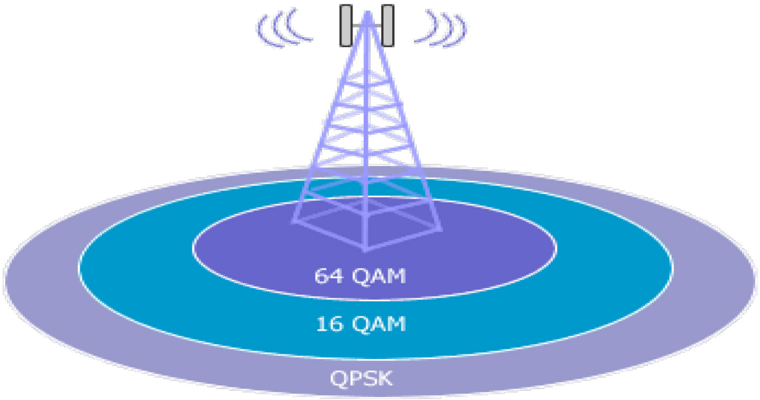
Introduction to Wireless Coding and Modulation



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Audio/Video recordings of this class lecture are available at:
http://www.cse.wustl.edu/~jain/cse574-20/

Student Questions

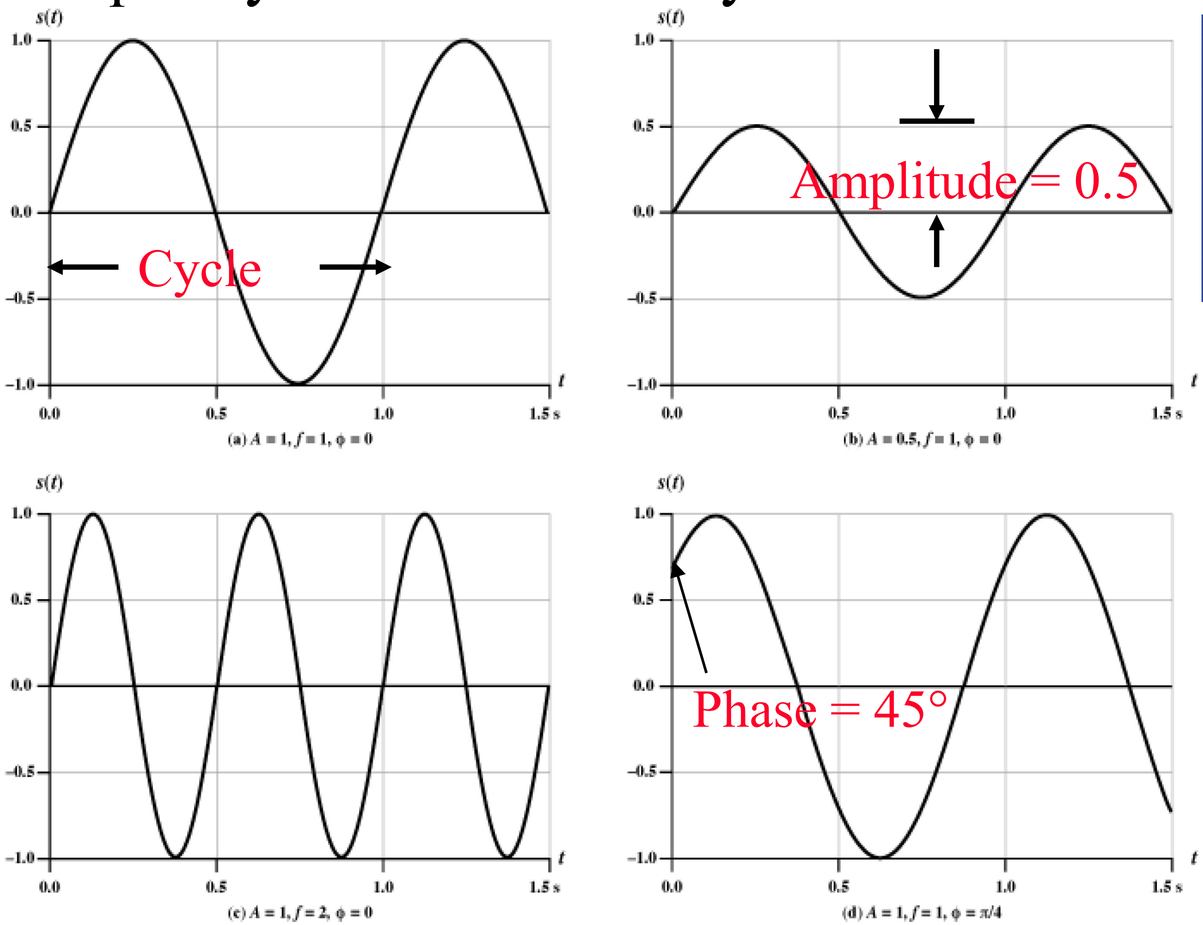
1. Frequency, Wavelength, and Phase
2. Electromagnetic Spectrum
3. Coding and modulation
4. Shannon's Theorem
5. Hamming Distance
6. Multiple Access Methods: CDMA
7. Doppler Shift

Note: This is the 1st in a series of 2 lectures on wireless physical layer. Signal Propagation, OFDM, and MIMO are covered in the next lecture.

Student Questions

Frequency, Period, and Phase

- A Sin(2πft + θ), A = Amplitude, f=Frequency,
  θ = Phase, Period T = 1/f,
  Frequency is measured in Cycles/sec or **Hertz**



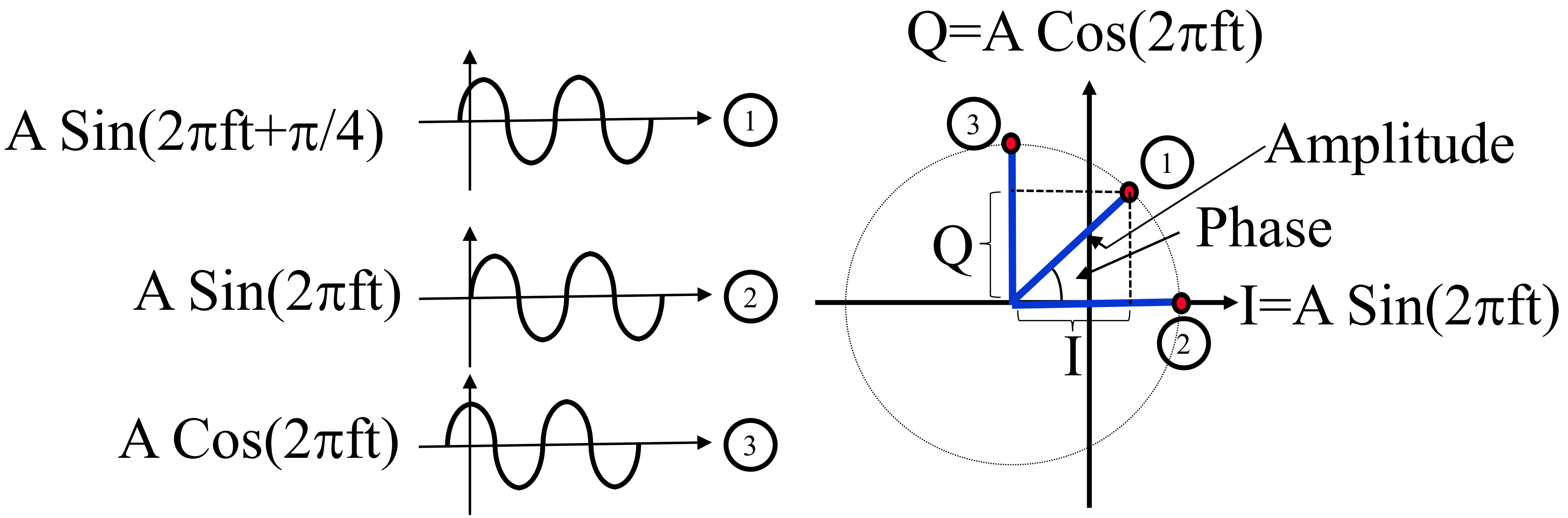
Student Questions

Phase

- Sine wave with a phase of 45°

$$\sin(2\pi ft + \frac{\pi}{4}) = \sin(2\pi ft)\cos(\frac{\pi}{4}) + \cos(2\pi ft)\sin(\frac{\pi}{4})$$
$$= \frac{1}{\sqrt{2}}\sin(2\pi ft) + \frac{1}{\sqrt{2}}\cos(2\pi ft)$$

