ECE5884 Wireless Communications

Week 5: Digital Modulation and Detection

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Course outline

This week: **Ref. Ch. 5 of [Goldsmith, 2005]**

- Week 1: Overview of Wireless Communications
- Week 2: Wireless Channel (Path Loss and Shadowing)
- Week 3: Wireless Channel Models
- Week 4: Capacity of Wireless Channels
- Week 5: Digital Modulation and Detection
- Week 6: Performance Analysis
- Week 7: Equalization
- Week 8: Multicarrier Modulation (OFDM)
- Week 9: Diversity Techniques
- Week 10: Multiple-Antenna Systems (MIMO Communications)
- Week 11: Multiuser Systems
- Week 12: Guest Lecture (Emerging 5G/6G Technologies)

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Communication system

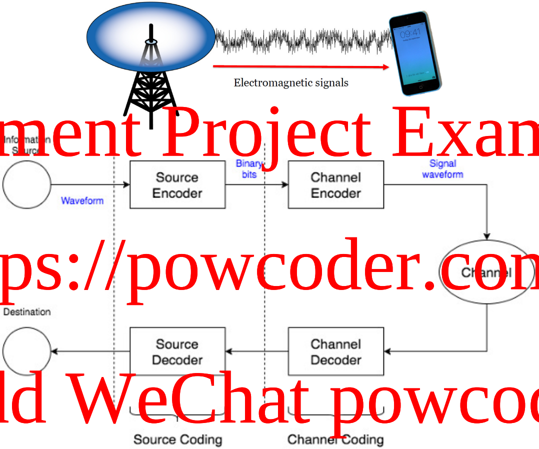

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Figure 1: Block diagram of a digital communication system.

- The source encoder converts information waveform (text, audio, image, video,..) to bits.
- The decoder converts bits back to waveform.

Channel coding

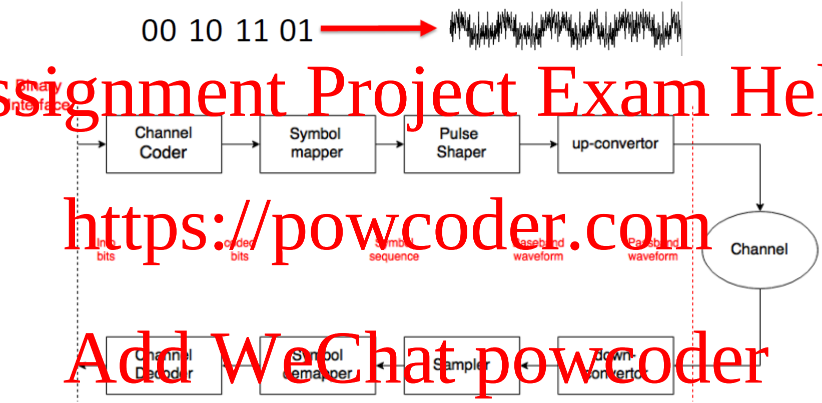

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Figure 2: Block diagram of channel coding.

- The channel encoder converts bits to signal waveform.

1. Convert digital bits into electromagnetic signals, i.e., transmit a few 0s/1s at a time (microseconds between transmissions).
2. Benefits: higher spectral efficiency, powerful error correction techniques, resistance to channel impairments; better security and privacy; etc.

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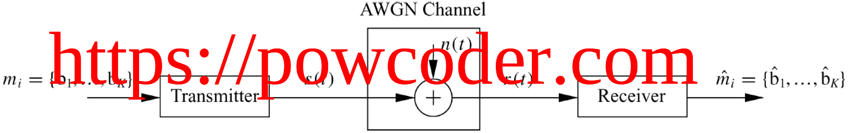

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Figure 3: Communication system model

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3. Digital modulation is the process of encoding a digital information signal into the amplitude, phase and/or frequency of the transmitted signal.

$$s(t) = A\cos(2\pi f t + \theta)$$

Digital modulation

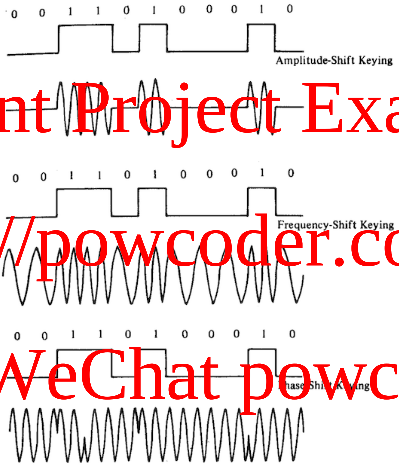

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Figure 4: Digital modulation schemes - ASK, FSK and PSK.

