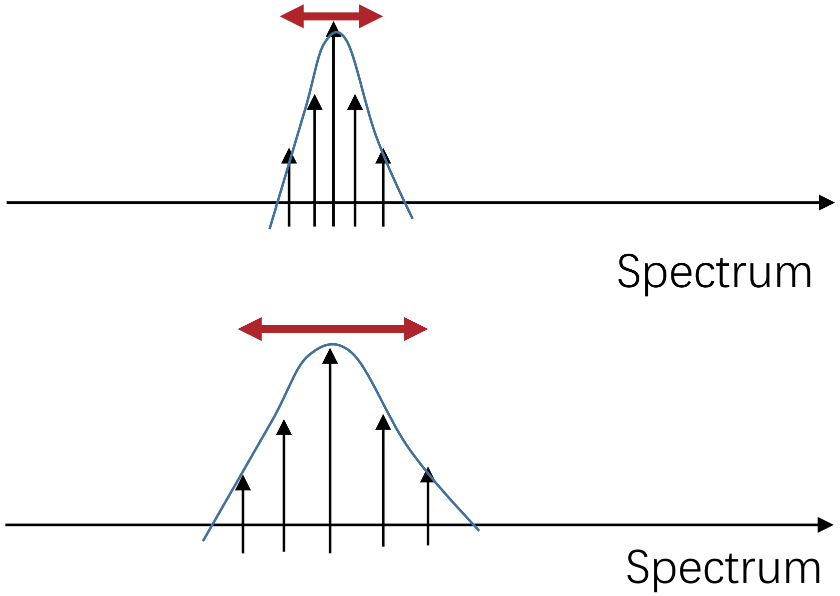
Channel Capacity

Noise Power

“Bandwidth” v.s. Bandwidth

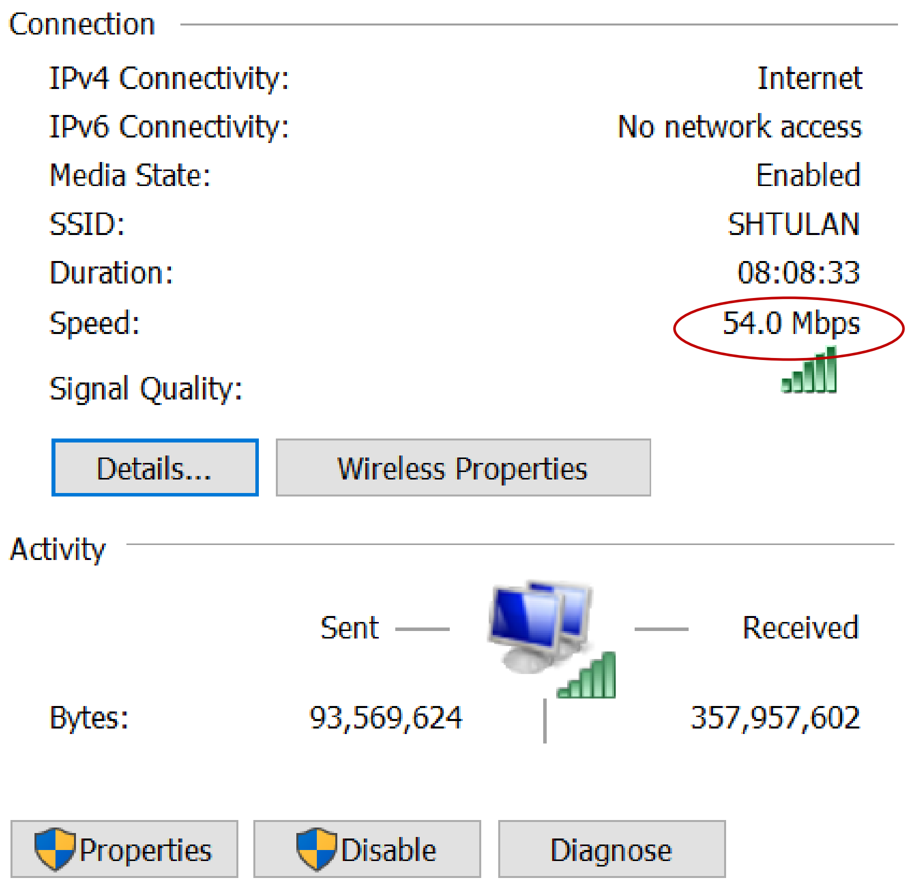
- The term “Bandwidth” is often used with two different meanings.
  - Rate: throughput (bps)
  - Spectrum: the width of the occupied the spectrum (Hz)





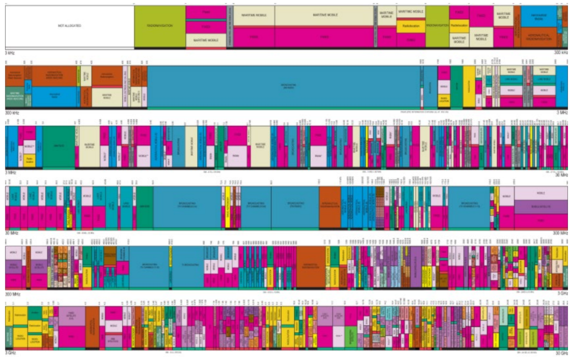
“Bandwidth” v.s. Bandwidth

- Be careful about the confusion



This is the rate bandwidth
The spectrum bandwidth is 20MHz !

How Fast can We Achieve ?



