CS120: Computer Networks

Lecture 3. Physical Links

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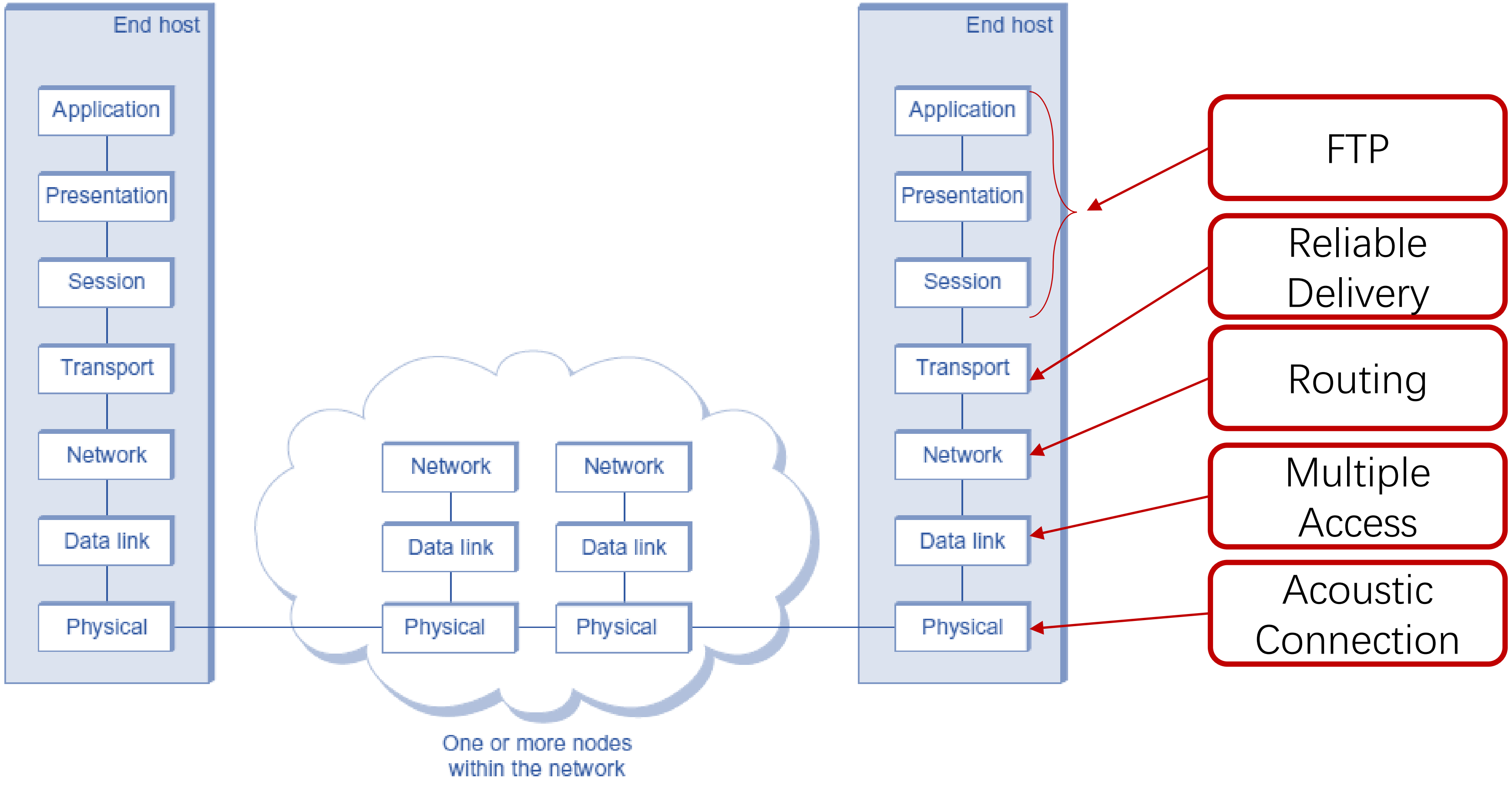
Network Layers



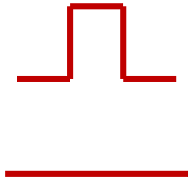
Outline

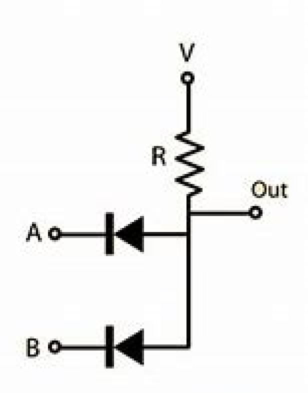
- Communication Basics
  - Communication Medium
    - Carrier
  - Modulation
- Upper Bound of Throughput
- Transmission Method

How to Transmit a Bit in Physical World ?

- Bits in the physical world

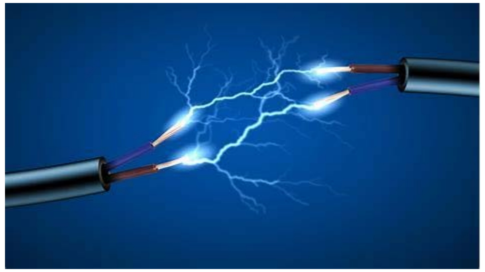
```
a = 1 & 0;
```



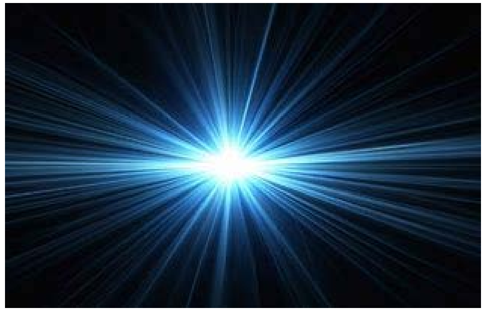


Bits are conveyed by physical medium (eg. electrical signal)

Basic Components of Communication



Electrical Signal



Light

Sound

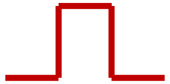
Medium + Modulation

Change/Manipulate the Physical Medium

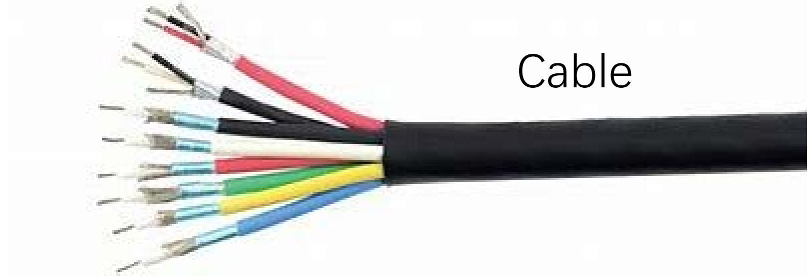
Communication Medium

Communication Medium

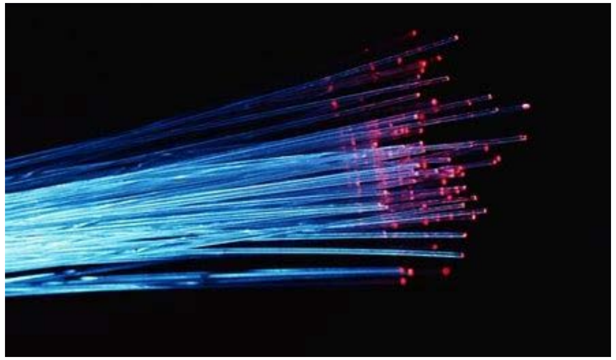
- How to propagate in the other medium



?



