A Review of Key Wireless Physical Layer Concepts

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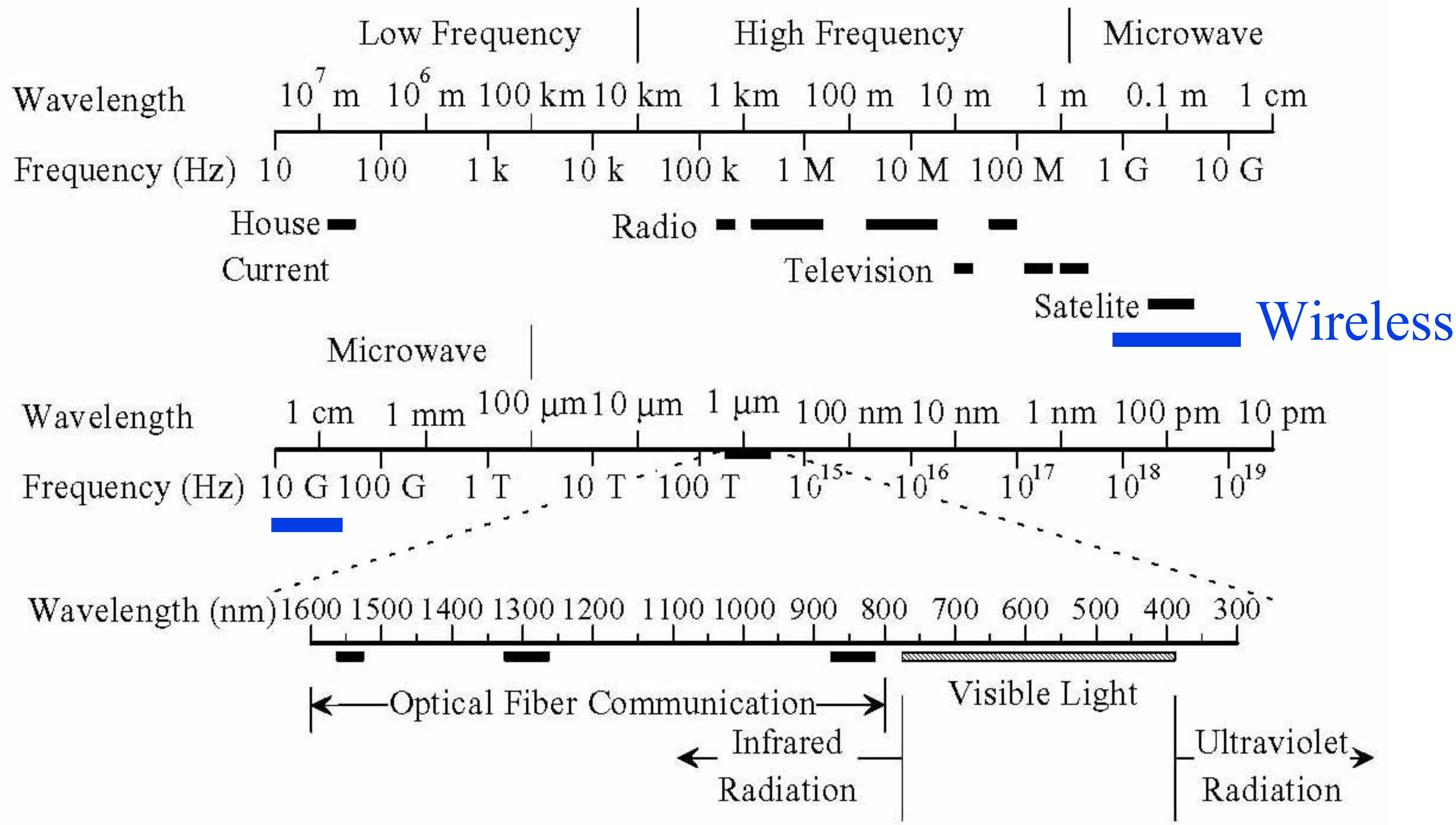
These slides are available on-line at:
http://www.cse.wustl.edu/~jain/cse574-08/

- Basic Concepts:
  - Coding, Phase-Shift Keying (PSK), QAM, Decibels
  - Channel Capacity, Nyquist Theorem, Shannon's Theorem, Hamming Distance, Error Correction
  - Antenna, Reflection, Diffraction and Scattering, Multipath Propagation
- Recent Development:
  - Spread Spectrum, Code Division Multiple Access
  - OFDM
  - Turbo Codes