Limited by ADC DAC rate,
Available Spectrum

Bandwidth

Limited by Power and
Safety Concern

Signal Power

$$C = B\log_2(1+\frac{S}{N})$$

Channel Capacity

Noise Power

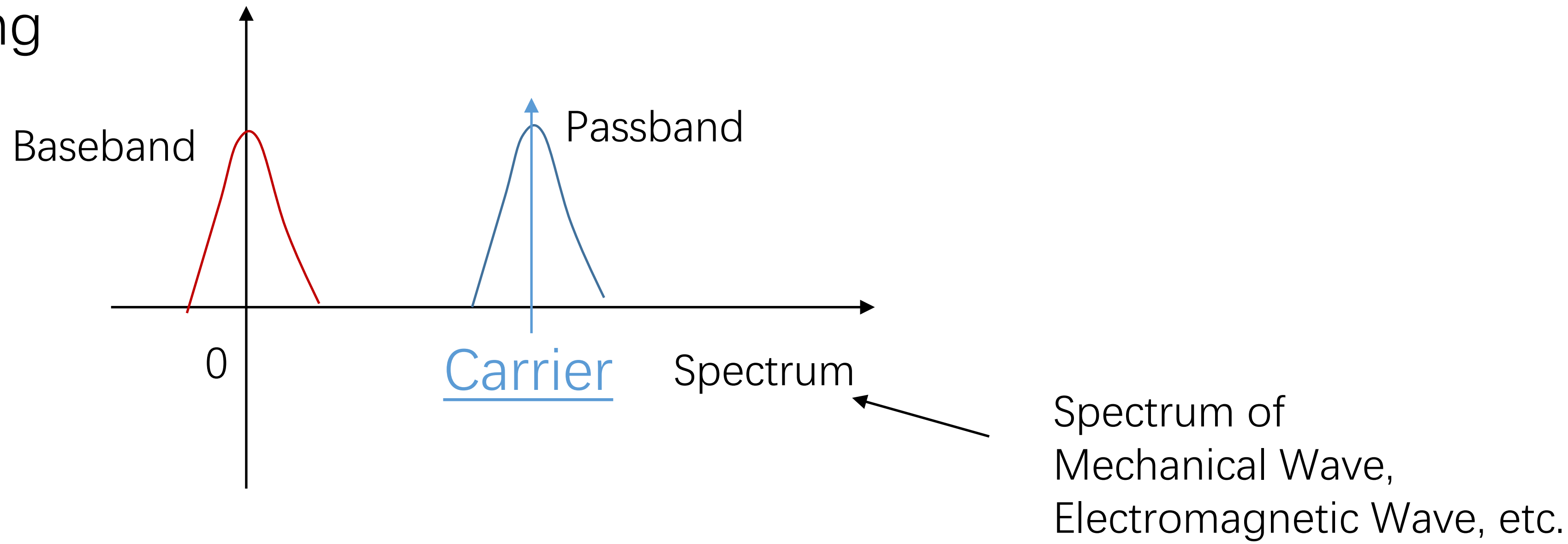
Limited by Thermal Noise
and Manufacturing

Outline

- Communication Basics
  - Communication Medium
    - Carrier
  - Modulation
- Upper Bound of Throughput
- ➢Transmission Method
  - Baseband Transmission
  - Passband Modulation

Transmission Method

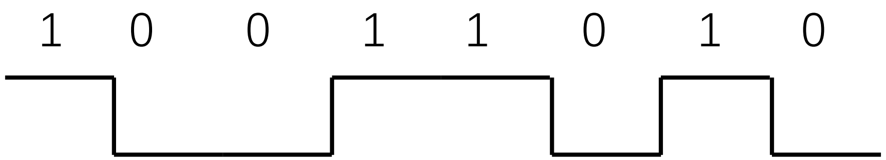
- Baseband Transmission (Line Coding)
  - No carrier wave, transmit bits or coded stream directly to the medium, might not be long-distance, eg. usb, Ethernet, hdmi, etc.
- Passband Modulation
  - Good transmission properties (suitable medium, distance, etc.)
  - Multiplexing



Baseband Transmission

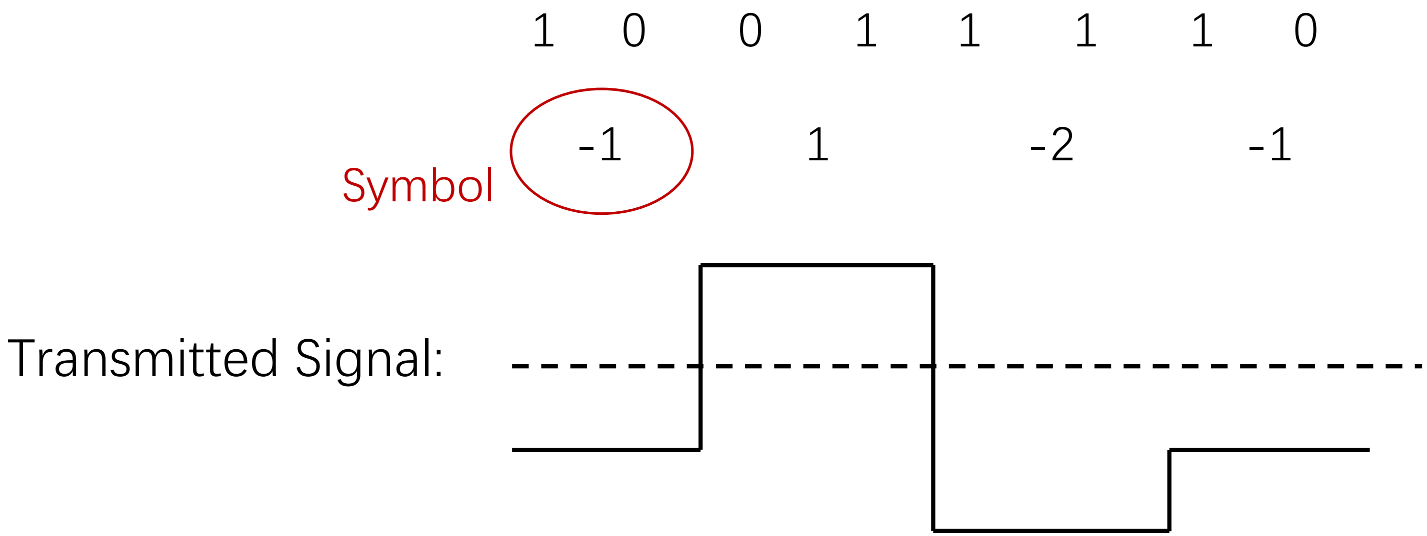
- “1” -> High Voltage
- “0” -> Low Voltage