https://www.researchgate.net/figure/Digital-modulation-schemes-ASK-FSK-and-PSK_fig3_303471153

Example: QPSK or 4-PSK

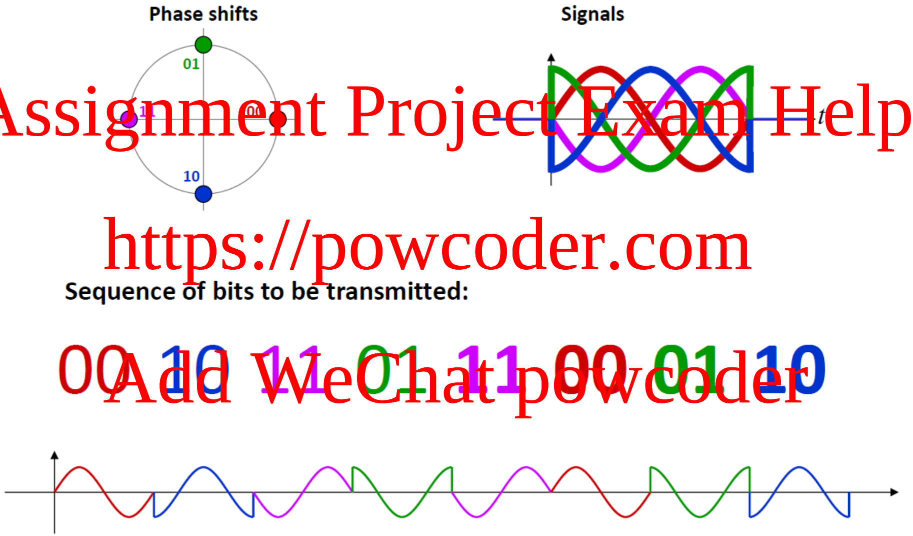

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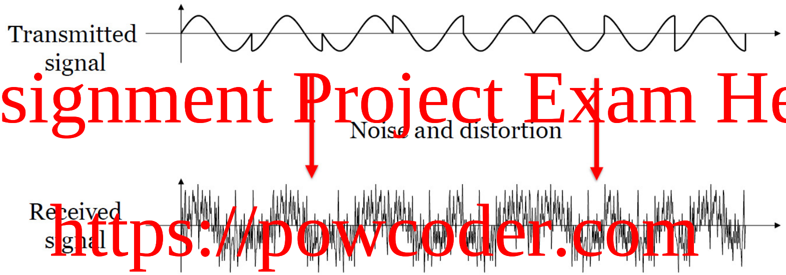
Figure 5: Phase-Shift Keying (PSK) digital modulation.

Digital modulation/demodulation



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- Challenges of communications/Research problem:
  1. Transmit as much data as possible per second (1G-6G+) - Modulation
  2. Estimating the original bit sequence based on the signal received over the channel -Detection/Demodulation
- Digital modulation technique - high data rate; high spectral efficiency (minimum BW occupancy); high power efficiency (minimum required transmit power); robustness to channel impairments (minimum probability of bit error); and low power/cost implementation.

Amplitude and Phase Modulation

1. Over a time interval of T_s,

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$$K = \log_2(M) \text{ bits per symbol time } T_s$$

   are encoded into the amplitude and/or phase of the transmitted signal $s(t)$, $0 \le t < T_s$.

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2. There are three main types of amplitude/phase modulation:
   - pulse amplitude modulation (MPAM) – information encoded in amplitude only;
   - phase-shift keying (MPSK) – information encoded in phase only;
   - quadrature amplitude modulation (MQAM) – information encoded in both amplitude and phase.

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3. M for M-ary transmission, usually $M = 2^K$.