Cable

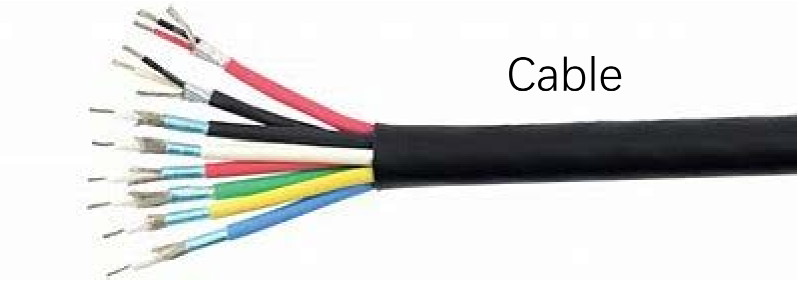


Fiber

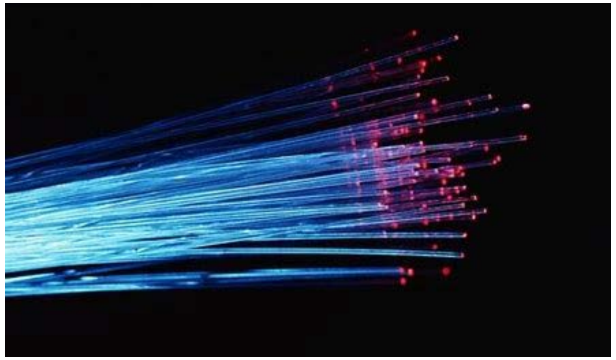
Free Space

Communication Medium

- How to propagate in the other medium



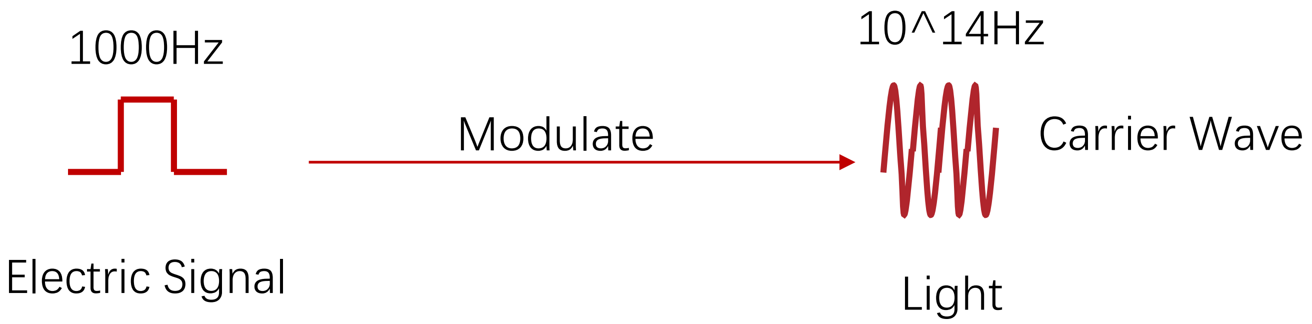
?

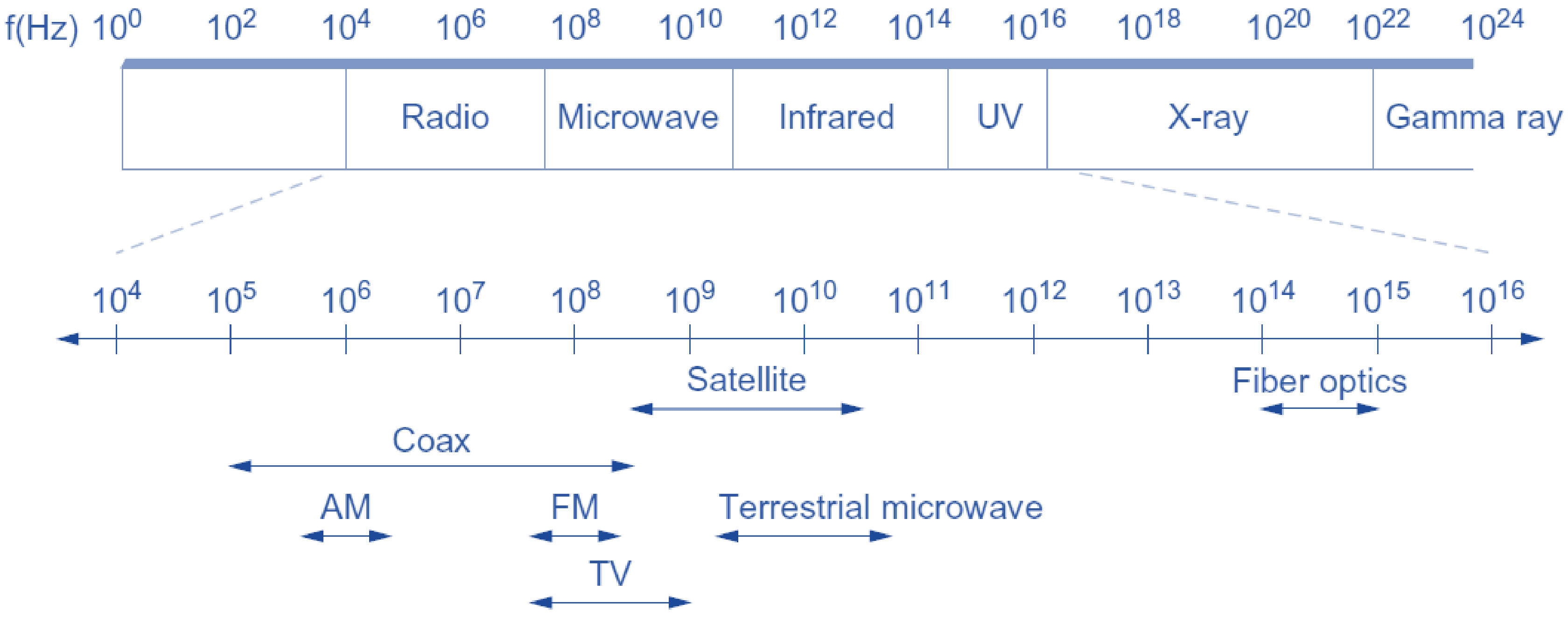


Fiber:
Light Wave

Free Space:
Radio Wave,
Acoustic Wave,
etc.