Transmitted Signal:



Baseband Transmission

- The communication signal is not necessarily changed in binary pattern
  - “00” -> 2v
  - “01” -> 1v
  - NONE -> 0v
  - “10” -> -1v
  - “11” -> -2v



- Symbol Rate := Baud Rate
  - The number of symbols per unit time

Symbol Rate

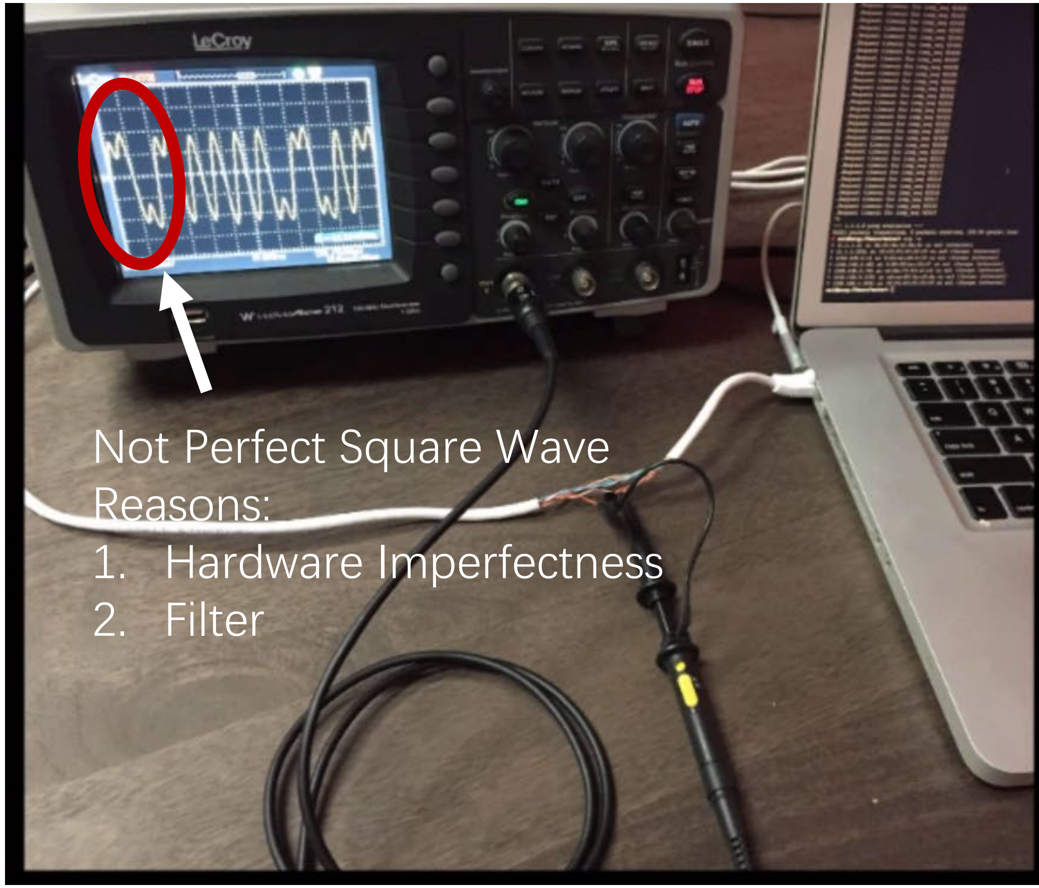
- Unit: baud (Bd) i.e. symbols per second
- Convert to bit rate
  - M: the number of different symbols
  - R_B: Baud Rate
  - R_b: Bit Rate

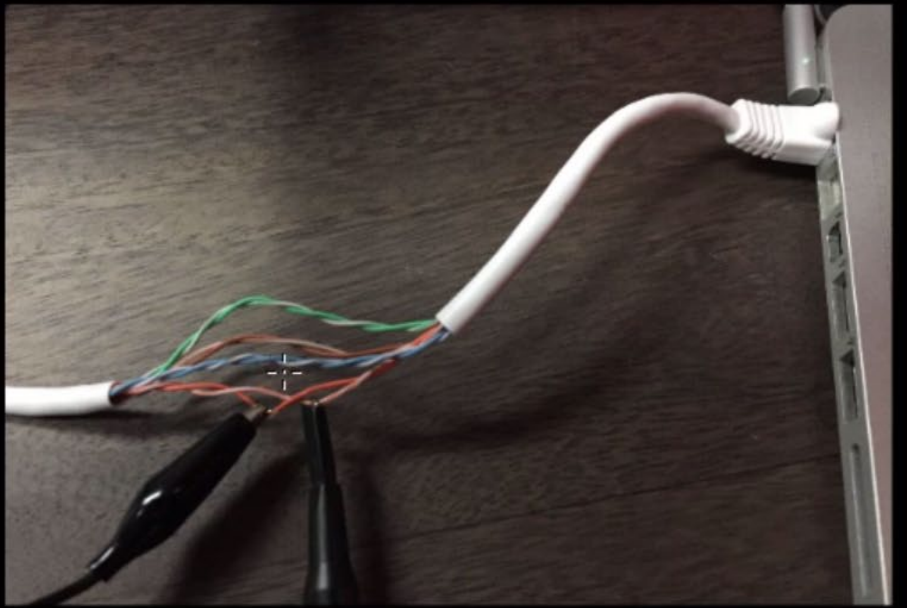
$$R_b = R_B \log_2 M$$

- Using the number of different symbols to increase Bandwidth ?
  - Signal/noise ratio is lower