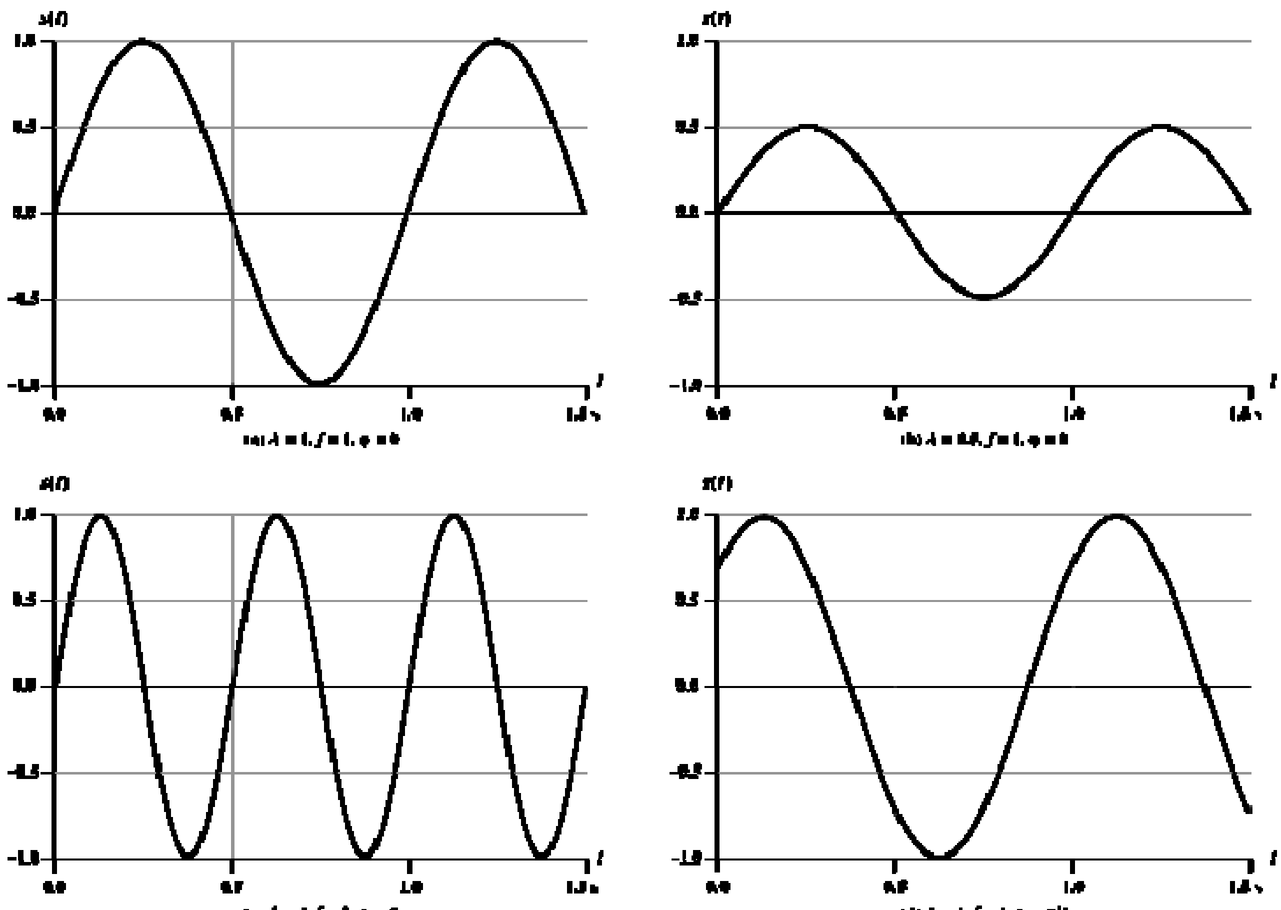
Electromagnetic Spectrum



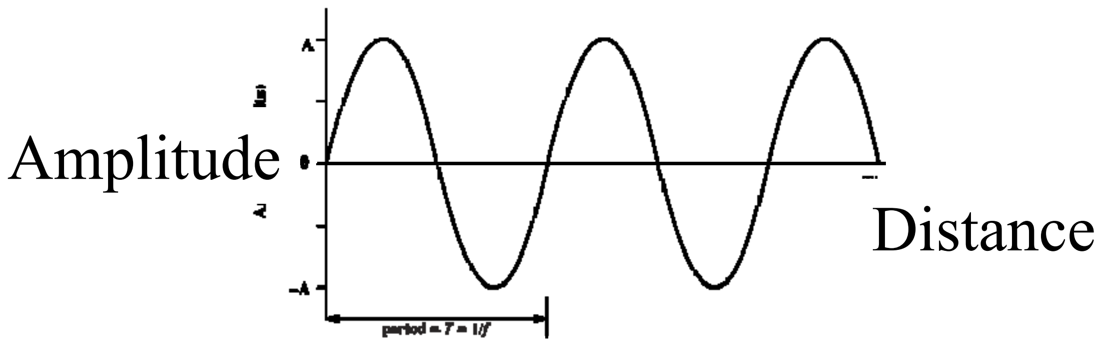
- Wireless communication uses 100 kHz to 60 GHz

Frequency, Period, and Phase

- $A \sin(2\pi f t + \theta)$, A = Amplitude, f=Frequency, θ = Phase
  Period $T = 1/f$, Frequency is measured in Cycles/sec or Hertz

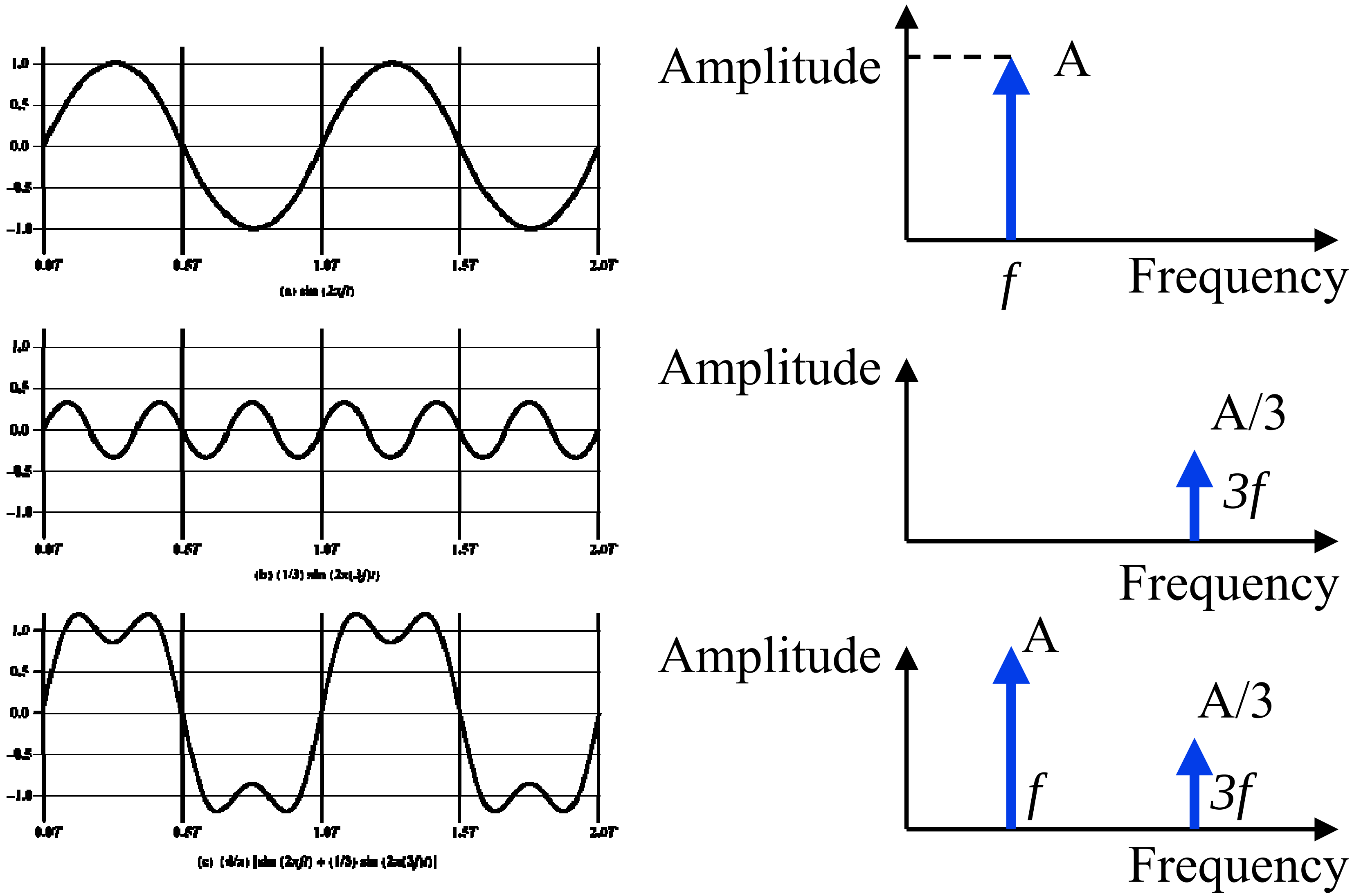


Wavelength



- Distance occupied by one cycle
- Distance between two points of corresponding phase in two consecutive cycles
- Wavelength = λ
- Assuming signal velocity *v*
  - $\lambda = vT$
  - $\lambda f = v$
  - c = $3*10^8$ m/s (speed of light in free space) = 300 m/μs