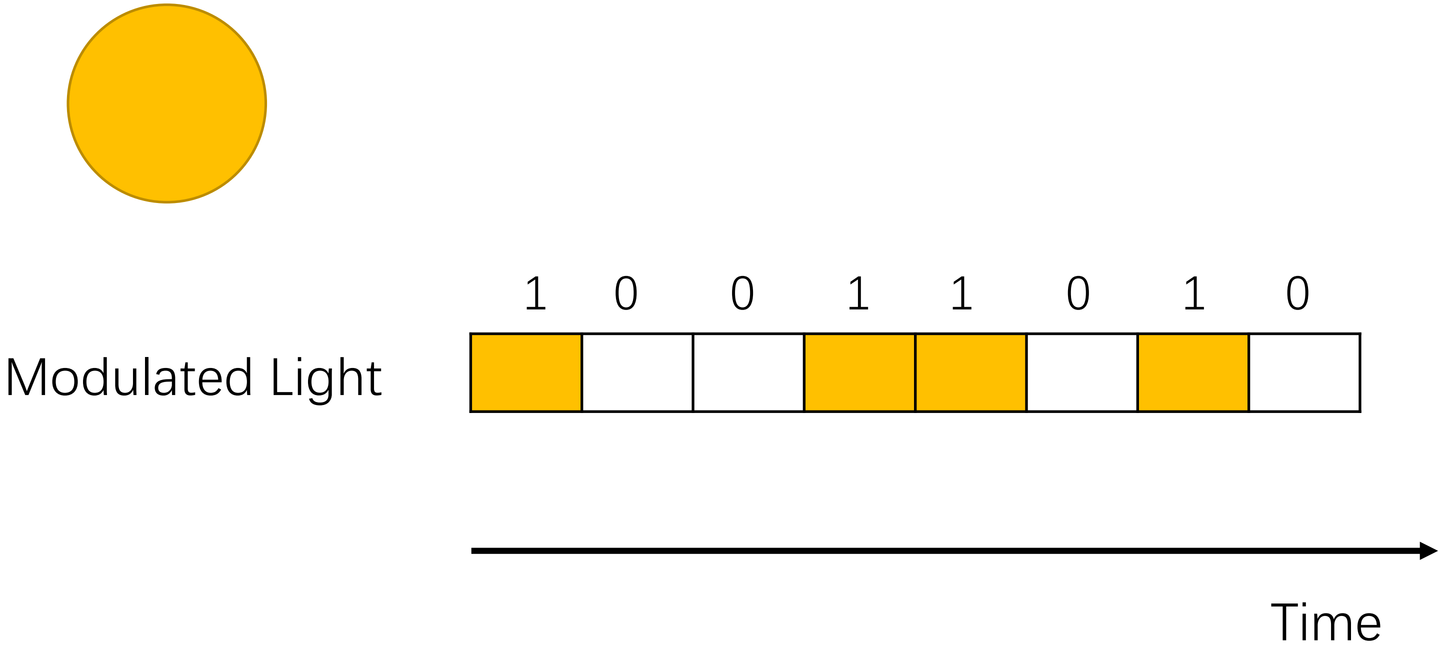
The Carrier Wave





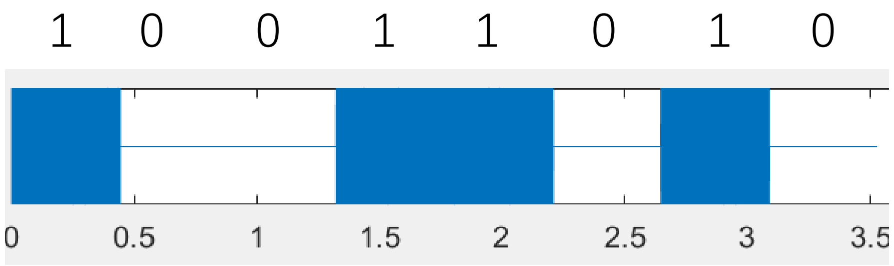
Modulation

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

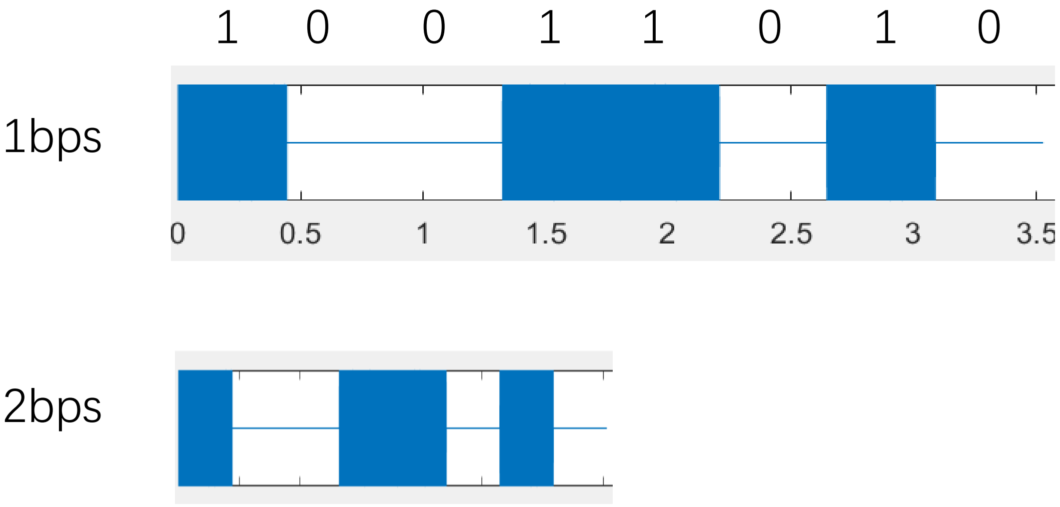


Demo: On-Off Modulation

```
%%
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);
```



How Fast can We Achieve ?