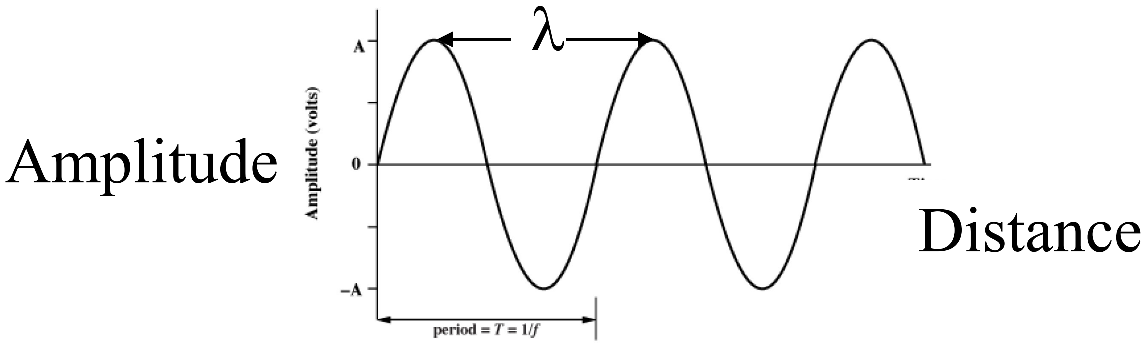
In-phase component I + Quadrature component Q



Student Questions

- When would we use the normal equation for phase, and when would we use the expanded version?
- Why do we ignore the Cos(π/4) for the Q component, and the sin(π/4) for the I component in the Phase graph on the bottom right?

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*

Student Questions

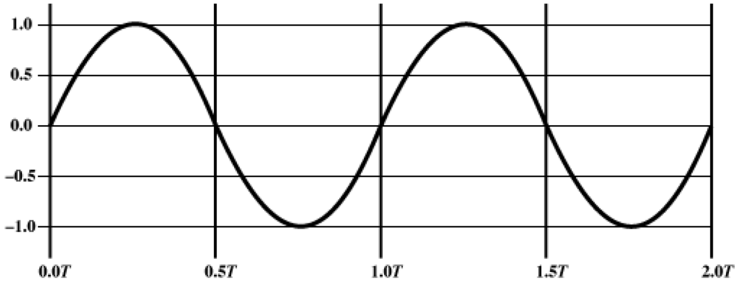
Example

- Frequency = 2.5 GHz

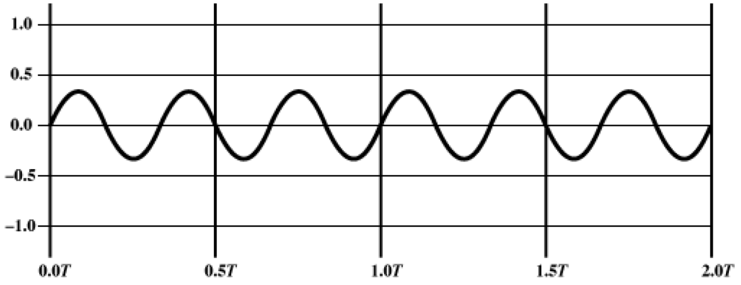
$$\text{Wavelength} = \lambda = \frac{c}{f} = \frac{300 \text{ m}/\mu\text{s}}{2.5 \times 10^9} = 120 \times 10^{-3} = 120 \text{ mm} = 12 \text{ cm}$$