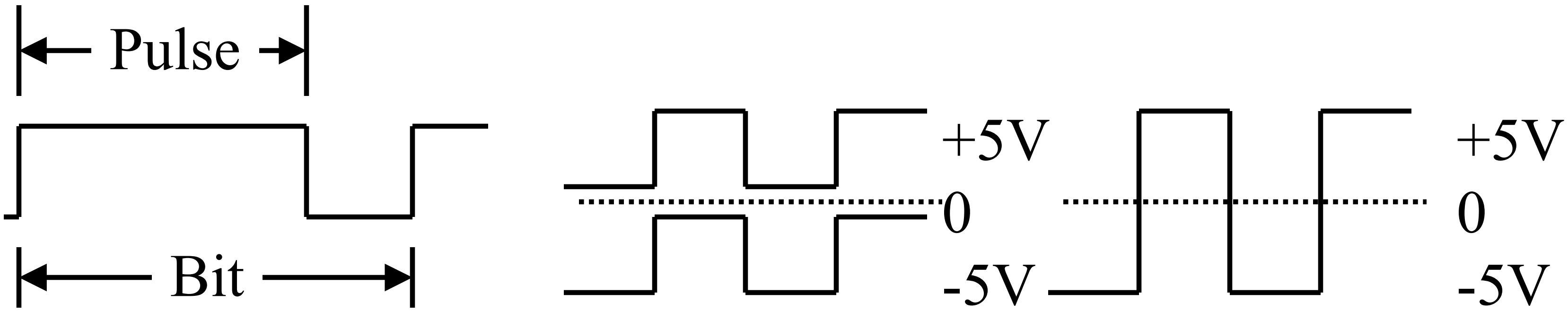
Time and Frequency Domains



Decibels

- Attenuation = $\log_{10} \frac{P_{in}}{P_{out}}$ Bel
- Attenuation = $10 \log_{10} \frac{P_{in}}{P_{out}}$ decibel
- Attenuation = $20 \log_{10} \frac{V_{in}}{V_{out}}$ decibel
- **Example 1**: Pin = 10 mW, Pout=5 mW
  Attenuation = $10 \log_{10}(10/5) = 10 \log_{10} 2 = 3$ dB
- **Example 2**: Pin = 100mW, Pout=1 mW
  Attenuation = $10 \log_{10}(100/1) = 10 \log_{10} 100 = 20$ dB

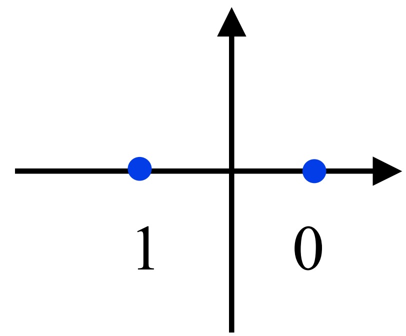
Coding Terminology



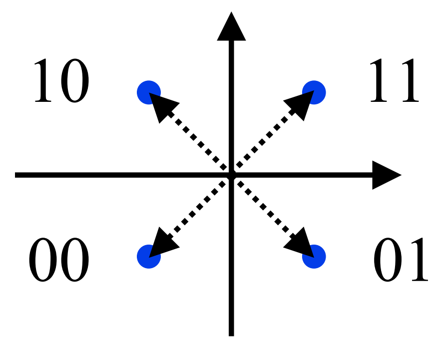
- **Signal element**: Pulse (of constant amplitude, frequency, phase)
- **Modulation Rate**: 1/Duration of the smallest element =Baud rate
- **Data Rate**: Bits per second
- Data Rate = Fn(Bandwidth, signal/noise ratio, encoding)

Phase-Shift Keying (PSK)

- **Differential PSK**:
  0 = Same phase, 1=Opposite phase
  A cos(2πft), A cos(2πft+π)

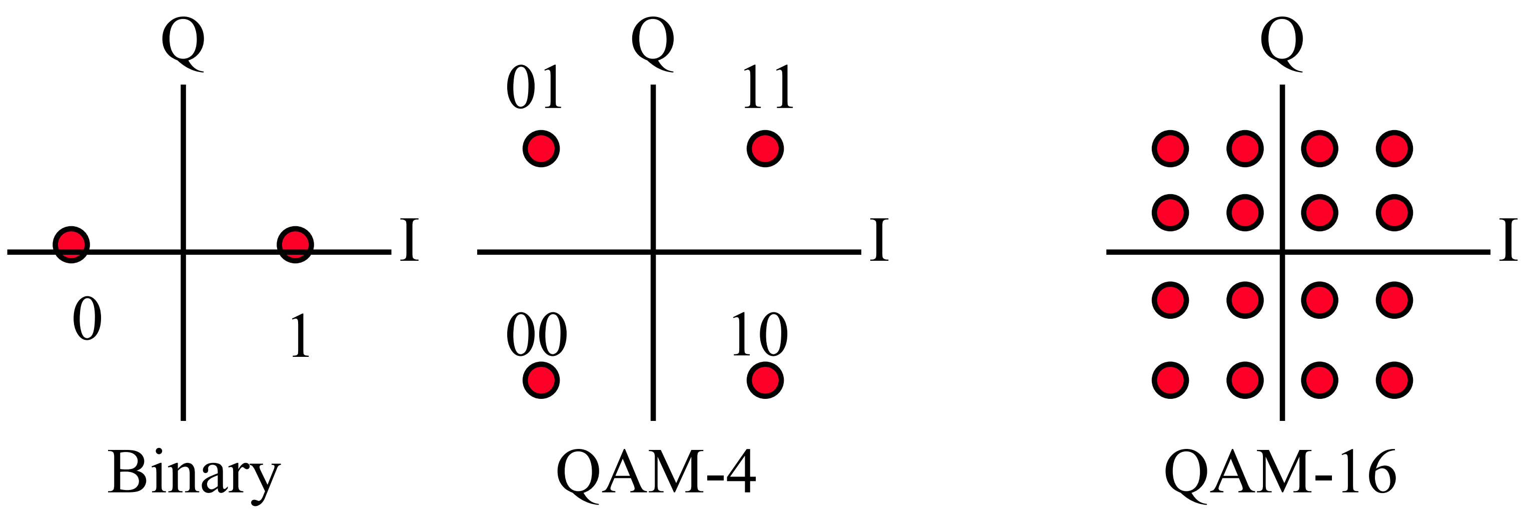


- **Quadrature PSK (QPSK):** Two bits
  11=A cos(2πft+45°), 10=A cos(2πft+135°),
  00=A cos(2πft+225°), 01=A cos(2πft+315°)
  Sum of two signals 90° apart in phase
  (In-phase I , Quadrature Q),
  Up to 180° phase difference between successive intervals