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

- The term “Bandwidth” is often used with two different meanings.
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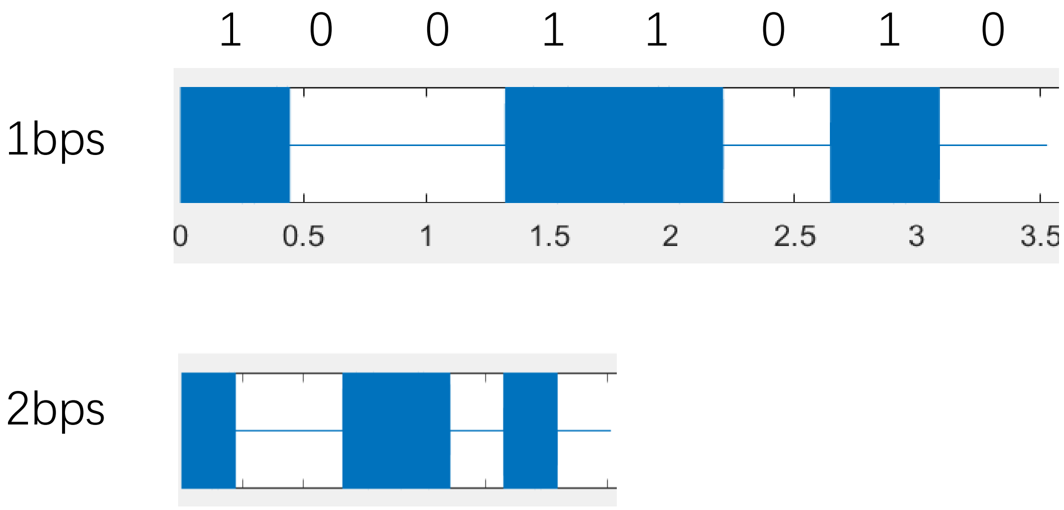
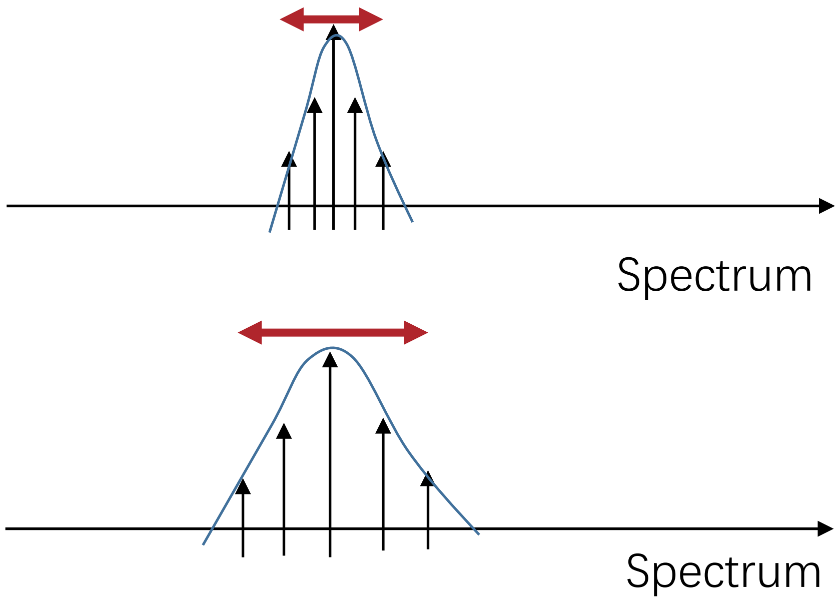
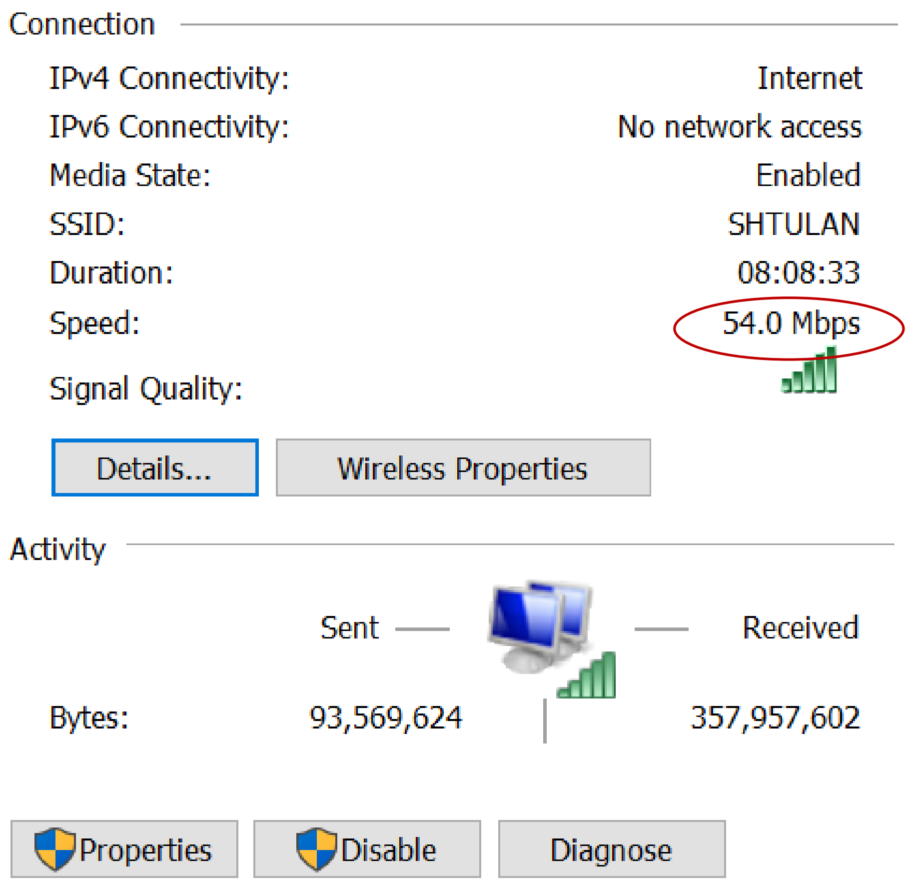