Student Questions

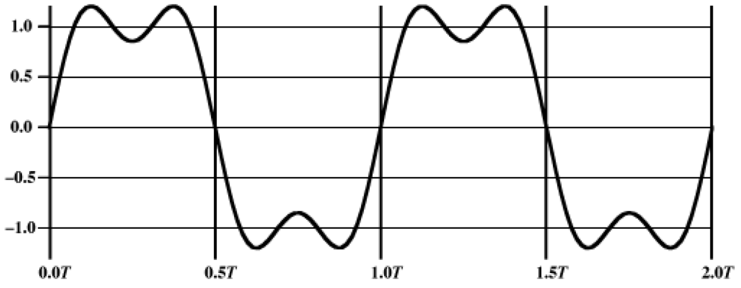
Time and Frequency Domains



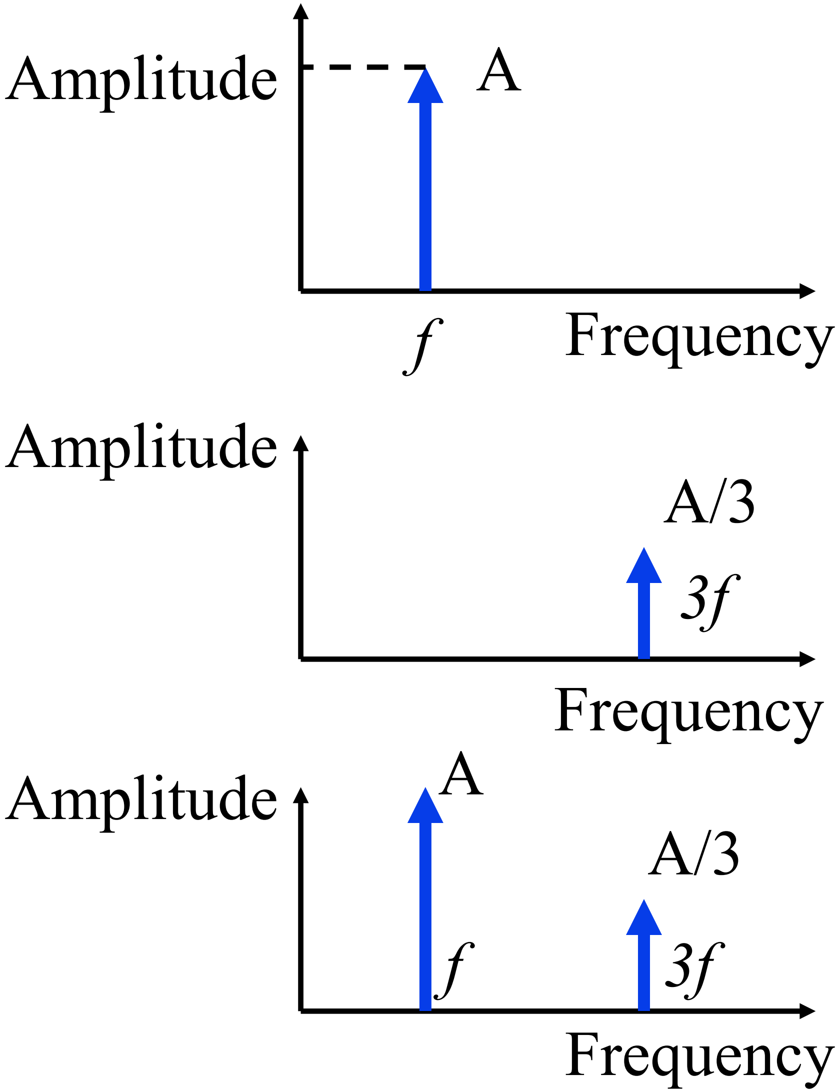
(a) sin $(2\pi ft)$



(b) (1/3) sin $(2\pi(3f)t)$



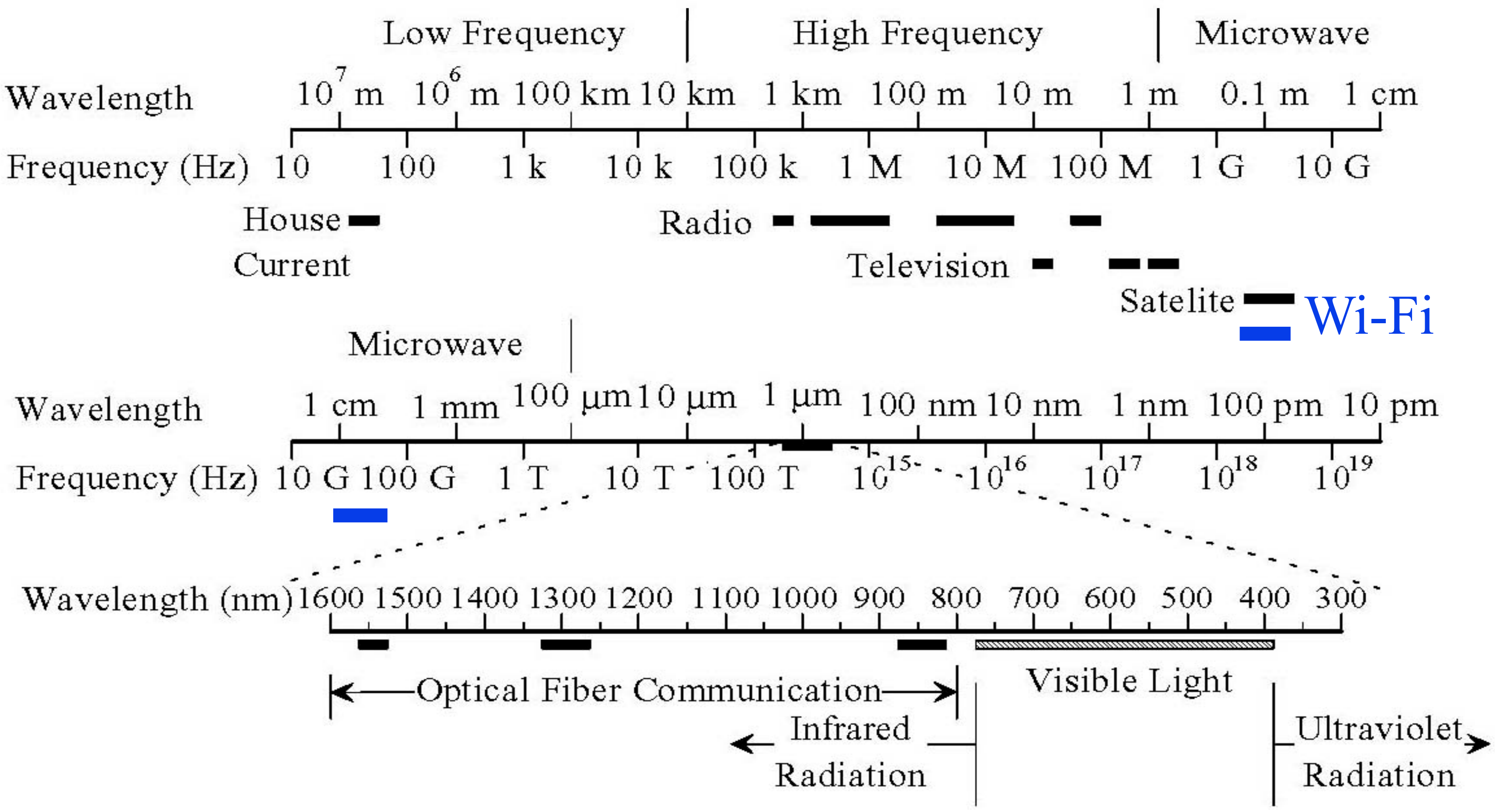
(c) $(4/\pi)$ [sin $(2\pi ft)$ + (1/3) sin $(2\pi(3f)t)$]



Student Questions

- Will Fourier transforms be important for wireless networking frequencies? *Yes, for EE students*

Electromagnetic Spectrum



- Wireless communication uses 100 kHz to 60 GHz

Student Questions

- Does THz domain have any wireless application at all?
  Yes. Li-Fi is light-based Wi-Fi like technology.
- For dual band wireless access points, does the equipment have two physical antennas?
  In the past.
  Now discrete Fourier transforms are used to separate frequencies.

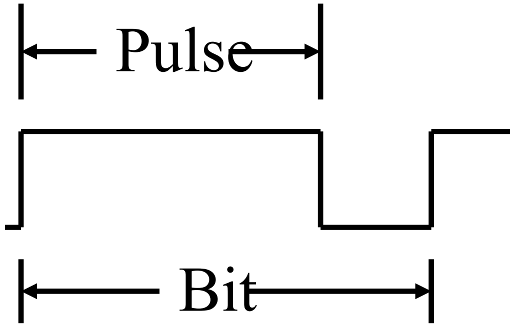
Decibels

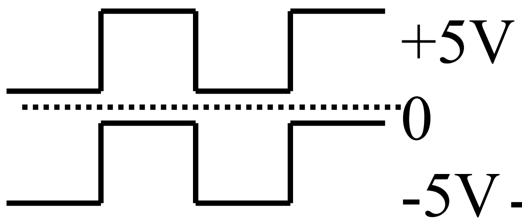
- Attenuation = $\text{Log}_{10} \dfrac{\text{Pin}}{\text{Pout}}$ Bel
- Attenuation = $10\ \text{Log}_{10} \dfrac{\text{Pin}}{\text{Pout}}$ deciBel
- Attenuation = $20\ \text{Log}_{10} \dfrac{\text{Vin}}{\text{Vout}}$ deciBel Since, $P=V^2I$
- **Example 1**: Pin = 10 mW, Pout=5 mW
  Attenuation = $10 \log_{10} (10/5) = 10 \log_{10} 2 \approx 3$ dB
- **Example 2**: Pin = 100mW, Pout=1 mW
  Attenuation = $10 \log_{10} (100/1) = 10 \log_{10} 100 = 20$ dB

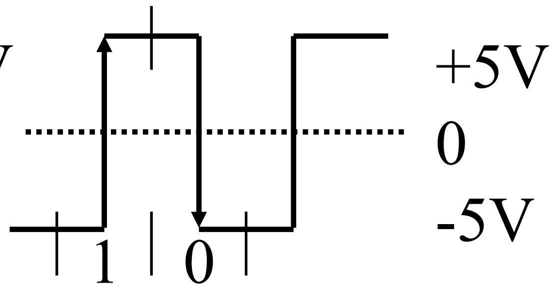
Student Questions

- So attenuation = Pin/Pout dB. What is Pin/Pout in this case, I am a bit unsure.
  Pin is the input power. Pout is the output power. Both measured in Watts.
- Why is the Voltage attenuation (third formula) 20 Log10 whereas the second formula for power is 10 Log10? (Does voltage decay twice as fast as power?)
  $P=V^2I$; V is the Voltage and I is the current. Log P = 2 Log V + Log I
- Can you go over the different ways of calculating attenuation again? Why can we get attenuation just using voltage_in and voltage_out, without power?
  Because the current (flow of photons or electrons) is constant.