QAM

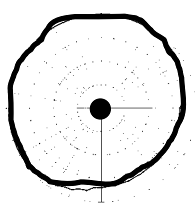
- Quadrature Amplitude and Phase Modulation
- QAM-4, QAM-16, QAM-64, QAM-256
- Used in DSL and wireless networks



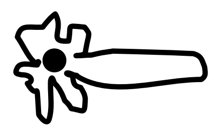
Antenna

- Transmitter converts electrical energy to electromagnetic waves
- Receiver converts electromagnetic waves to electrical energy
- Same antenna is used for transmission and reception
- Omni-Directional: Power radiated in all directions
- Directional: Most power in the desired direction
- Isotropic antenna: Radiates in all directions equally
- Antenna Gain = Power at particular point/Power with Isotropic
  Expressed in dBi

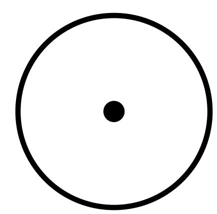
$$P_r = P_t G_t G_r (\lambda/4\pi d)^2$$



Omni-Directional

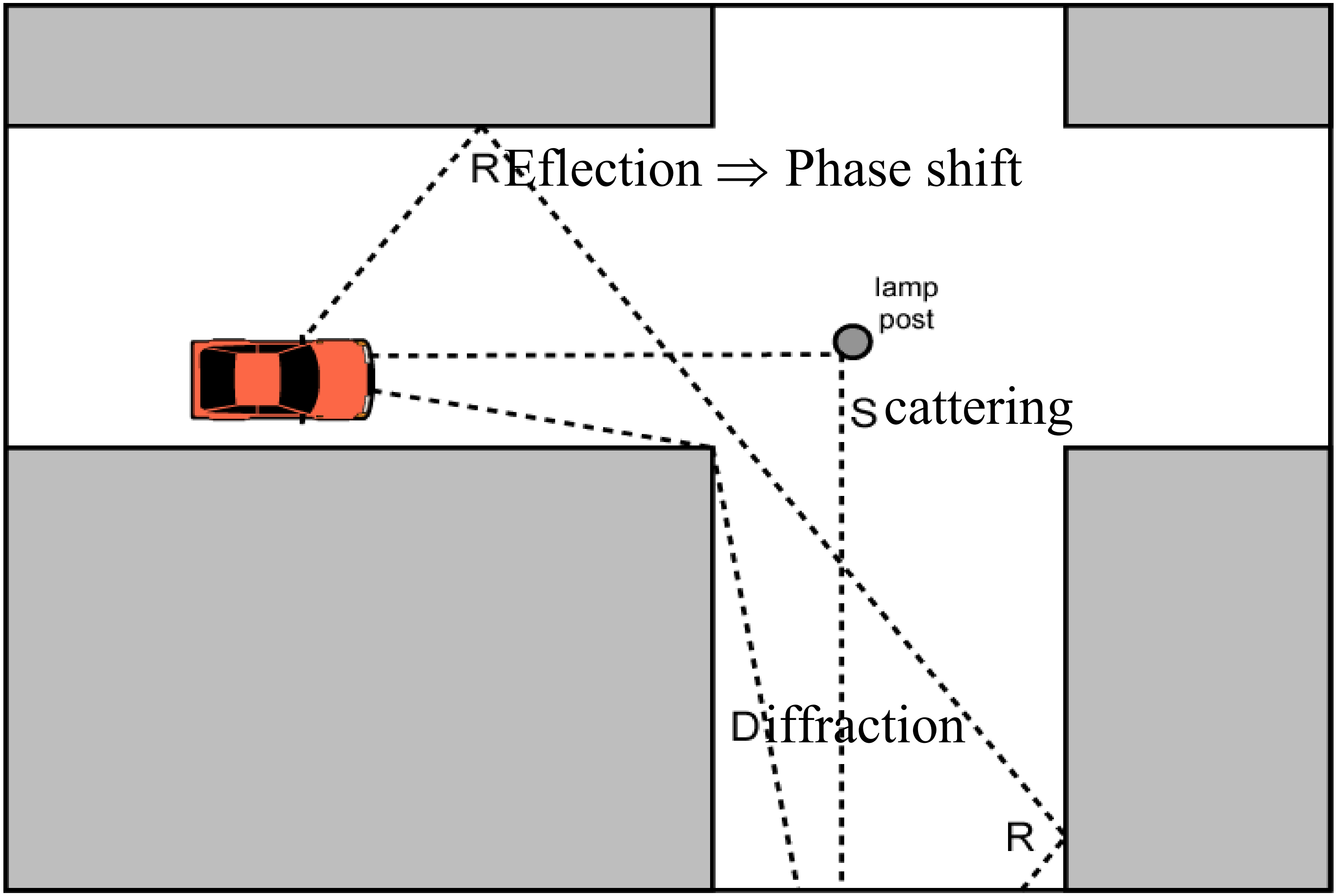


Directional



Isotropic

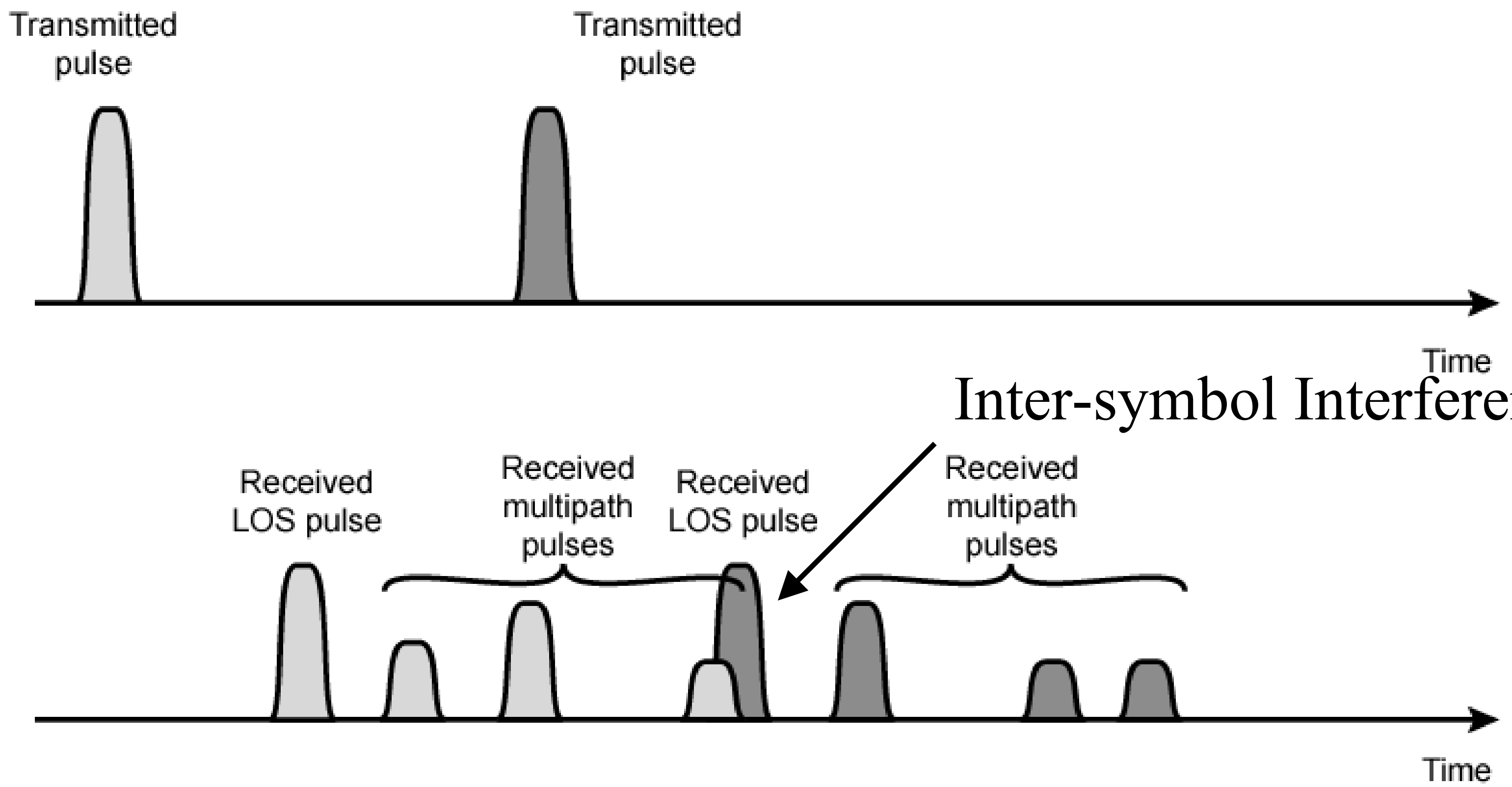
Reflection, Diffraction, Scattering



Reflection, Diffraction and Scattering

- **Reflection**: Surface large relative to wavelength of signal
  - May have phase shift from original
  - May cancel out original or increase it
- **Diffraction**: Edge of impenetrable body that is large relative to λ