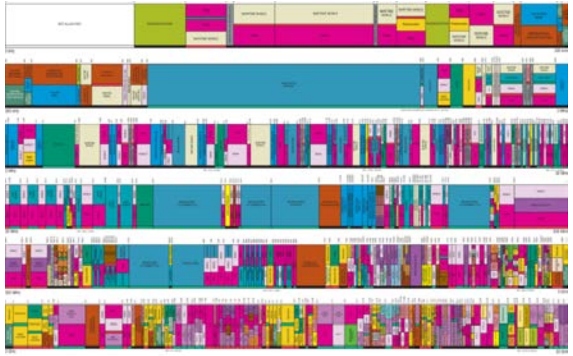
“Bandwidth” v.s. Bandwidth

- 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

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

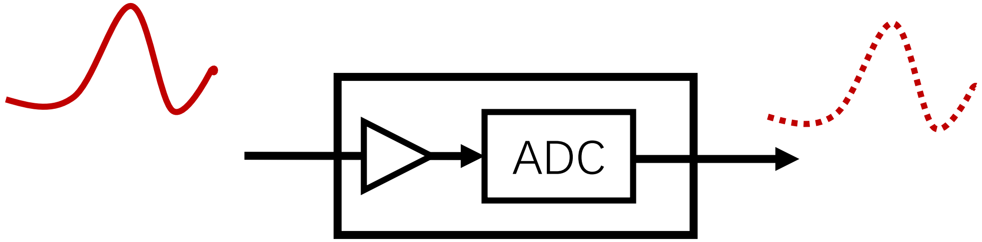
Channel Capacity

Noise Power

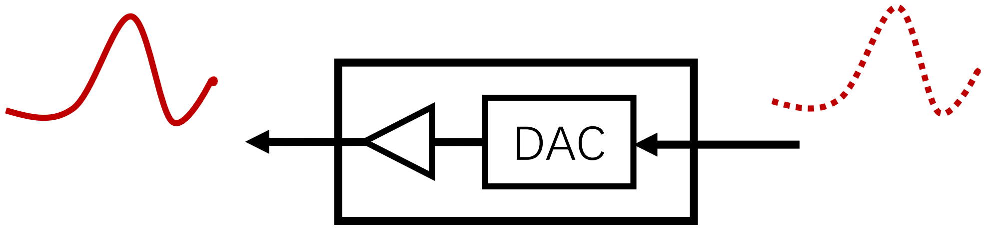
Limited by Thermal Noise
and Manufacturing

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

Reference

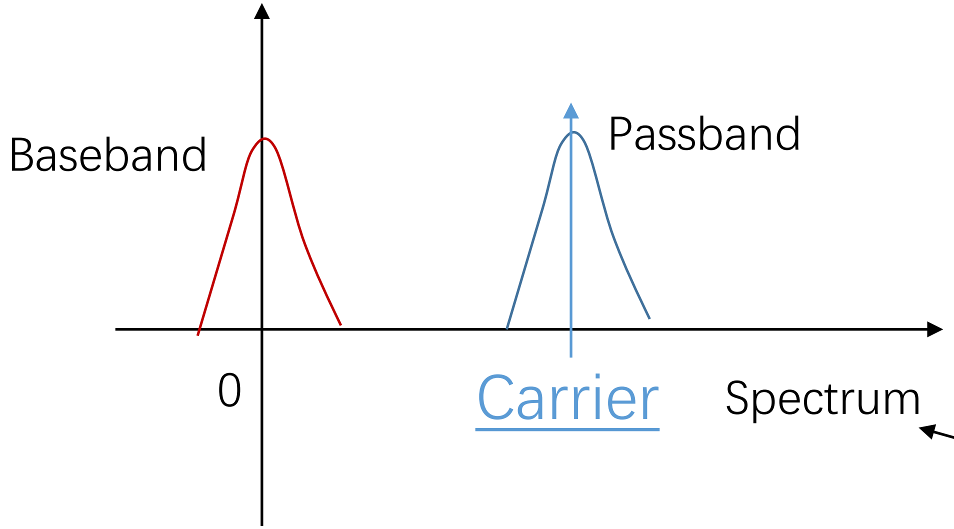
- Textbook 2.1

Outline

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

Transmission Method

- Baseband Transmission (Line Coding)
- Passband Modulation
  - Good transmission property (suitable medium, distance, etc.)
  - Multiplexing



Spectrum of
Mechanical Wave,
Electromagnetic 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
```

Demo: Baseband and Passband Signal

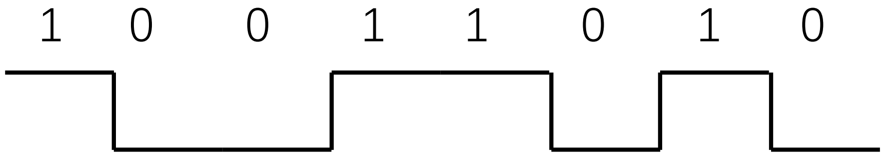
```
transmit_1000Hz_baseband=zeros(1,length(transmit_05Hz_passband));

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

Baseband Transmission

- "1" -> High Voltage
- "0" -> Low Voltage

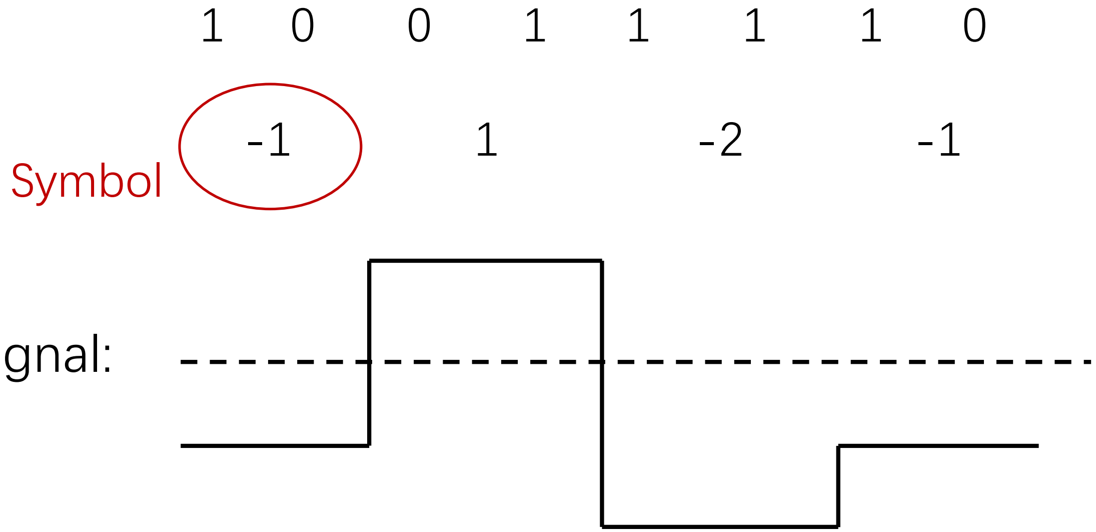
Transmitted Signal:



Baseband Transmission

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

Transmitted Signal:



- Symbol/Baud Rate
  - The number of symbol changes in transmission medium
- Cost Efficiency <-> Bandwidth
  - Complex symbol -> high cost DAC/ADC