Coding Terminology







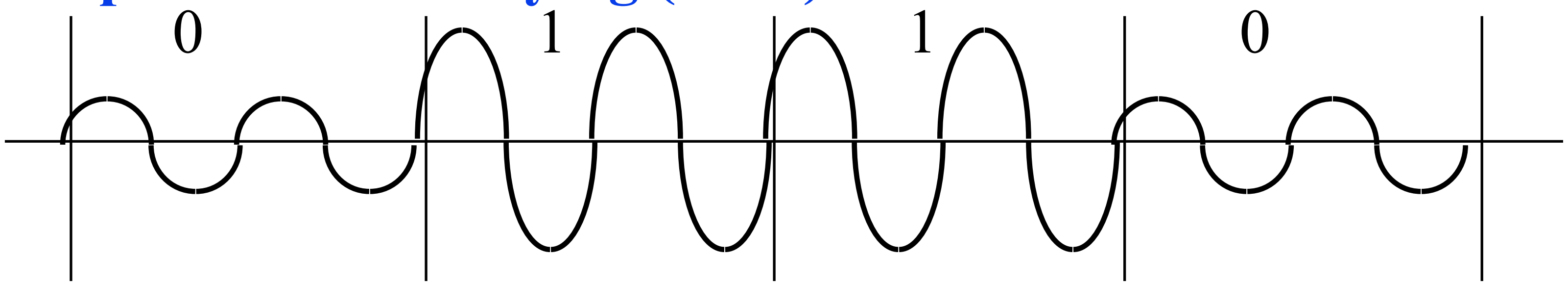
- **Signal element**: Pulse (of constant amplitude, frequency, phase) = **Symbol**
- **Modulation Rate**: 1/Duration of the smallest element =Baud rate
- **Data Rate**: Bits per second

Student Questions

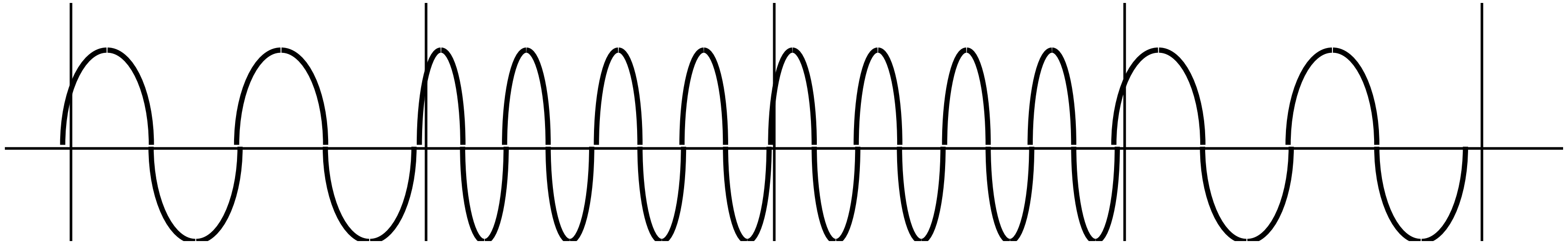
- Can you go over what the "duration of the smallest element" is in the example? You pointed to something in the video but we can't see the board.
  The first figure shows a code consisting of a long element followed by a short element. Like Morse Code. In this case, the small element is the shortest. In the other two figures, all elements are one size.
- Multiple elements (pulses) can comprise a symbol?
  Yes. In the first figure, 1 symbol=2 Elements. In the other two figures one symbol=one element.
- I am confused about the element and Baud and how the figures explain the terminology
  A symbol consists of one or more bits. Each symbol is transmitted as one or more elements. The smallest element determines the baud rate. Users care about bits. Coders care about symbols. Electronics has to be designed to be able to transmit/receive smallest element, i.e., the Baud rate. The medium (air) has a limited bandwidth (frequency or Hertz).

Modulation

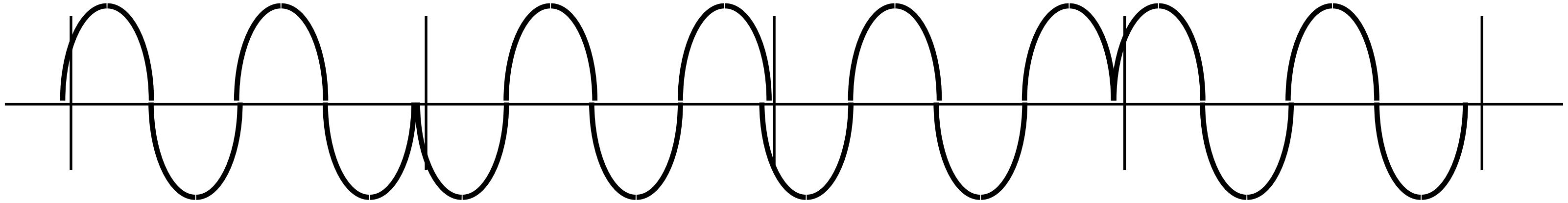
- Digital version of modulation is called **keying**
- **Amplitude Shift Keying (ASK):**



- **Frequency Shift Keying (FSK):**



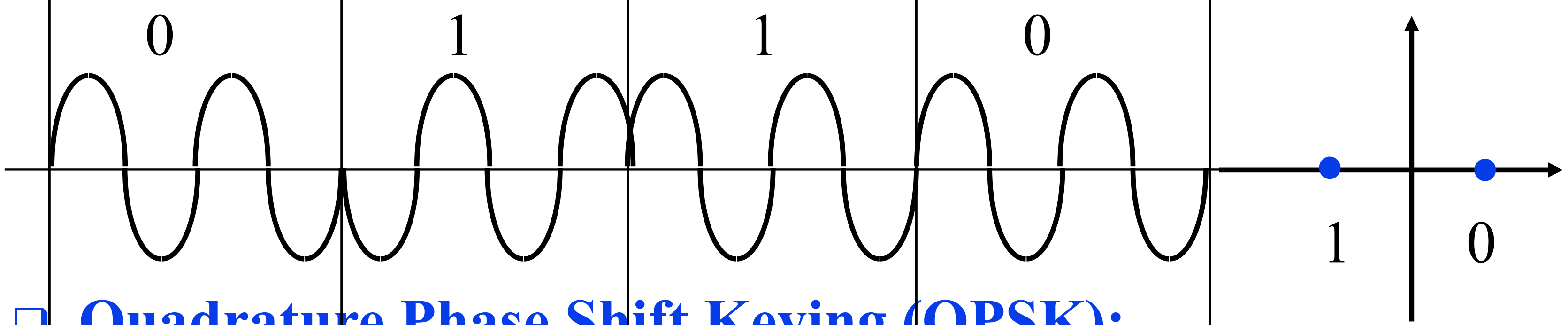
- **Phase Shift Keying (PSK):** Binary PSK (BPSK)



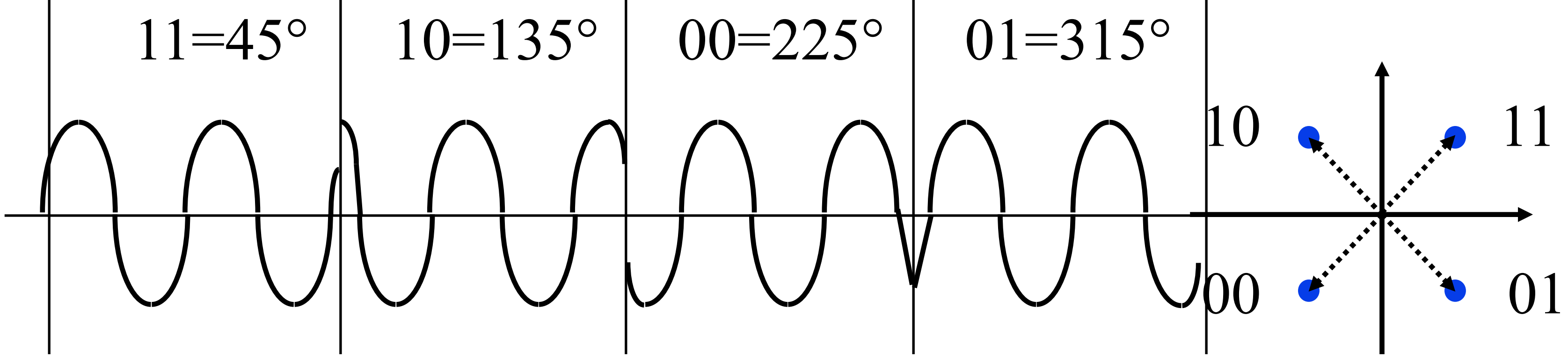
Student Questions

Modulation (Cont)