  - May receive signal even if no line of sight (LOS) to transmitter
- **Scattering**
  - Obstacle size on order of wavelength. Lamp posts etc.
- If LOS, diffracted and scattered signals not significant
  - Reflected signals may be
- If no LOS, diffraction and scattering are primary means of reception

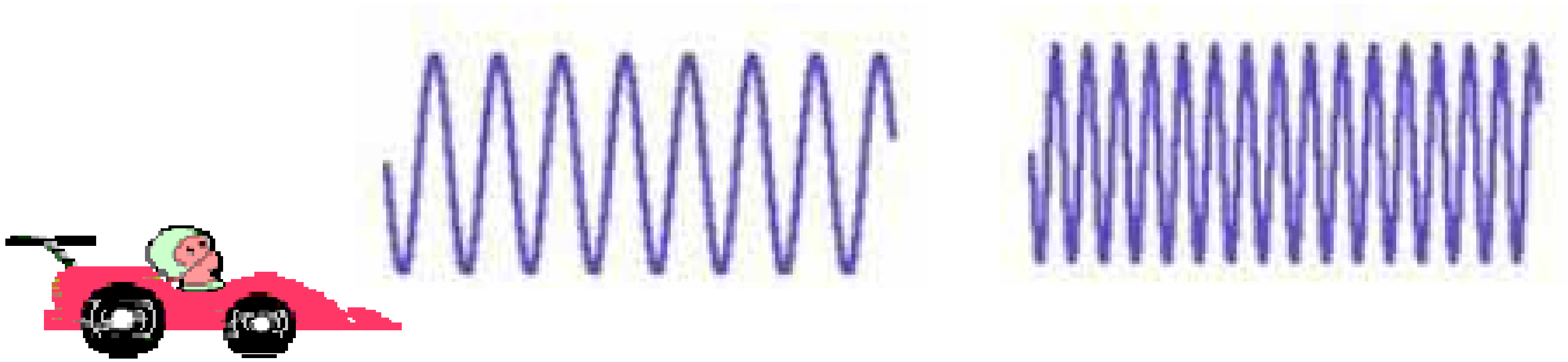
Multipath Propagation



Inter-symbol Interference

- Delay Spread = Time between first and last versions of signal
- Fading: Fluctuation in amplitude, phase or delay spread
- Multipath may add constructively or destructively
  ⇒ Fast fading

Doppler Shift



- If the transmitter or receiver or both are mobile the frequency of received signal changes
- Moving towards each other => Frequency increases
- Moving away from each other => Frequency decreases

Frequency difference = velocity/Wavelength

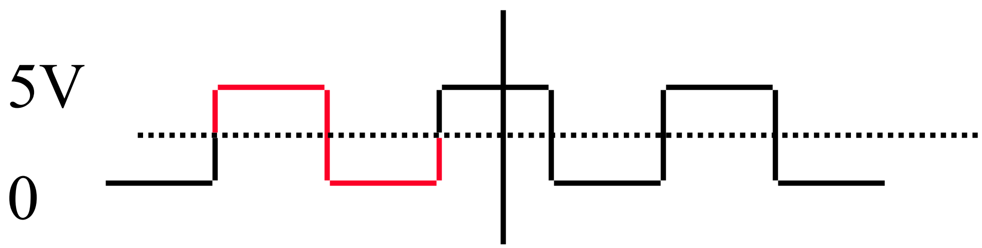
Example: 2.4 GHz => l= $3x10^8/2.4x10^9$ = .125m

120km/hr = 120x1000/3600 = 33.3 m/s

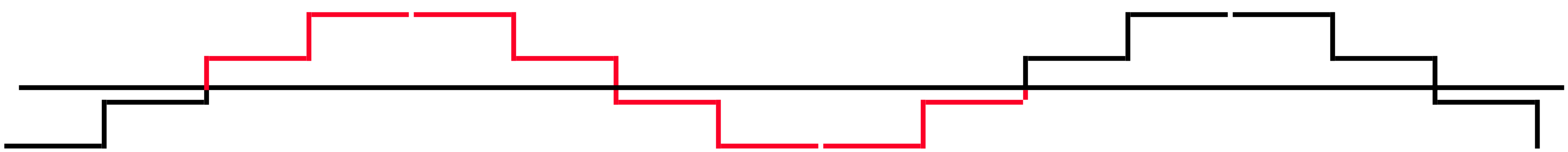
Freq diff = 33.3/.125 = 267 Hz

Channel Capacity

- Capacity = Maximum data rate for a channel
- **Nyquist Theorem**: Bandwidth = B
  Data rate ≤ 2 B
- Bi-level Encoding: Data rate = 2 × Bandwidth