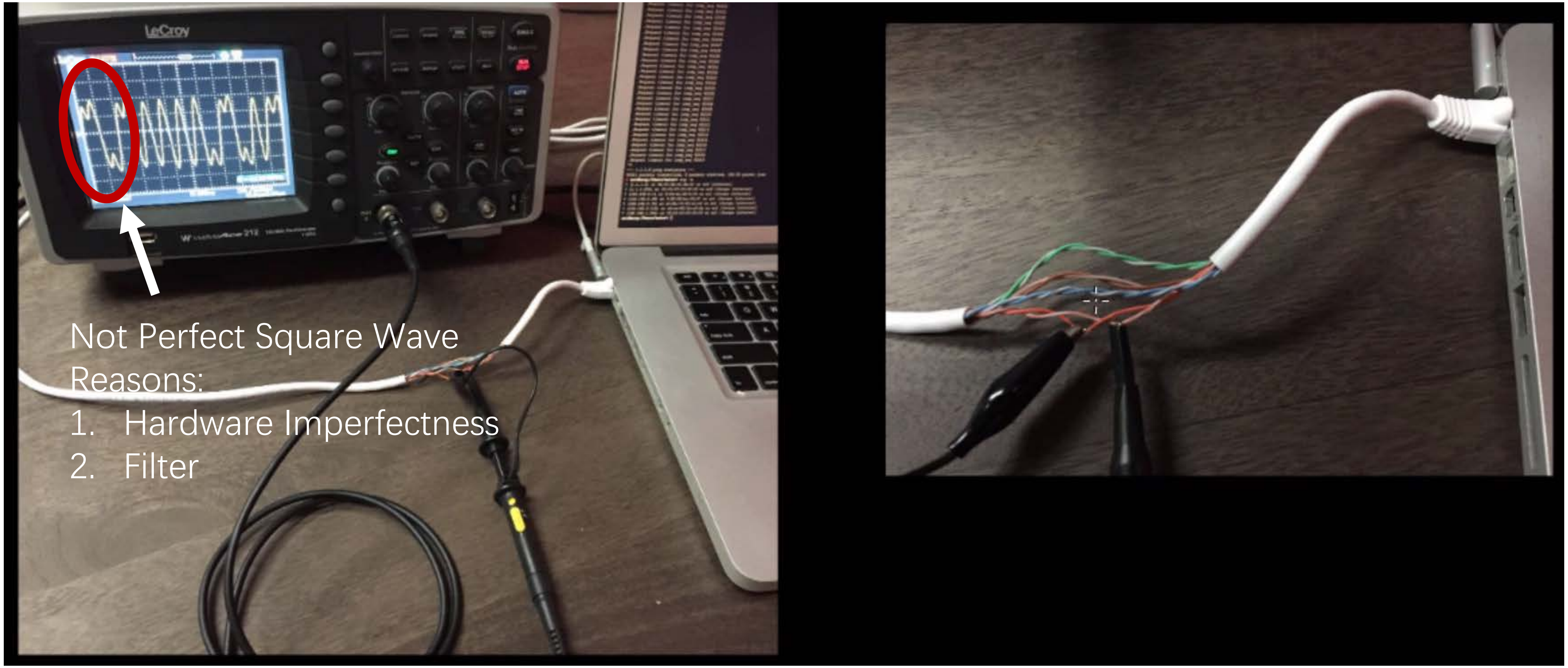
More about Symbol Rate

- Symbol/Baud 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

$$R_b = R_B \log_2 M$$

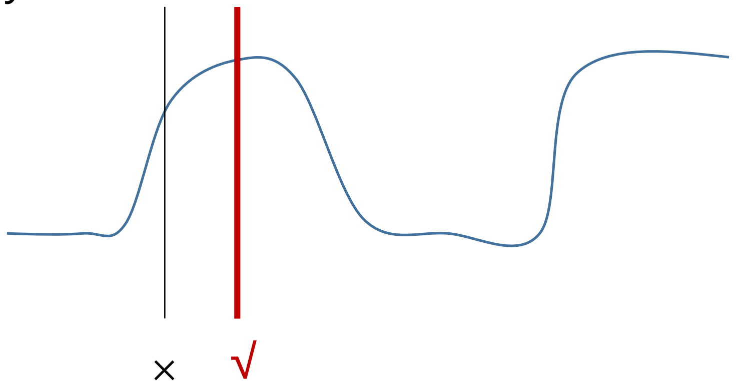
Baseband Transmission

- How to Receive ?



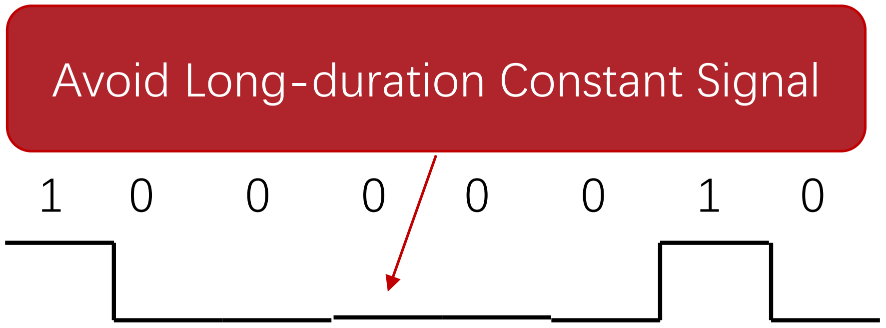
Baseband Transmission

- How to Receive ?
  - Sampling
    - Clock Recovery



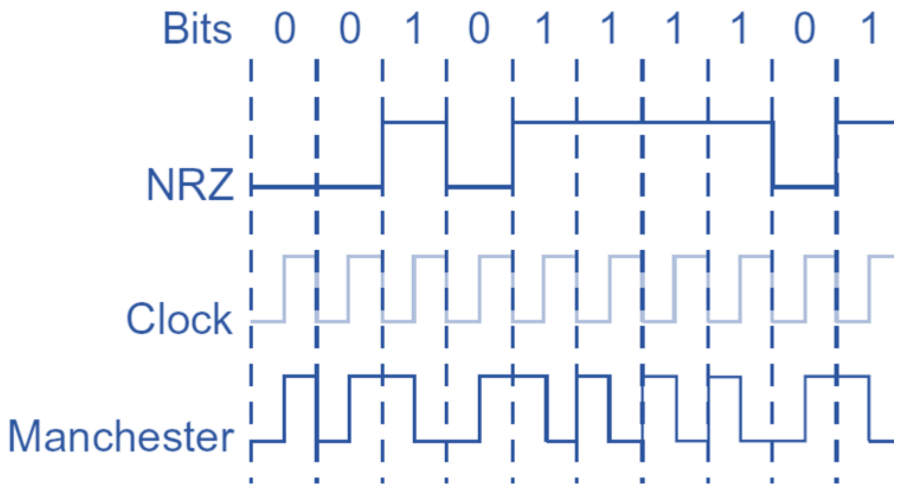
  - Thresholding
    - Balanced DC

Transmitted Signal:



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.)