- **Differential BPSK:** Does not require original carrier



- **Quadrature Phase Shift Keying (QPSK):**



- In-phase (I) and Quadrature (Q) or 90 ° components are added

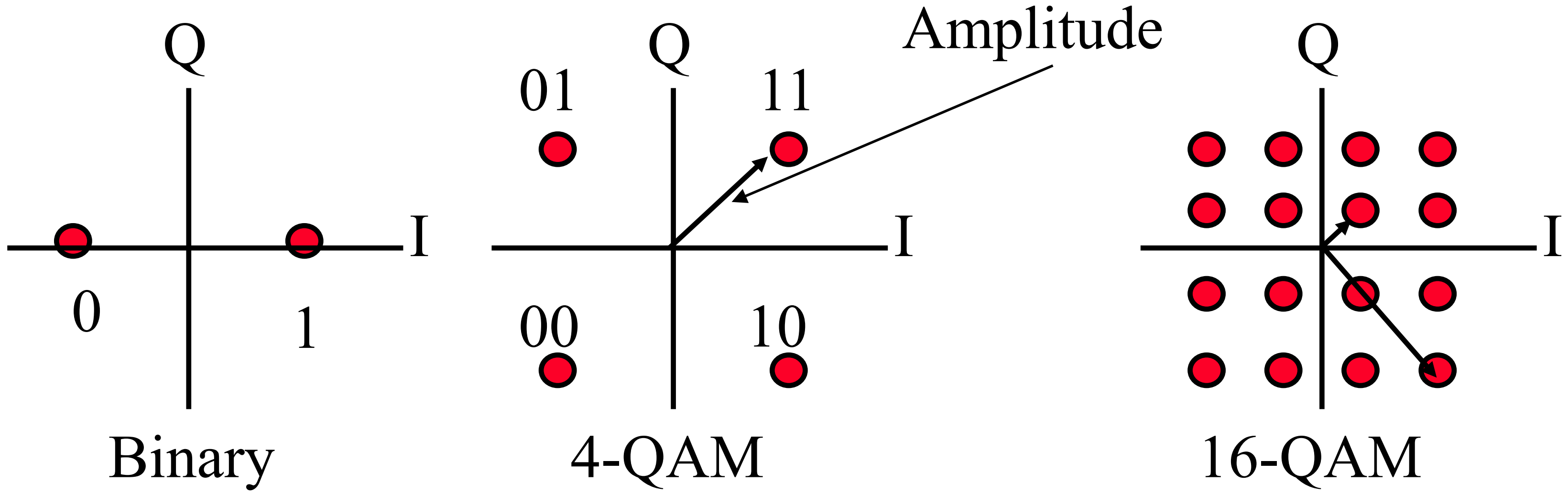
Ref: Electronic Design, "Understanding Modern Digital Modulation Techniques," https://www.electronicdesign.com/communications/understanding-modern-digital-modulation-techniques

Student Questions

- Please go over the QPSK. I am specifically confused on how you translate the wavelengths to the graphs on the right to depict the change in signal.
  See Slide 3-4 for relationship between the waveform and the polar representation. QPSK uses 4 (Quad) different phases. BPSK use 2 (binary) phases.
- Could you explain the x-y coordinates of Differential BPSK?
  Differential=>The difference between two consecutive signals is used to code the symbol. Here, 1=Change of Phase, 0=No change in phase.
- How are we able to create and send the non-continuous waveforms for QPSK?
  Electronic circuits are used to generated sine waves, change their phases and transmit a different phase, frequency, or amplitude as needed.

QAM

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



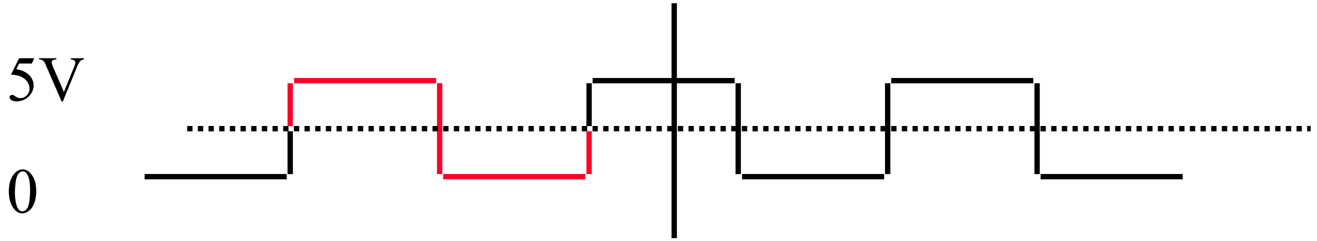
- 4-QAM⇒ 2 bits/symbol, 16-QAM ⇒4 bits/symbol, …

Student Questions

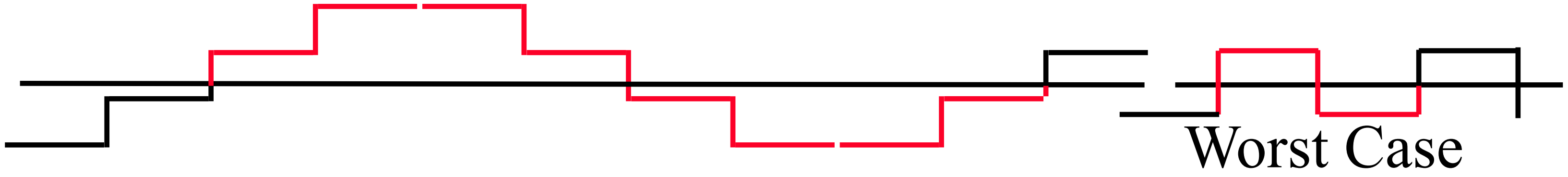
- Is QAM used in both wired and wireless networks?
  Yes. QAM is very common in both wired and wireless networking.
- Is there a relationship between QAM, and ASK and QPSK modulation? and If QAM is an extension of QPSK, why the positions of 01 and 10 in QPSK are different from 4-QAM?
  ASK uses only amplitude change. QAM uses both amplitude and phase as in 16-QAM shown. QPSK is same as 4-QAM.
- Are these graphs the result of Fourier transforms?
  Yes, Fourier transforms are used to go from time domain to frequency domain and vice versa. EE students do all the math and design Layer 1. CS students work on Layer 2-7.

Channel Capacity

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



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



Example: M=4, Capacity = 4 × Bandwidth

Student Questions

- What does a level represent? A bit combination?
  The level is the amplitude of the signal. The bottom left diagram has 4 levels -2, -1, 1, and 2. Other diagrams have only two levels -1, +1.
- Can you indicate the baud length on the first diagram?
  In the first diagram, all elements have the same size. The red part indicates one cycle. If it is 1ms long, then each element is 0.5 ms and Baud rate is 2 kBaud.

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

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

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

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

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

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

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

Student Questions

- What is the unit of the "S/N" when it is 1000? I know it is deciBel when it is 30.
  Power is measured in Watts, mW, or micro-W. Watts can be added, subtracted, multiplied and devided. When converted to dB, the logs are only added or subtracted. dBs are not multiplied.
- My calculator calculated it to be 30898.4, I am not sure why it is different than your calculations.
  My calculator is old. It used 32-bit real numbers and has only 4 digit precision.