Pulse Amplitude Modulation (MPAM)

1. all of the information is encoded into the signal amplitude A_i. The transmitted signal over one symbol time is given by

$$s_i(t) = \Re\{A_i g(t) e^{j2\pi f_c t}\} = A_i g(t)\cos(2\pi f_c t), 0 \le t < T_s$$

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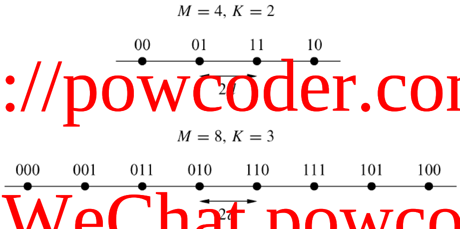

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Figure 6: Gray encoding for MPAM

2. The minimum distance between constellation points is

$$d_{min} = \min_{i,j} |A_i - A_j| = 2d.$$

3. Gray code mapping: all adjacent symbols differ by a single bit.

1. The ith constellation has energy $E_{si} = A_i^2$, and the average energy is

$$\bar{E}_s = \frac{1}{M}\sum_{i=1}^{M} A_i^2 \tag{1}$$

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Example 5.4: For $g(t) = \sqrt{2/T_s}(0 \leq t < T_s)$ a rectangular pulse shape, find the average energy of 4-PAM modulation. *Solution:* For 4-PAM the A_i values are $A_i = \{-3d, -d, d, 3d\}$, so the average energy is

$$\overline{E}_s = \frac{d^2}{4}(9+1+1+9) = 5d^2.$$

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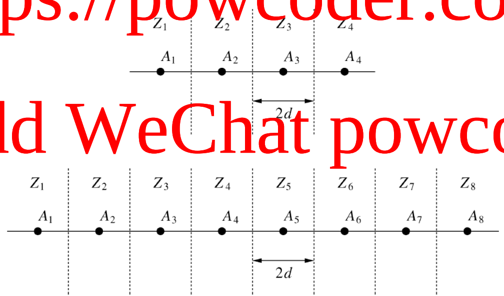

Figure 7: Decision regions for MPAM.

1. All of the information is encoded in the phase of the transmitted signal. The transmitted signal over one symbol time is given by

$$s_i(t) = \Re\{A g(t) e^{j2\pi(i-1)/M} e^{j2\pi f_c t}\}, \; i = 1, \dots, M$$

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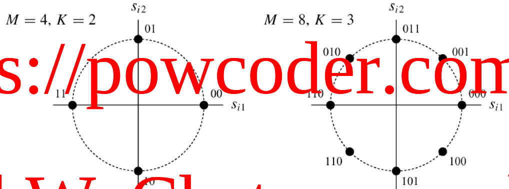

Figure 8: Gray encoding for MPSK (Constellation diagram).

2. The minimum distance between constellation points is

$$d_{min} = \min_{i,j} |A_i - A_j| = 2A \sin(\pi/M).$$

where A is typically a function of the signal energy.

Phase-Shift Keying (MPSK)

1. All possible transmitted signals $s_i(t)$ have equal energy:

$$\bar{E}_s = \frac{1}{M}\sum_{i=1}^{M} A^2 = A^2 \tag{2}$$

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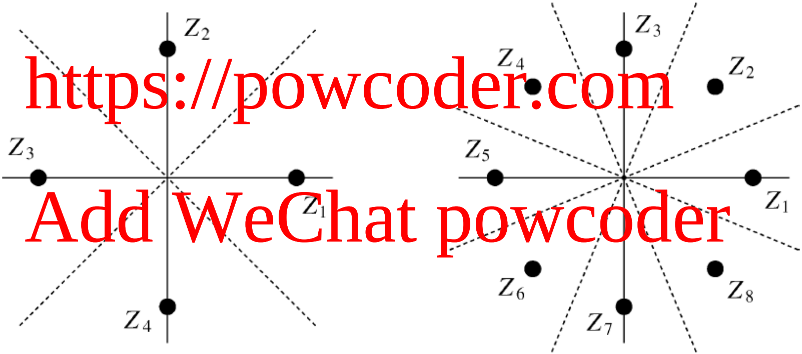

Figure 9: Decision regions for MPSK.

1. The information bits are encoded in both the amplitude and phase of the transmitted signal. MQAM is more spectrally efficient than MPAM and MPSK in that it can encode the most number of bits per symbol for a given average energy.
2. The transmitted signal over one symbol time is given by

$$s_i(t) = \Re\{A_i e^{j\theta_i} g(t) e^{j2\pi f_c t}\},\ i = 1, \ldots, M$$

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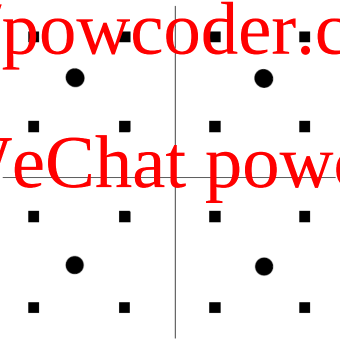

Figure 10: 4-QAM and 16-QAM constellations.