Baseband Transmission

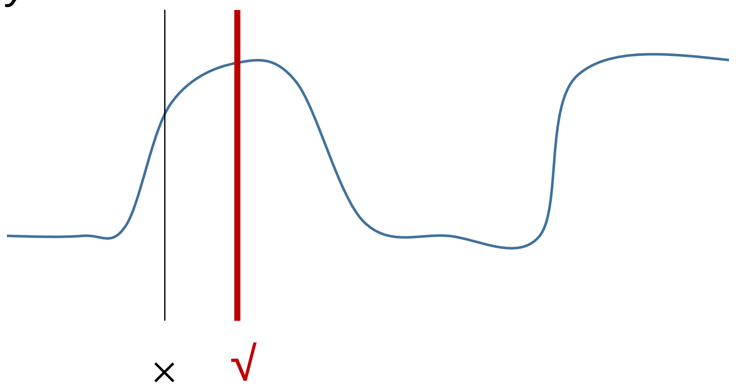
- How to Receive ?



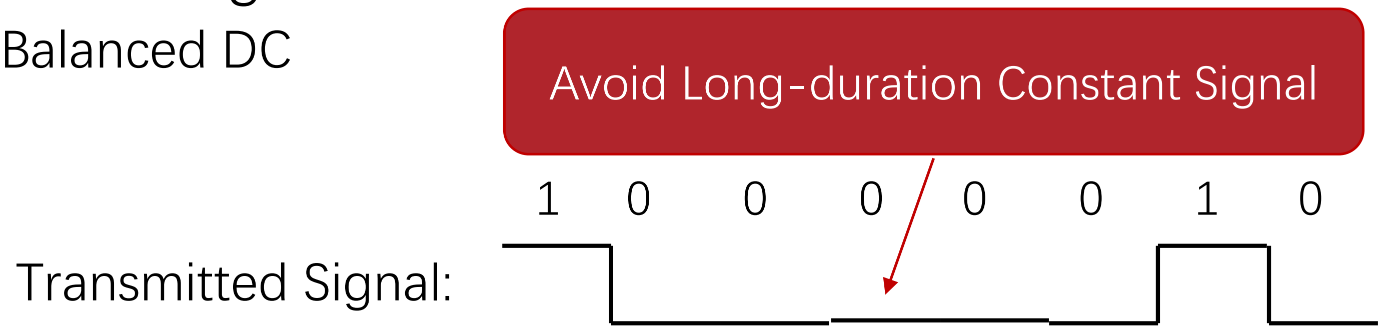


Baseband Transmission

- Problems at Receiver
  - Sampling
    - Clock Recovery



  - Thresholding
    - Balanced DC

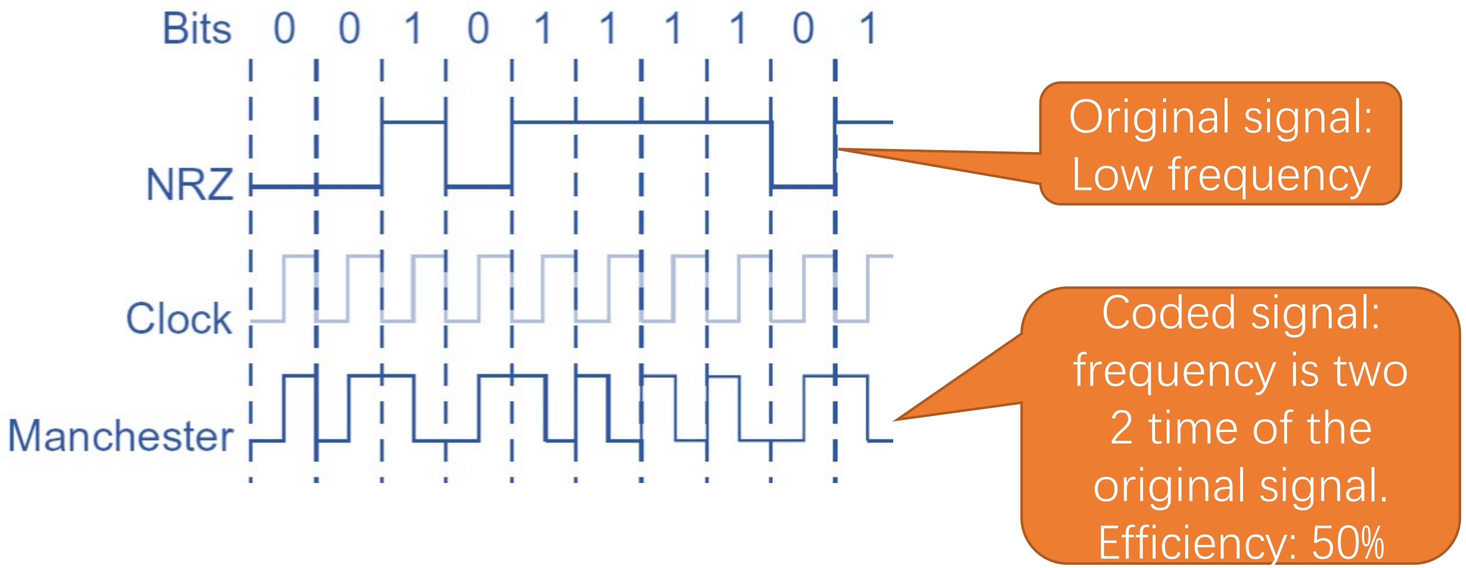


Baseband Transmission

- Clock Recovery
  - Synchronous Transmission
    - Transmit the clock directly through (additional line, frequency band, etc.)
    - Less processing (decoding or encoding) overhead but low efficiency
  - Asynchronous Transmission
    - Recover the clock from data signal
    - Use line encoder/decoder, high efficiency
    - Design
      - Goal: should avoid constant 0s or 1s
      - Reason: the hardware needs “changes” to track the clock
        - If the signal has transitions between level 0 and level 1, PLL (Phase Locked Loop) can keep tracking the frequency and phase of the signal (the signal from the transmitter). However, the tracking has errors. The error accumulates after each valid track action, which only happens when the transition takes place. That’s why we must avoid long constant 1s or 0s, which do not contribute to the transitions.