Hamming Distance

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

  Difference 101010 $\Rightarrow$ Distance =3

Student Questions

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.

Student Questions

- Do we always use extended codewords to detect errors, or are there low-noise applications where we don't need to worry about error correction?
Yes, extra bits are required for error detection. Error correction requires even more extra bits.

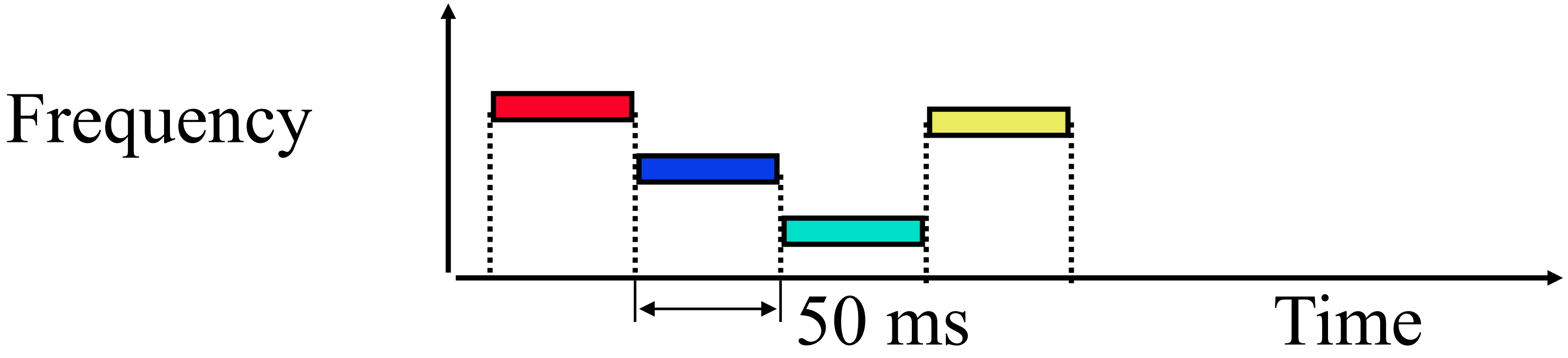
Multiple Access Methods

Time Division Multiple Access

Code Division Multiple Access

Student Questions

Frequency Hopping Spread Spectrum



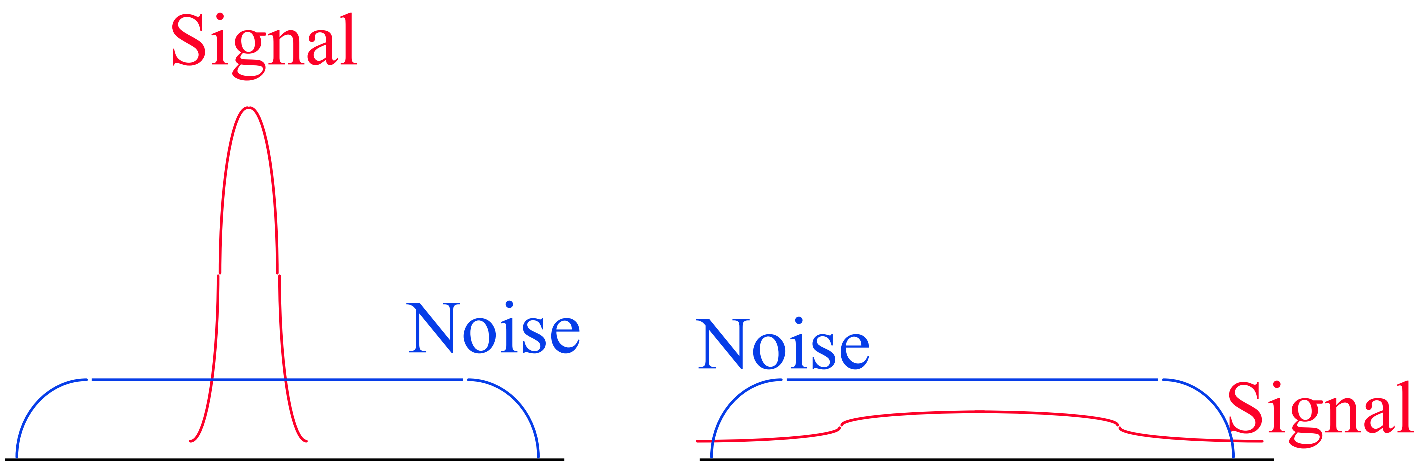
- Pseudo-random frequency hopping
- Spreads the power over a wide spectrum
  ⇒ Spread Spectrum
- Developed initially for military
- Patented by actress Hedy Lamarr
- Narrowband interference can't jam

Student Questions

- Do we then listen to each frequency for the same period of time (50ms for each frequency in this example)?

  Yes, we tune to a different frequency every 50 ms.