- Multilevel: Data rate = 2 × Bandwidth × $\log_2 M$



Example: M=4, Capacity = 4 × Bandwidth

Shannon's Theorem

- Bandwidth = B Hz
  Signal-to-noise ratio = S/N
- Maximum number of bits/sec = $B \log_2 (1+S/N)$
- Example: Phone wire bandwidth = 3100 Hz

$$S/N = 30 \text{ dB}$$

$$10 \text{ Log}_{10} S/N = 30$$

$$\text{Log}_{10} S/N = 3$$

$$S/N = 10^3 = 1000$$

$$\text{Capacity} = 3100 \log_2 (1+1000)$$

$$= 30{,}894 \text{ bps}$$

Hamming Distance

- Hamming Distance between two sequences
  = Number of bits in which they disagree
- Example: 011011
  110001

  Difference 101010 ⇒ Distance =3

Error Correction Example

- 2-bit words transmitted as 5-bit/word

Data	**Codeword**
00	00000
01	00111
10	11001
11	11110

Received = 00100 ⇒ Not one of the code words ⇒ Error

Distance (00100,00000) = 1   Distance (00100,00111) = 2

Distance (00100,11001) = 4   Distance (00100,11110) = 3

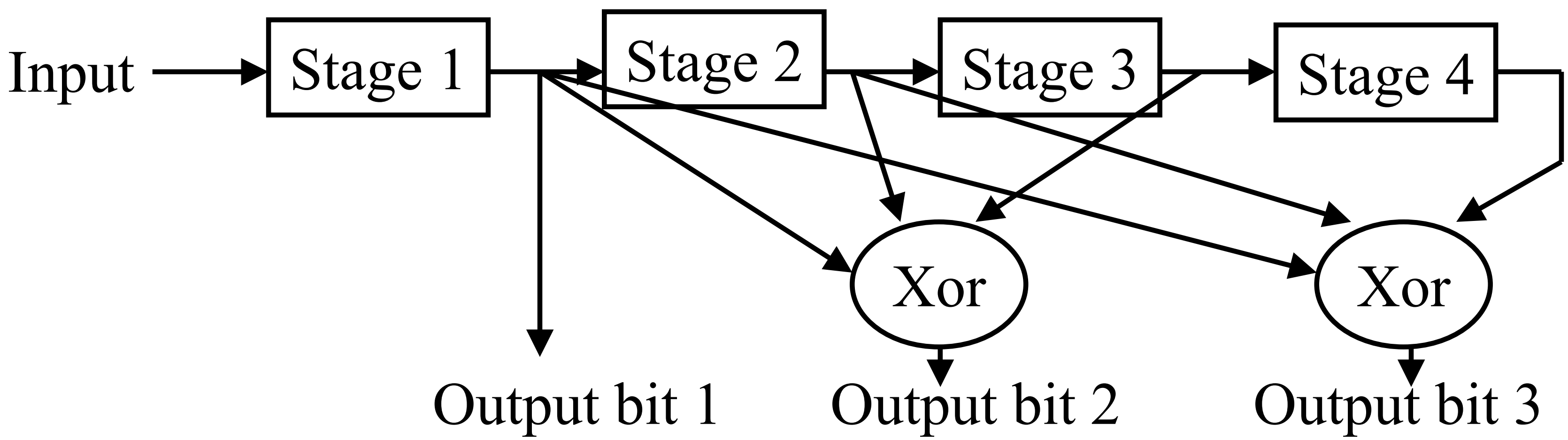
⇒ Most likely 00000 was sent. Corrected data = 00

b. Received = 01010 Distance(…,00000) = 2 = Distance(…,11110)
   Error detected but cannot be corrected

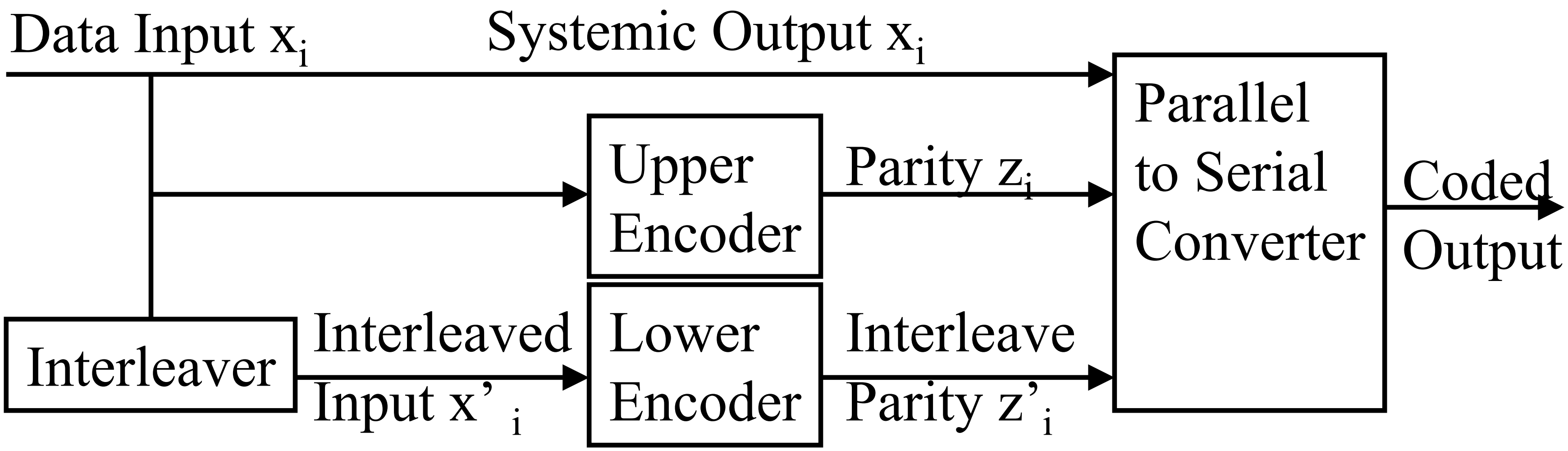
c. Three bit errors will not be detected. Sent 00000, Received 00111.

Convolutional Coding

- Block codes: Take k-bit blocks and output k+r-bit blocks
- Convolutional codes: Designed for long bit streams
- Code Rate = # of bits input/# bits output
- Constraint Length = Number of stages in the coder