Baseband Transmission

- Clock Recovery
  - Option 1: Synchronous Transmission
    - e.g. Manchester Code (Ethernet 10BaseT)



Baseband Transmission

- Clock Recovery
  - Option 2: Asynchronous Transmission
    - e.g. 4B5B Code (Ethernet 100BASE-TX etc.)
    - Map 4Bit data to 5Bit code
      - To ensure there is no >=4 consecutive 0s in the coded data
        - No guarantee for 1s.
      - Efficiency: 80% (much higher than Manchester code)

Table 2.2 4B/5B Encoding

4-Bit Data Symbol	5-Bit Code
0000	11110
0001	01001
0010	10100
0011	10101
0100	01010
0101	01011
0110	01110
0111	01111
1000	10010
1001	10011
1010	10110
1011	10111
1100	11010
1101	11011
1110	11100
1111	11101

Baseband Transmission

- Clock Recovery
  - Option 2: Asynchronous Transmission
    - e.g. 4B5B Code (Ethernet 100BASE-TX etc.)+NRZI
  - NRZI take transitions at bit 1
    - Use to break consecutive 1s.

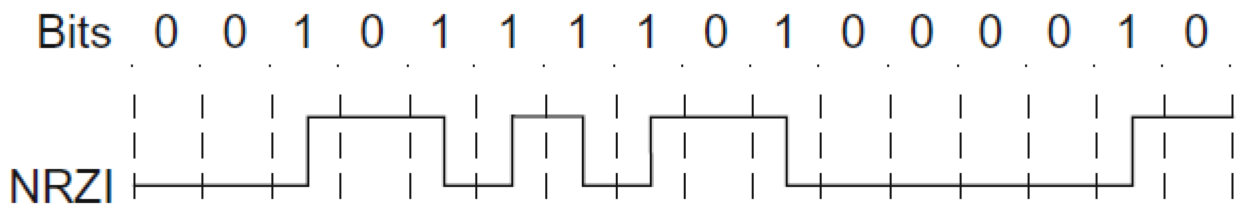
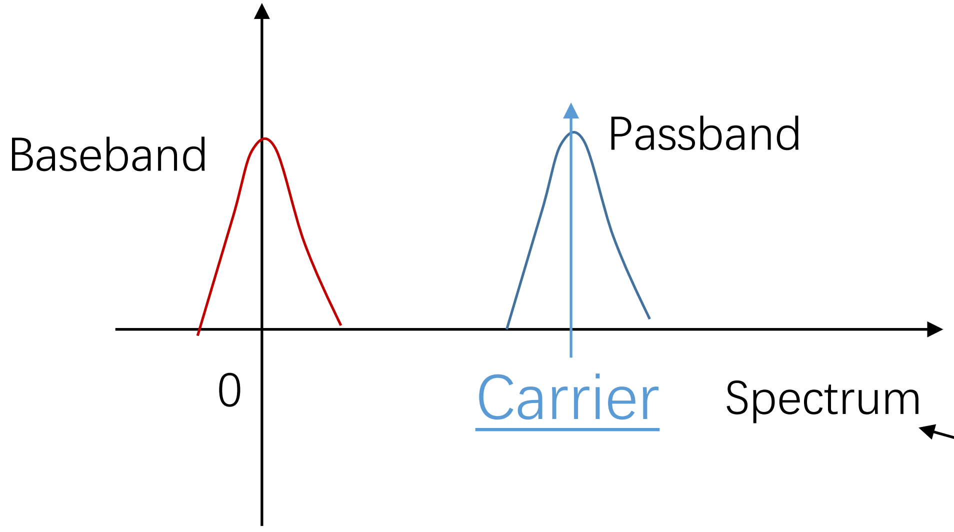


Table 2.2 4B/5B Encoding

4-Bit Data Symbol	5-Bit Code
0000	11110
0001	01001
0010	10100
0011	10101
0100	01010
0101	01011
0110	01110
0111	01111
1000	10010
1001	10011
1010	10110
1011	10111
1100	11010
1101	11011
1110	11100
1111	11101

Transmission Method

- Baseband Transmission (Line Coding)
- Passband Modulation
  - Good transmission property
  - Multiplexing



Spectrum of Mechanical Wave, Sound Wave, etc.

Demo: Baseband and Passband Signal

```
clear all;
fs=44100;
t=linspace(0,1,44100);
one=ones(1,length(t));% no carrier wave
zero=zeros(1,length(one));
transmit_05Hz_baseband=([one,zero,zero,one,one,zero,one,zero]); % 1bps 0.5Hz
fs_unit=fs*(0:length(transmit_05Hz_baseband)-1)/length(transmit_05Hz_baseband);
figure;
plot(fs_unit, abs(fft(transmit_05Hz_baseband))); % spectrum
figure;
plot(transmit_05Hz_baseband)
```

Baseband signal is used to modulate a carrier signal to get a passband signal

```
clear all;
fs=44100;
t=linspace(0,1,44100);
one=sin(2*pi*1000*t);% carrier wave
zero=zeros(1,length(one));
transmit_05Hz_passband=([one,zero,zero,one,one,zero,one,zero]); % 1bps 0.5Hz
fs_unit=fs*(0:length(transmit_05Hz_passband)-1)/length(transmit_05Hz_passband);
figure;
plot(fs_unit, abs(fft(transmit_05Hz_passband))); % spectrum
```

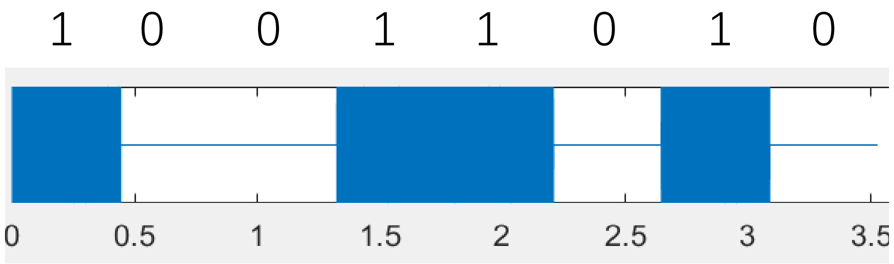
How to Describe the Carrier ?