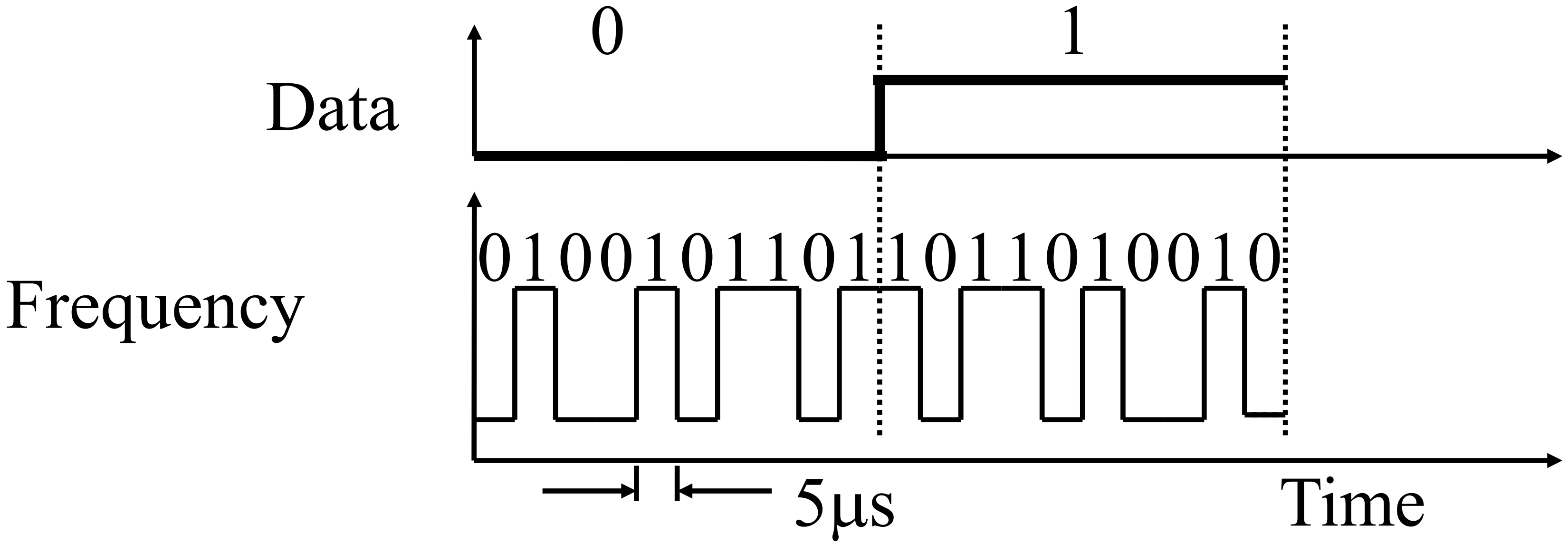
Spectrum



(a) Normal (b) Frequency Hopping

Student Questions

Direct-Sequence Spread Spectrum



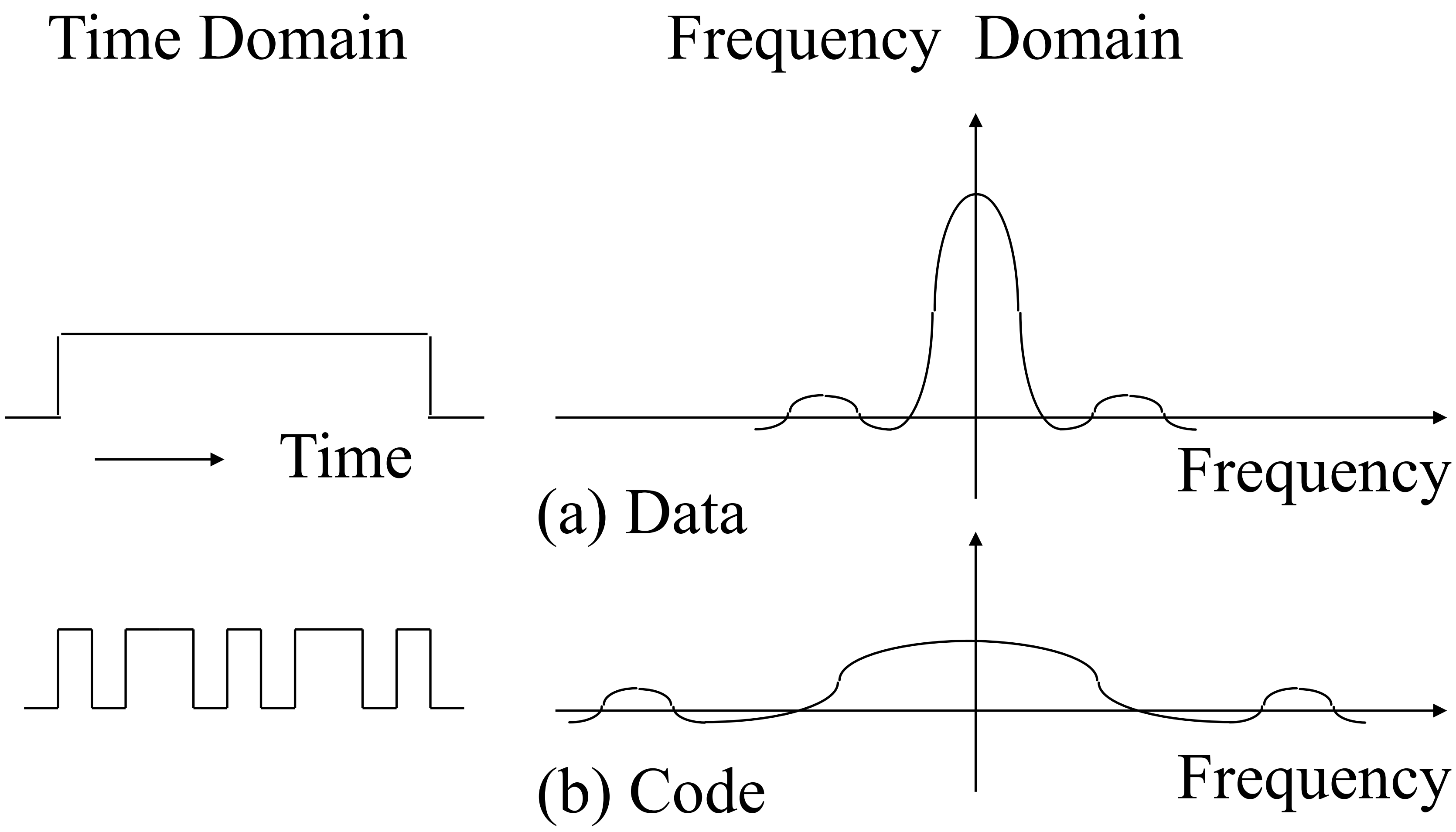
- Spreading factor = Code bits/data bit, 10-100 commercial (Min 10 by FCC), 10,000 for military
- Signal bandwidth >10 × data bandwidth
- Code sequence synchronization
- Correlation between codes ⇒Interference□□Orthogonal

Student Questions

- Could you compare DS spread spectrum with frequency hopping spread spectrum?

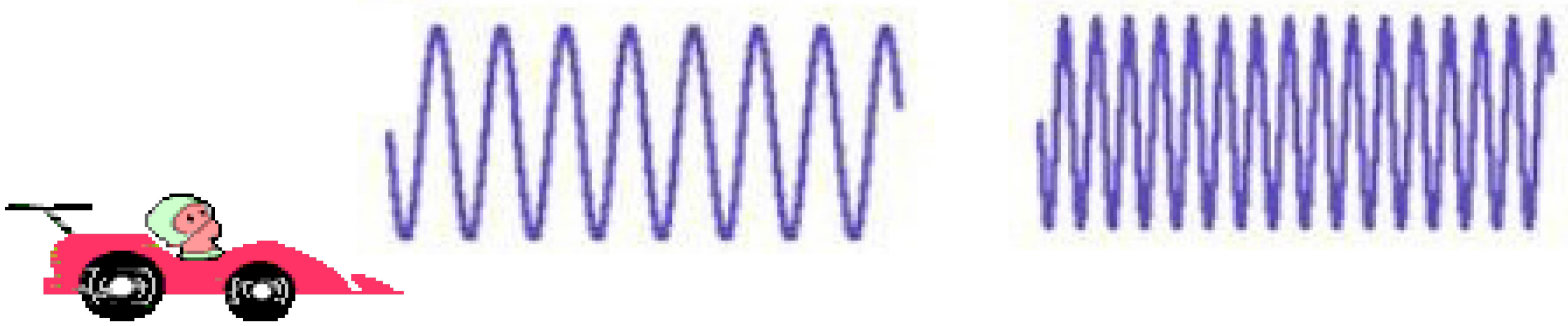
  In DSSS, frequency is high but it is constant. In FHSS, frequency changes every elelment.

DS Spectrum



Student Questions

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

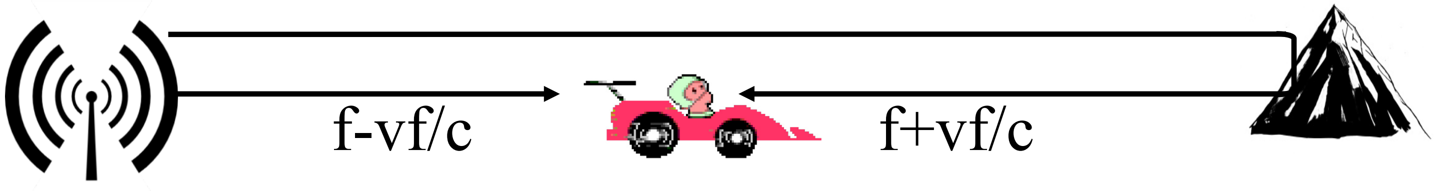
Frequency difference = velocity/Wavelength = vf/c

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

Student Questions

Doppler Spread and Coherence Time

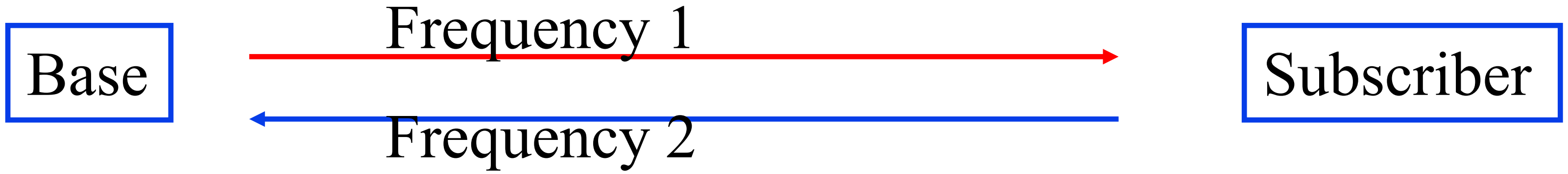


- Two rays will be received
- **Doppler Spread** = 2vf/c = 2 × Doppler shift
- They will add or cancel-out each other as the receiver moves
- **Coherence time**: Time during which the channel response is constant = 1/Doppler spread