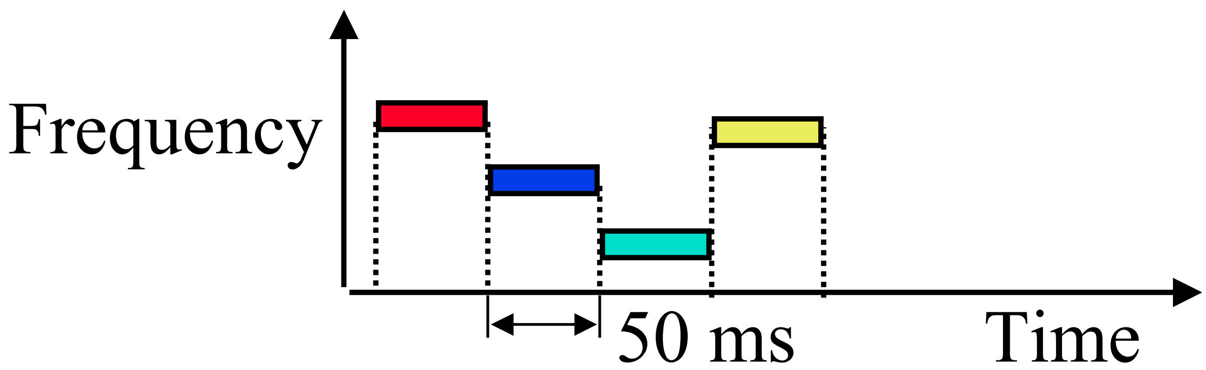


Turbo Codes



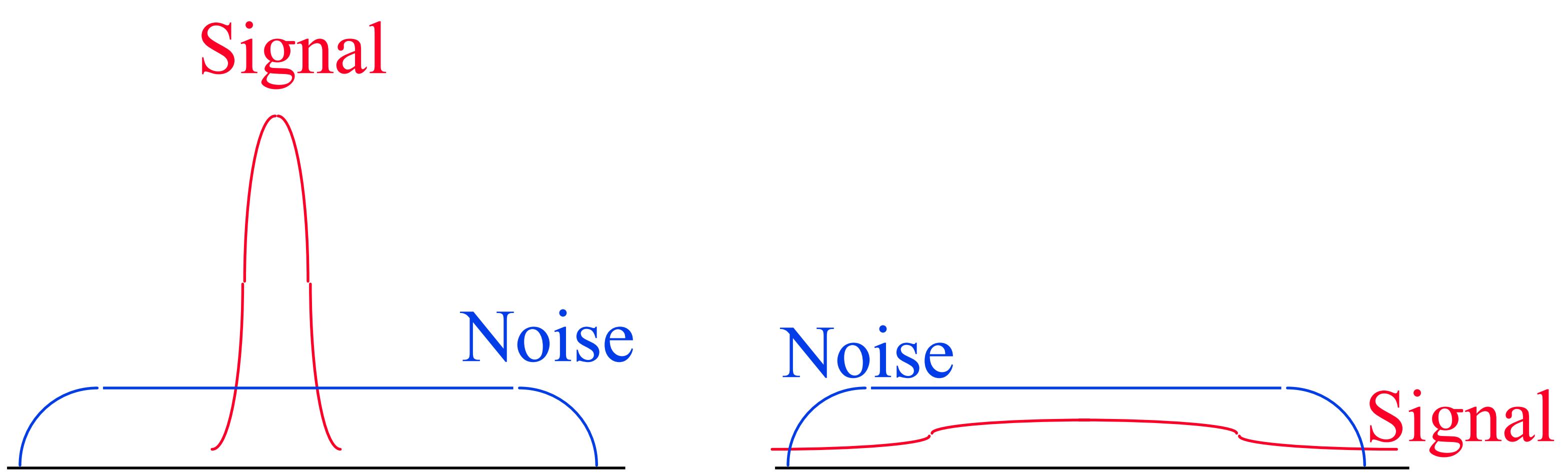
- Normal FEC codes: 3dB below the Shannon limit
- Turbo Codes: 0.5dB below Shannon limit
  Developed by French coding theorists in 1993
- Use two coders with an interleaver
- Interleaver rearranges bits in a prescribed but irregular manner
- 3rd Generation cellular networks use turbo codes

Frequency Hopping Spread Spectrum



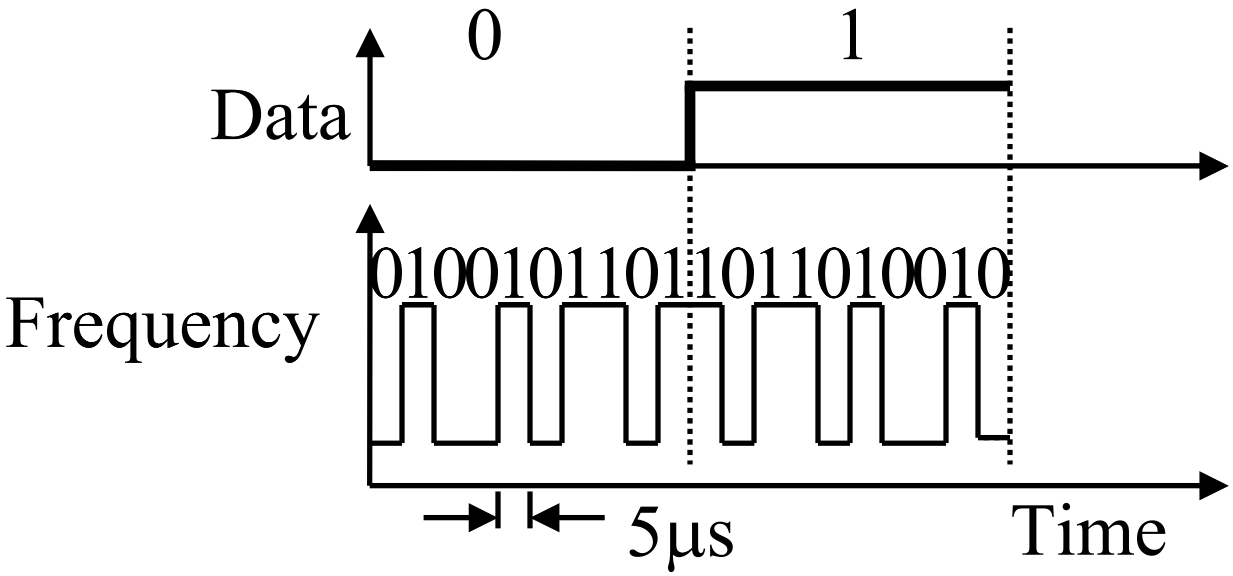
- Pseudo-random frequency hopping
- Spreads the power over a wide spectrum
  ⇒Spread Spectrum
- Developed initially for military
- Patented by actress Hedy Lamarr
- Narrowband interference can't jam