- Carrier is a Wave
  - Amplitude
  - Frequency
  - Phase

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

Passband Modulation

- On-Off Keying (OOK)
  - Switching the working state (on or off) of the carrier wave to express symbols
  - A special case of modifying the amplitude of the carrier.
- Demodulation
  - Averaging the received power (low pass filter)
  - Thresholding



Demo: OOK Modulation

```
clear all;
t=linspace(0,1,44100);
one=sin(2*pi*10*t);
zero=zeros(1,length(one));
transmit=([one,zero,zero,one,one,zero,one,zero]);

receive=transmit;
receive_power=receive.^2;
receive_power_smooth=smooth(receive_power,44100);
sampling_point=(44100/2:44100:length(receive));
figure;
plot(receive_power_smooth);
hold on;
for i=1:length(sampling_point)
    plot([sampling_point(i),sampling_point(i)],[0.3,0.7], 'r');
end
hold off;

samples=receive_power_smooth(sampling_point);
bits=samples>mean(receive_power);
```

Passband Modulation

- Amplitude Shift Keying (ASK)
  - Switching in amplitude of the carrier wave to express symbols
  - e.g. :

“0”

“1”

- Demodulation
  - non-coherent
    - Find the envelop (low pass filtering)
    - Thresholding
  - Coherent
    - Dot product with the carrier wave
    - $\mathrm{A}\cos(2\pi f t)\cdot\cos(2\pi f t) = \frac{1}{2}\mathrm{A}(\cos(2\pi 2 f t) + 1)$
    - Low pass filtering
    - Thresholding

```
%% ASK demo
clear all;
t=linspace(0,1,44100);
one=sin(2*pi*10*t);
zero=0.5*sin(2*pi*10*t);
transmit=([one,zero,zero,one,one,zero,one,zero]);

receive=transmit;
receive_shift=receive.*[one,one,one,one,one,one,one,one];
figure;
plot(smooth(receive_shift,44100))
```

Passband Modulation

- Frequency Shift Keying (FSK)
  - Switching the frequency of the carrier wave to express symbols
  - e.g.

"0"

"1"

- Demodulation
  - Similar as ASK

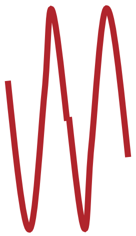
```
%% FSK demo
clear all;
t=linspace(0,1,44100);
one=sin(2*pi*10*t);
zero=cos(2*pi*20*t);
transmit=([one,zero,zero,one,one,zero,one,zero]);

receive=transmit;
receive_shift=receive.*[one,one,one,one,one,one,one,one];
figure;
plot(receive_shift)
figure;
plot(smooth(receive_shift,44100))
```

Passband Modulation

- Phase Shift Keying (PSK)
  - Switching the phase of the carrier wave to express symbols
  - e.g.

“0”



“1”

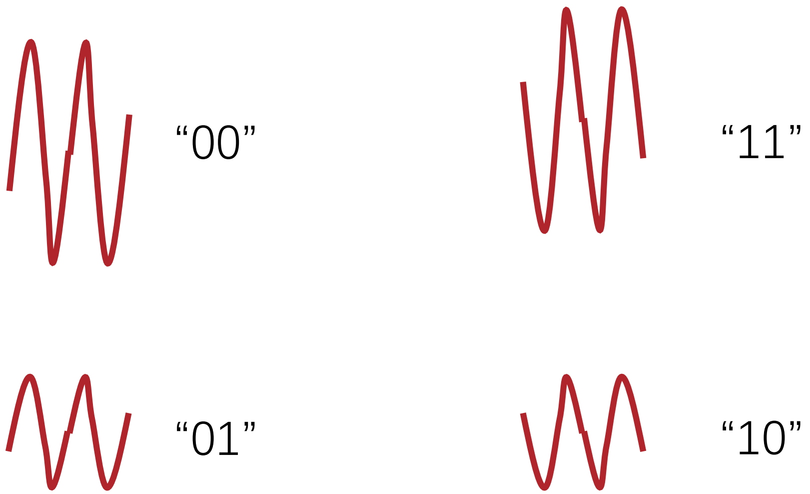
- Demodulation
  - Coherent
    - Dot product with the carrier wave
      - $\cos(2\pi f t) \cdot \cos(2\pi f t) = \frac{1}{2}(\cos(2\pi 2 f t) + 1)$
      - $\cos(2\pi f t + \pi) \cdot \cos(2\pi f t) = \frac{1}{2}(\cos(2\pi 2 f t) - 1)$
    - Low pass filtering
    - Thresholding

```
%% PSK demo
clear all;
t=linspace(0,1,44100);
one=sin(2*pi*10*t);
zero=cos(2*pi*10*t);
transmit=([one,zero,zero,one,one,zero,one,zero]);

receive=transmit;
receive_shift=receive.*[one,one,one,one,one,one,one,one];
figure;
plot(smooth(receive_shift,44100))
```