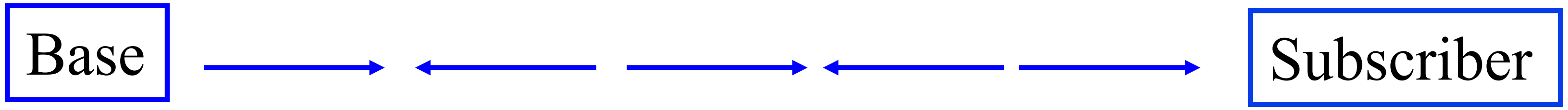
Student Questions

Duplexing

- Duplex = Bi-Directional Communication
- Frequency division duplexing (FDD) (Full-Duplex)



- Time division duplex (TDD): Half-duplex

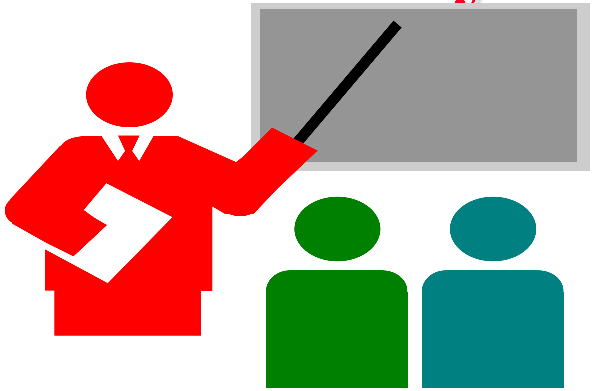


- Many LTE deployments will use TDD.
  - Allows more flexible sharing of DL/UL data rate
  - Does not require paired spectrum
  - Easy channel estimation ⇒ Simpler transceiver design
  - Con: All neighboring BS should time synchronize

Student Questions

- Does half duplex mean only one frequency go and come?
  It is about the direction. In half-duplex, only one side at a time can transmit. Depending upon the coding, one ore more frequency may be used even in one bit.

Summary



1. Electric, Radio, Light, X-Rays, are all electromagnetic waves
2. Wireless radio waves travel at the speed of light 300 m/μs
   Wavelength $\lambda = c/f$
3. 16-QAM uses 16 combinations of amplitude and phase using 4 bits per symbol.
4. Hertz and Bit rate are related by Nyquist and Shannon's Theorems
5. Frequency hopping and Direct Sequence are two methods of code division multiple access (CDMA).

Student Questions

Homework 3

A. What is wavelength of a signal at 60 GHz?

B. How many Watts of power is 30dBm?

C. 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.

D. 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?

E. What signal to noise ratio (in dB) is required to achieve 10 Mbps through a 5 MHz channel?

F. Compute the average Doppler frequency shift at 36 km/hr using 3 GHz band? Doppler spread is twice the Doppler shift. What is the channel coherence time?

Student Questions

Reading List

- Electronic Design, "Understanding Modern Digital Modulation Techniques," https://www.electronicdesign.com/communications/understanding-modern-digital-modulation-techniques
- Jim Geier, "Designing and Deploying 802.11 Wireless Networks: A Practical Guide to Implementing 802.11n and 802.11ac Wireless Networks, Second Edition," Cisco Press, May 2015, 600 pp., ISBN:1-58714-430-1 (Safari Book), Chapter 2.
- Jim Geier, "Wireless Networks first-step," Cisco Press, August 2004, 264 pp., ISBN:1-58720-111-9 (Safari Book), Chapter 3.
- Steve Rackley, "Wireless Networking Technology," Newnes, March 2007, 416 pp., ISBN:0-7506-6788-5 (Safari Book), Chapter 4.

Student Questions

Wikipedia Links

- https://en.wikipedia.org/wiki/Frequency
- https://en.wikipedia.org/wiki/Wavelength
- https://en.wikipedia.org/wiki/Phase_(waves)
- https://en.wikipedia.org/wiki/Quadrature_phase
- https://en.wikipedia.org/wiki/Frequency_domain
- https://en.wikipedia.org/wiki/Time_domain
- https://en.wikipedia.org/wiki/Fourier_transform
- https://en.wikipedia.org/wiki/Electromagnetic_spectrum
- https://en.wikipedia.org/wiki/Decibel
- https://en.wikipedia.org/wiki/DBm
- https://en.wikipedia.org/wiki/Modulation
- https://en.wikipedia.org/wiki/Amplitude-shift_keying
- https://en.wikipedia.org/wiki/Phase-shift_keying
- https://en.wikipedia.org/wiki/Frequency-shift_keying
- https://en.wikipedia.org/wiki/Quadrature_phase-shift_keying

Student Questions

Wikipedia Links (Cont)

- https://en.wikipedia.org/wiki/Differential_coding
- https://en.wikipedia.org/wiki/Quadrature_amplitude_modulation
- https://en.wikipedia.org/wiki/Shannon%E2%80%93Hartley_theorem
- https://en.wikipedia.org/wiki/Channel_capacity
- https://en.wikipedia.org/wiki/Hamming_distance
- https://en.wikipedia.org/wiki/Channel_access_method
- https://en.wikipedia.org/wiki/Time_division_multiple_access
- https://en.wikipedia.org/wiki/Frequency-division_multiple_access
- https://en.wikipedia.org/wiki/CDMA
- https://en.wikipedia.org/wiki/Spread_spectrum
- https://en.wikipedia.org/wiki/Direct-sequence_spread_spectrum
- https://en.wikipedia.org/wiki/Frequency-hopping_spread_spectrum
- https://en.wikipedia.org/wiki/Doppler_effect
- https://en.wikipedia.org/wiki/Duplex_(telecommunications)
- https://en.wikipedia.org/wiki/Time-division_duplex
- http://en.wikipedia.org/wiki/Frequency_division_duplex

Student Questions

Optional Listening Material

Those not familiar with modulation, coding, CRC, etc may want to listen to the following lectures from CSE473S:

- Transmission Media, http://www.cse.wustl.edu/~jain/cse473-11/i_1cni.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

Student Questions

Acronyms

- ASK Amplitude Shift Keying
- BPSK Binary Phase Shift Keying
- BS Base Station
- CDMA Code division multiple access
- CRC Cyclic Redundancy Check
- dB Decibel
- dBm Decibel milliWatt
- DL Downlink
- DS Direct Sequence
- DSL Digital Subscriber Line
- FCC Federal Communications Commission
- FDD Frequency Division Duplexing
- FSK Frequency Shift Keying
- GHz Giga Hertz
- LAN Local Area Network
- MHz Mega Hertz

Student Questions

Acronyms (Cont)

- mW milli Watt
- OFDM Orthogonal Frequency Division Multiplexing
- PSK Phase Shift Keying
- QAM Quadrature Amplitude Modulation
- QPSK Quadrature Phase Shift Keying
- SS Subscriber Station
- TDD Time Division Duplexing
- UL Uplink

Student Questions

Scan This to Download These Slides

Raj Jain
http://rajjain.com

http://www.cse.wustl.edu/~jain/cse574-20/j_03phy.htm

Student Questions

Related Modules

CSE567M: Computer Systems Analysis (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),
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Student Questions