Spectrum



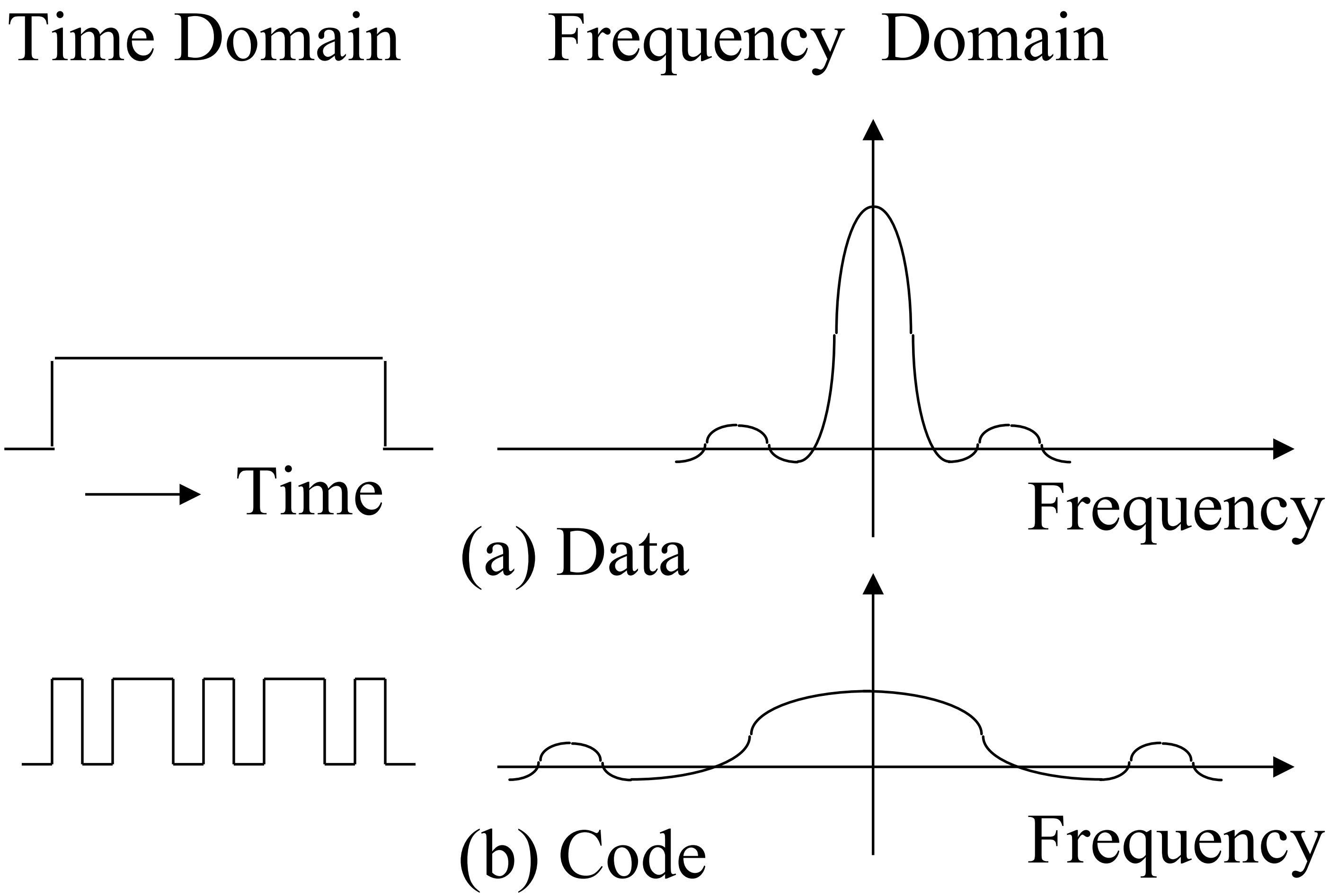
(a) Normal (b) Frequency Hopping

Direct-Sequence Spread Spectrum



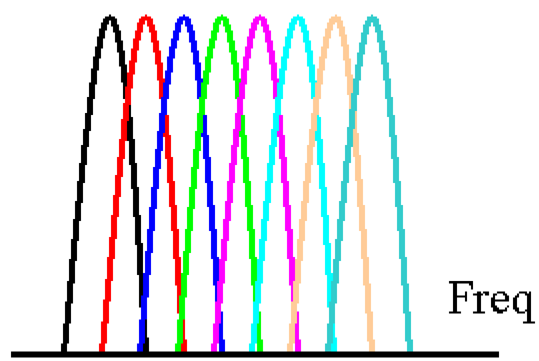
- Spreading factor = Code bits/data bit, 10-100 commercial (Min 10 by FCC), 10,000 for military
- Signal bandwidth >10 × data bandwidth
- Code sequence synchronization
- Correlation between codes ⇒Interference ⇒Orthogonal

DS Spectrum

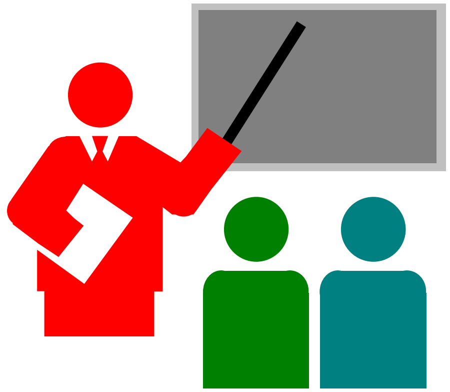

Time Domain
Frequency Domain
Time
Frequency
(a) Data
(b) Code
Frequency

OFDM

- Orthogonal Frequency Division Multiplexing
- Multicarrier modulation similar to DMT
- Available frequency band is divided into 256 or more sub-bands. Orthogonal $\Rightarrow$ Peak of one at null of others
- Each carrier is modulated with a BPSK, QPSK, 16-QAM, 64-QAM etc depending on the noise (Frequency selective fading)
- Used in 802.11a/g, 802.16, HDTV



Summary



1. Hertz and Bit rate are related by Nyquist and Shannon's Theorems
2. Wireless signals have reflections, diffraction, scattering, multipath, fading, and Doppler shift
3. Frequency hopping and Direct Sequence are two methods of code division multiple access
4. OFDM splits a band in to many orthogonal subcarriers
5. Turbo codes use two coders and a interleaver and operate very close to Shannon's limit

Listening Assignment

Those not familiar with modulation, coding, CRC, etc may want to listen to the following lectures from CSE473S:
(Text book: William Stallings, "Data & Computer Communications," **Seventh Edition**, Prentice-Hall, ISBN 0-13-100681-9, **2004**.)

- Transmission Media, http://www.cse.wustl.edu/~jain/cse473-05/i_4med.htm
- Signal Encoding Techniques, http://www.cse.wustl.edu/~jain/cse473-05/i_5cod.htm
- Digital Communications Techniques, http://www.cse.wustl.edu/~jain/cse473-05/i_6com.htm

Listening Assignment (Cont)

Those who have not taken CSE473S with me may want to listen to the following lectures:

- Wireless LANs, http://www.cse.wustl.edu/~jain/cse473-05/i_bwir.htm
- Cellular Wireless Networks, http://www.cse.wustl.edu/~jain/cse473-05/i_ccel.htm
- Network Security, http://www.cse.wustl.edu/~jain/cse473-05/i_isec.htm http://www.cse.wustl.edu/~jain/cse473-05/i_hsec.htm

Homework 3

1. A telephone line is known to have a loss of 20 dB. The input signal power is measured at 1 Watt, and the output signal noise level is measured at 1 mW. Using this information, calculate the output signal to noise ratio in dB.
2. What is the maximum data rate that can be supported on a 10 MHz noise-less channel if the channel uses eight-level digital signals?
3. What signal to noise ratio (in dB) is required to achieve 10 Mbps through a 5 MHz channel?