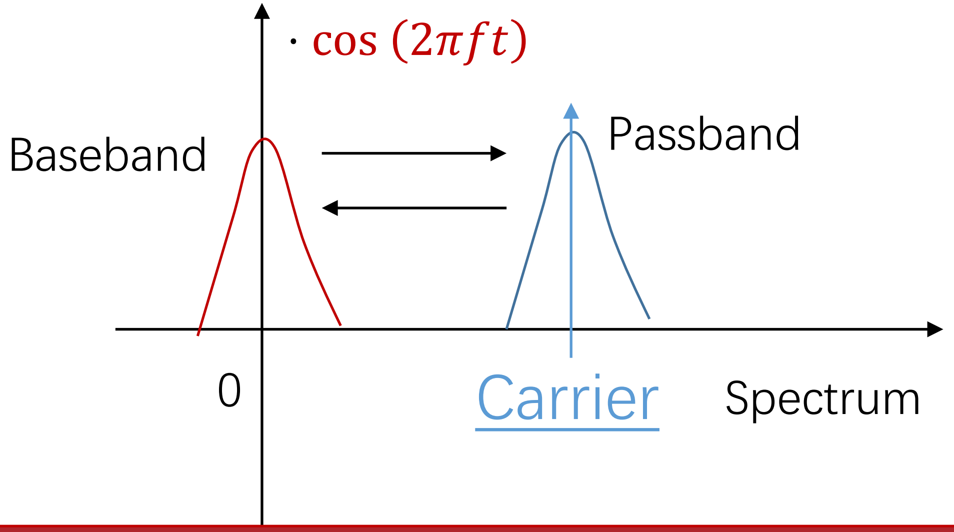
Passband Modulation

- Quadrature Amplitude Modulation (QAM)
  - ASK + PSK



Spectrum Shifting

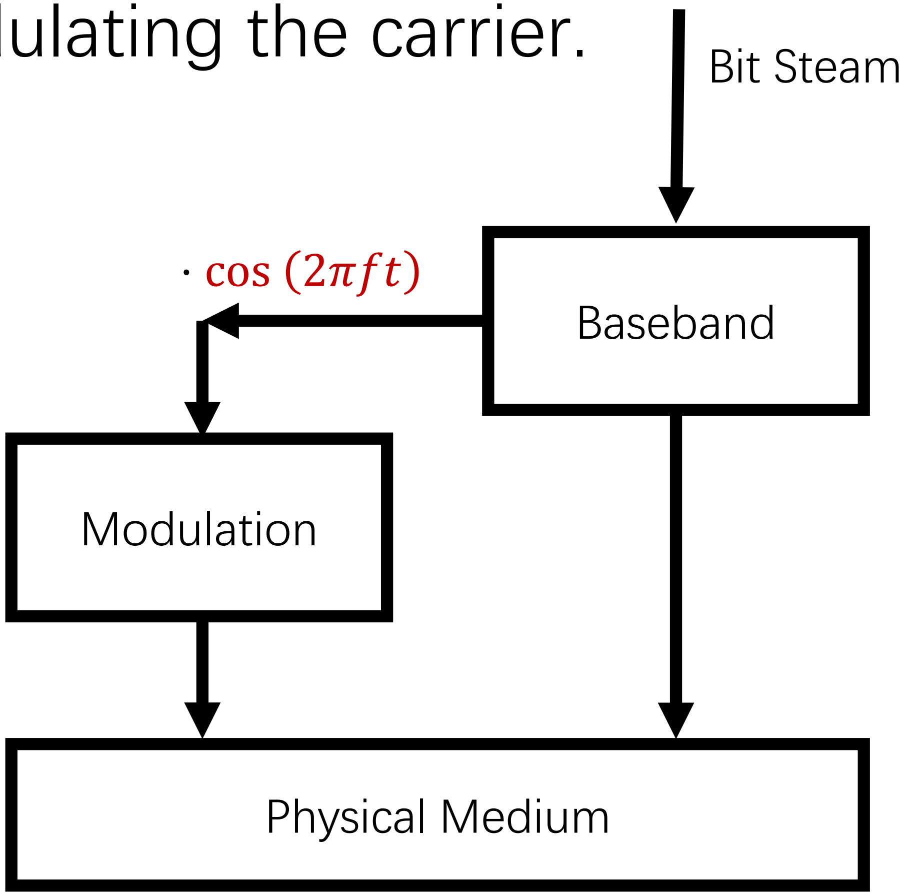
- How to conveniently/digitally modulate the carrier ?
  - Generate its baseband digitally, convert to the passband via multiplier



Mathematically, passband signal is frequency-shifted from the baseband signal

By Now

- Bit stream can either be converted to analog signal via line coding or through modulating the carrier.