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

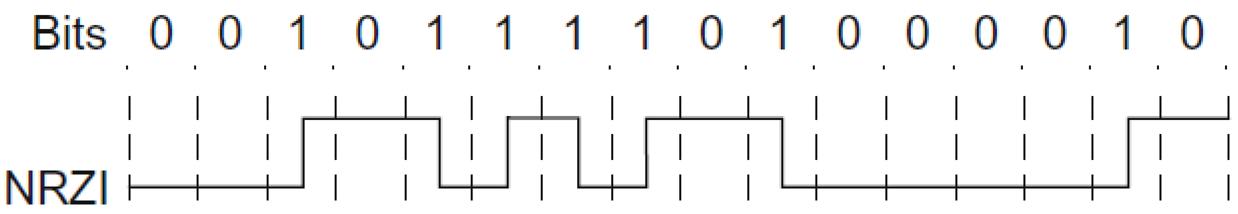


Table 2.2 4B/5B Encoding

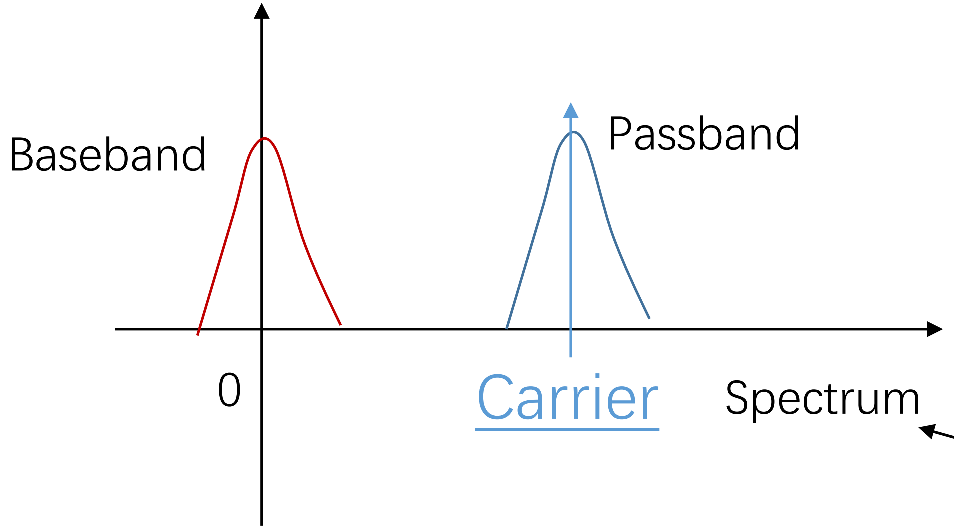
4-Bit Data Symbol	5-Bit Code
0000	11110
0001	01001
0010	10100
0011	10101
0100	01010
0101	01011
0110	01110
0111	01111
1000	10010
1001	10011
1010	10110
1011	10111
1100	11010
1101	11011
1110	11100
1111	11101

Baseband Transmission

- Clock Recovery
  - Synchronous Transmission
    - Transmit the clock
    - Complex, Less Overhead
  - Asynchronous Transmission
    - Recover the clock from signal
    - Simple, Cheap

Transmission Method

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



Spectrum of
Mechanical Wave,
Sound Wave, etc.

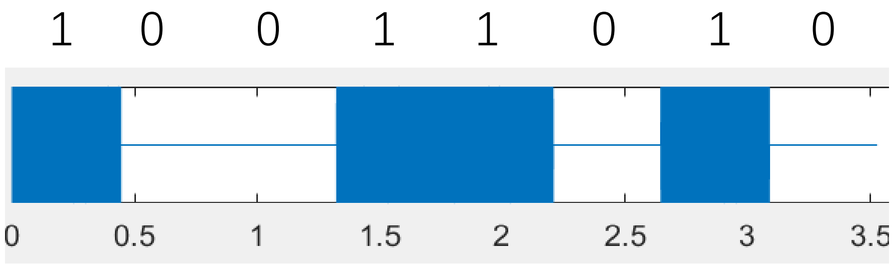
How to Describe the Carrier ?

- 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 of the carrier wave to express symbols
- Demodulation
  - Averaging the received power (low pass filter)
  - Thresholding



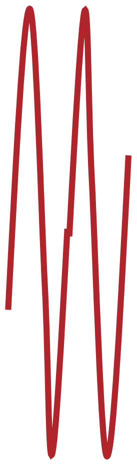
Demo: OOK Modulation

```
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
    - $\mathrm{A}\cos(2\pi f t) * \cos(2\pi f t) = \frac{1}{2}\mathrm{A}(\cos(2\pi 2 f t) + 1)$

```
%% 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”

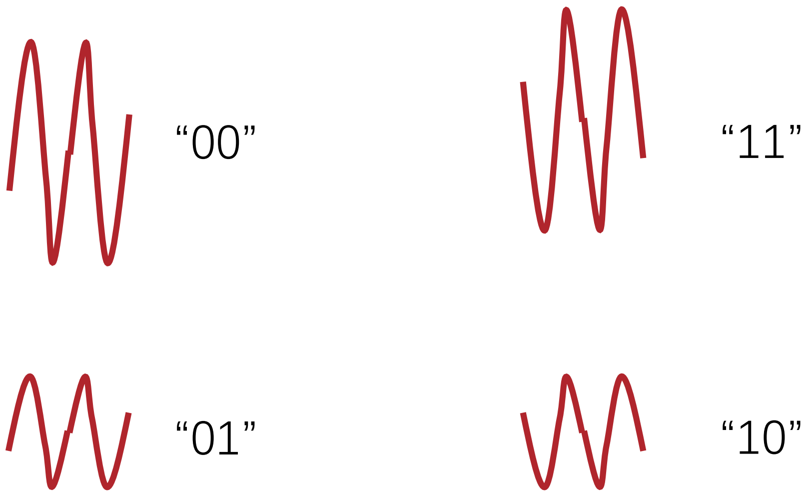
“1”