Quadrature Amplitude Modulation (MQAM)

1. The energy in $s_i(t)$ is $E_{si} = A_i^2$, and thus $E_s = \frac{1}{M}\sum_{i=1}^{M} A_i^2$.
2. The distance between any pair of symbols:
   $d_{ij} = ||\mathbf{s}_i - \mathbf{s}_j|| = \sqrt{(s_{i1} - s_{j1})^2 + (s_{i2} - s_{j2})^2}$.
3. The minimum distance between signal $d_{min} = 2d$

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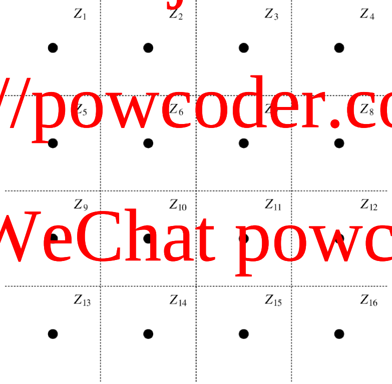

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Figure 11: Decision regions for MQAM with $M = 16$.

Average power

$$\bar{P} = \frac{1}{M}\sum_{i=1}^{M} A_i^2 \quad (3)$$

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- For BPSK:

$$\bar{P} = \frac{1}{2}2A^2 = A^2 \Rightarrow A = \sqrt{\bar{P}} \quad (4)$$

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- For 4-QAM:

$$\bar{P} = \frac{1}{4}4(2A^2) = 2A^2 \Rightarrow A = \sqrt{\frac{\bar{P}}{2}} \quad (5)$$

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- Signal model (kth sample):

$$r_k = \sqrt{P_t}\left(\frac{1}{\sqrt{\bar{P}}}x_k\right)h + n_k \quad (6)$$

Conventionally, we can assume $\bar{P} = 1$.

- Thus, $A = 1$ for BPSK; and $A = 1/\sqrt{2}$ for 4-QAM.

Decision regions

$$\textit{Received signal}: r = h s_i + n \tag{7}$$

$$\textit{AWGN channel}: r = s_i + n \tag{8}$$

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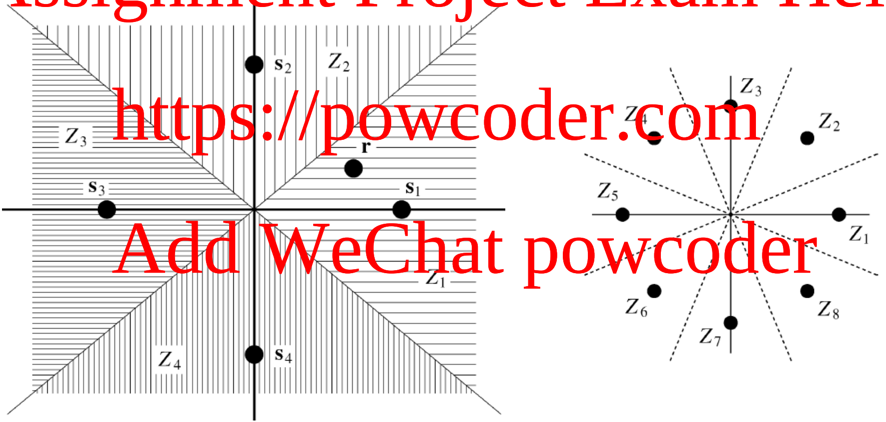

Figure 12: Decision regions for 4-PSK and 8-PSK.

Receiver structure

- Maximum likelihood receiver: is simple to implement because the decision criterion depends only on vector distances.

$$\hat{s} = \arg\min_{s_i,\forall i} ||r - s_i|| \quad (9)$$

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- Matched filter receiver: This structure makes use of a bank of filters matched to each of the different basis functions. If a given input signal is passed through a filter matched to that signal then the output SNR is maximized.

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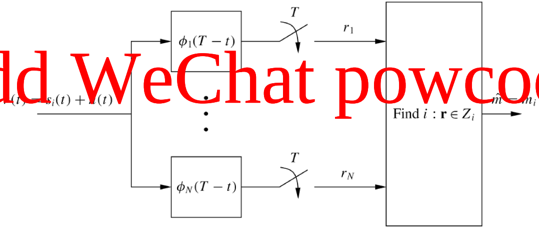

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Figure 13: Matched filter receiver structure.

References

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A. Goldsmith, *Wireless Communications*, Cambridge University Press, USA, 2005.

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Thank You!

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