Other Issues in Implementation

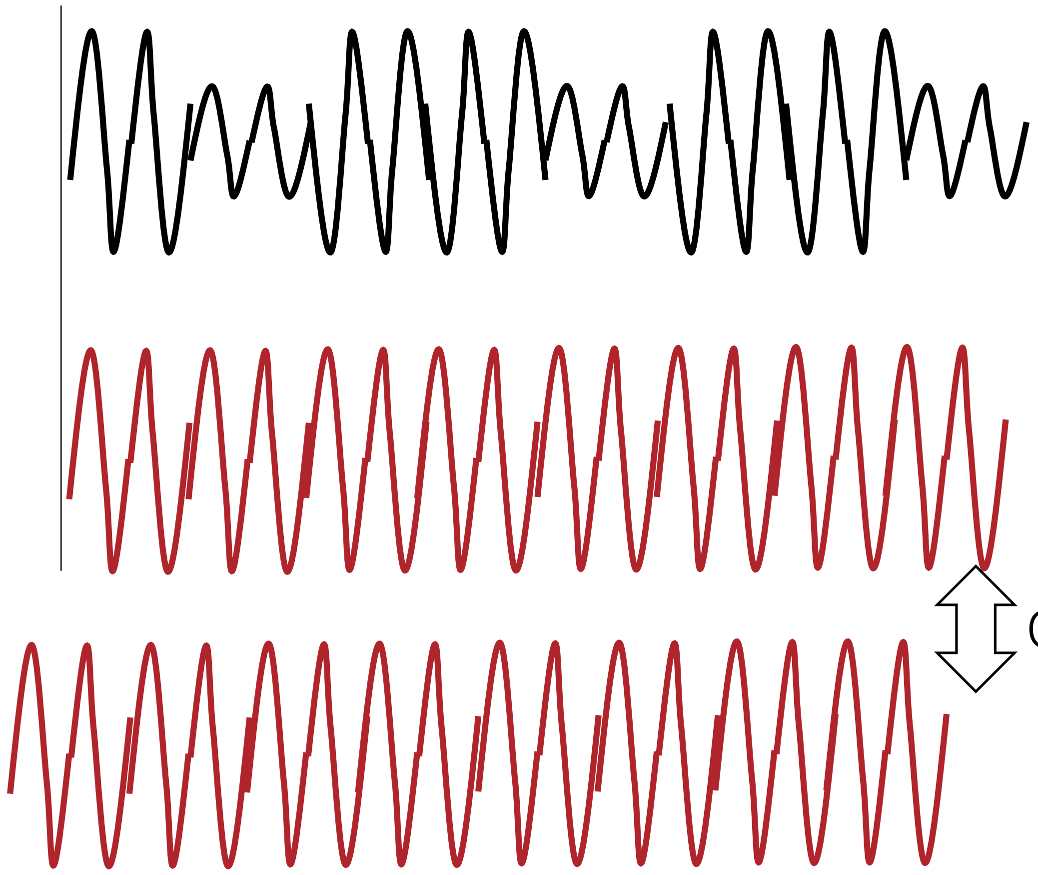
Carrier Phase Misalignment

- The Problem

Received Signal:

Transmitter Carrier Wave:

Local Carrier Wave:



Carrier Phase Misalignment

- Solution
  - Option1: find the accurate start of received signal
    - to align the local carrier phase to the transmitter's carrier phase
  - Option2: use orthogonal carrier waves to find and align the phase shift
    - Transmitter Carrier Wave: $\cos(2\pi f t + \phi)$
    - Local Carrier Wave 1: $\cos(2\pi f t)$
    - Local Carrier Wave 2: $\cos\left(2\pi f t + \frac{\pi}{2}\right)$

$$\cos(2\pi f t + \phi) = \mathrm{A} \cdot \cos(2\pi f t) + \mathrm{B} \cdot \cos\left(2\pi f t + \frac{\pi}{2}\right)$$

Carrier Frequency Offset

- There is a frequency offset between two nodes
  - $\cos(2\pi f t) * \cos(2\pi f t + 2\pi \Delta f t) = \frac{1}{2}(\cos(2\pi 2 f t + 2\pi \Delta f t) + \cos(2\pi \Delta f t))$
- Solution
  - Calibration
  - Do not use long frame in PSK

Rate Selection

- S/N is not stable in the wireless scenario
- When a baud rate (bandwidth) is selected, the number of different symbols must match S/N

Upper Bound

Matches

Actual Rate

$$R_b = R_B \log_2 M \qquad C = B\log_2\left(1+\frac{S}{N}\right)$$

Determine

- What if $R_b > C$
  - Error
- What if $R_b < C$
  - 100% correct ?

Reference

- Textbook 2.2
- Physical Layer
  - Passband Modulation is not covered in the textbook, refer to https://web.stanford.edu/class/ee102b/contents/DigitalModulation.pdf

Backup

Demo: Baseband and Passband Signal

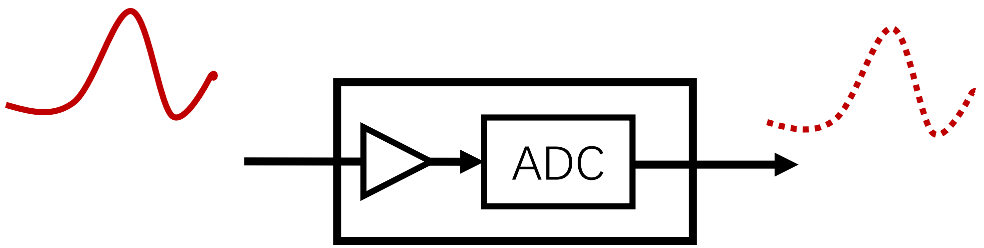
```
transmit_1000Hz_baseband=zeros(1,length(transmit_05Hz_passband));

for i=1:22:length(transmit_1000Hz_baseband)-22 %44100/2000=22 2000bps 1kHz bandwidth
    if rand()>0.5
        transmit_1000Hz_baseband(i:i+21)=1;
    else
        transmit_1000Hz_baseband(i:i+21)=-1;
    end
end
figure;
plot(fs_unit, abs(fft(transmit_1000Hz_baseband))); % spectrum
```

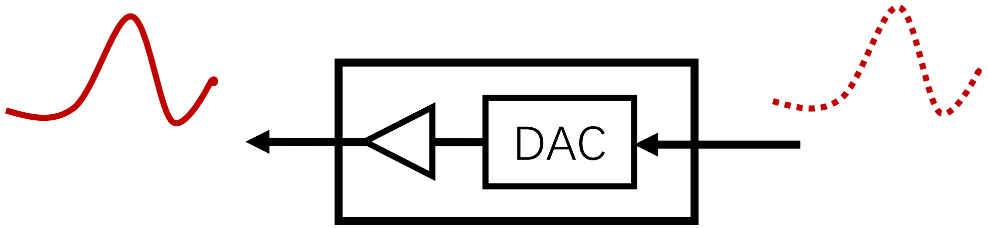
Passband != High Frequency

A/D and D/A Converter

- A/D Converter



- D/A Converter



(1/the space of the samples) is defined
as the rate of the ADC or DAC

The rate of the ADC or DAC must 2 times
of the bandwidth of the analog signal (Sampling
Theorem) to avoid aliasing