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

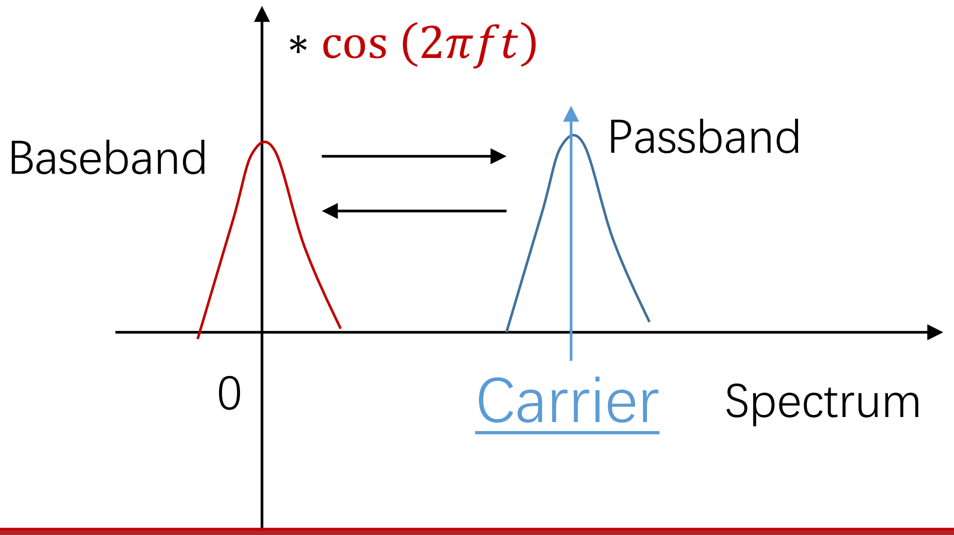
```
%% PSK demo
clear all;
t=linspace(0,1,44100);
one=sin(2*pi*10*t);
zero=cos(2*pi*10*t);
transmit=([one,zero,zero,one,one,zero,one,zero]);

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

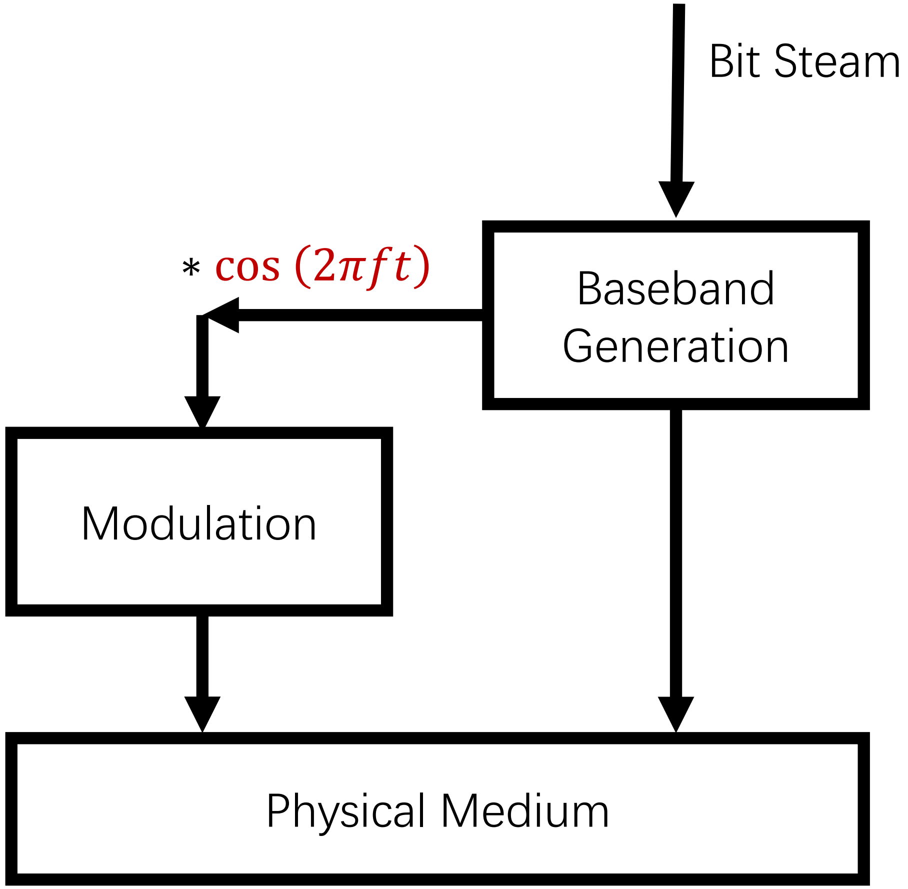


Spectrum Shifting



Mathematically, there is no big difference between baseband signal and passband

By Now

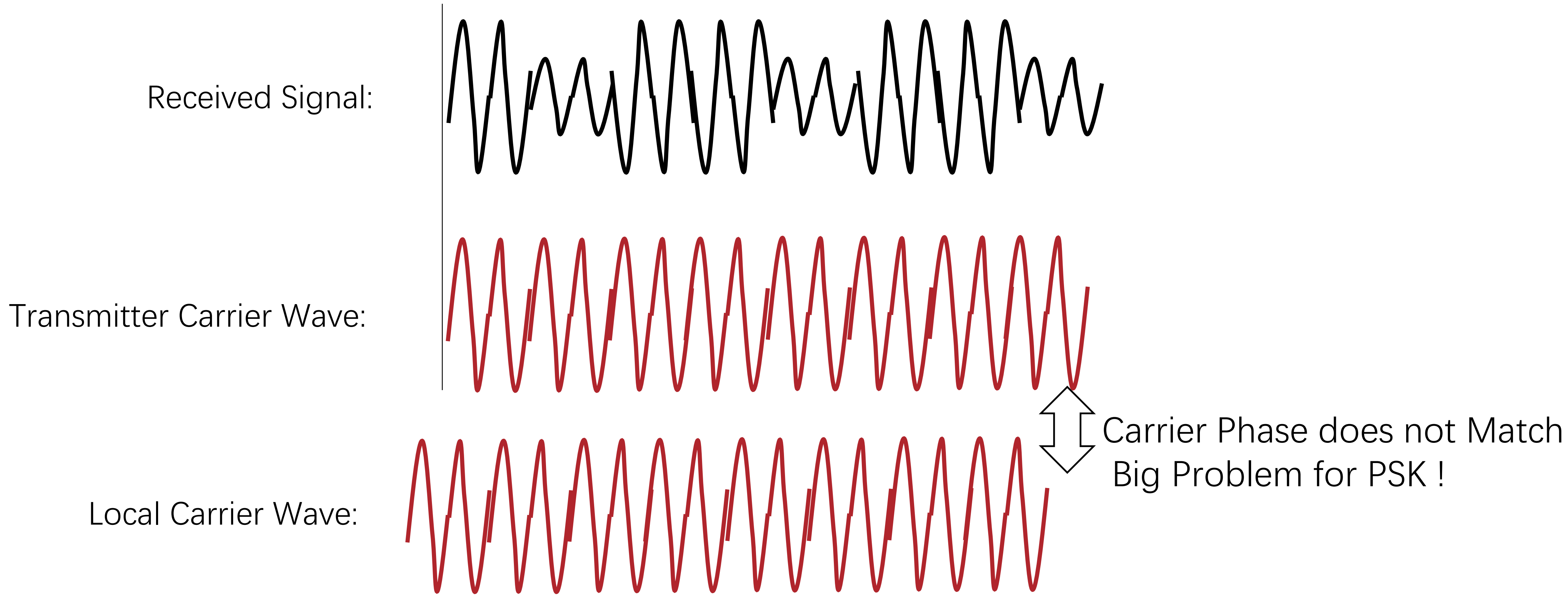


Bit Steam
* $\cos(2\pi f t)$
Baseband Generation
Modulation
Physical Medium

Other Issues in Implement

Carrier Phase Misalignment

- The Problem



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

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

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