ECE5884 Wireless Communications

Week 5 Workshop: 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)

Course Information - Assessments

- The assessments in this unit are divided into two parts:
  1. Continuous assessment (Quizzes, Assignments and Labs), which accounts for 50% of the mark
  2. Final assessment, which accounts for the rest 50% of the mark
- This unit contains hurdle requirements:
  - You are required to achieve at least 45% in the total continuous assessment component.
  - You are required to achieve at least 45% 45% in the final assessment component.

Assessment Item	**Weight**	**Due Data**
Weekly Quizzes ($\times$12)	12	End of each week
Assignments ($\times$3)	18	Each (roughly) fourth week
Labs ($\times$5)	20	Each second week, excl. Week 1
Final Exam	50	TBA

Communication system

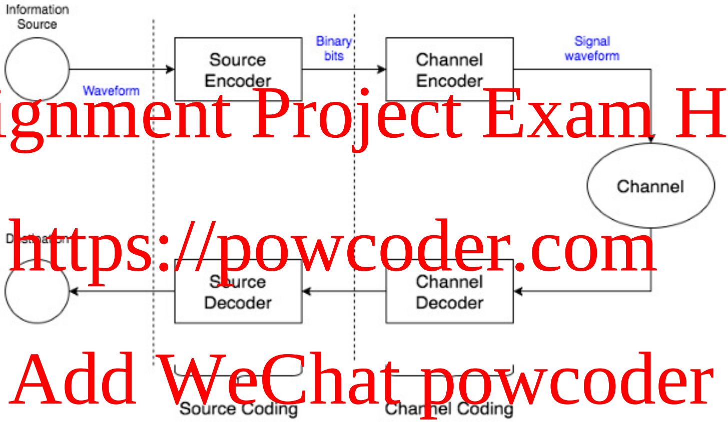


Figure 1: Block diagram of a digital communication system.

- The source encoder converts information waveform to bits.
- The source decoder converts bits back to waveform.

Channel coding

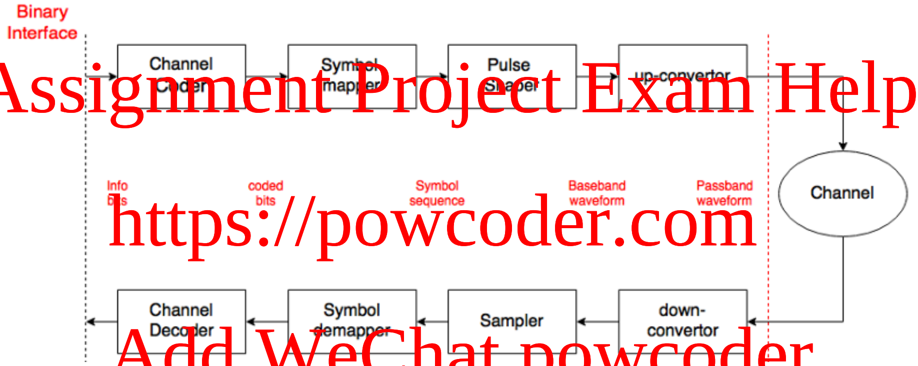


Figure 2: Block diagram of channel coding.

- The channel encoder converts bits to signal waveform.
- The channel decoder converts signal waveform back to bits.

Digital communications

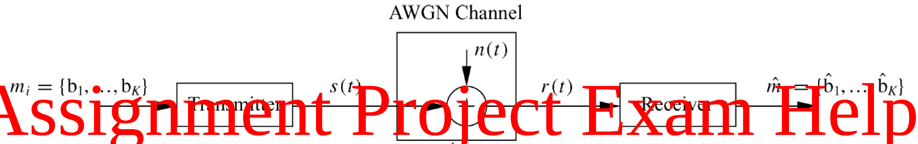


Figure 3: Communication system model.

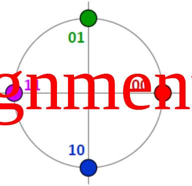
1. Digital modulation is the process of encoding a digital information signal into the amplitude, phase and/or frequency of the transmitted signal.

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

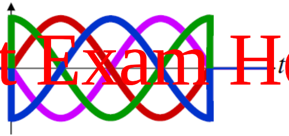
2. There are three main types of amplitude/phase modulation:
   - pulse amplitude modulation (MPAM) – information encoded in amplitude only;
   - phase-shift keying (MPSK) – information encoded in phase only;
   - quadrature amplitude modulation (MQAM) – information encoded in both amplitude and phase.

Example: QPSK or 4-PSK

Phase shifts



Signals



Sequence of bits to be transmitted:

00 10 11 01 11 00 01 10

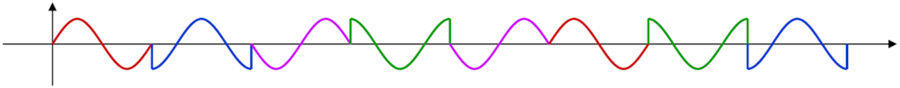
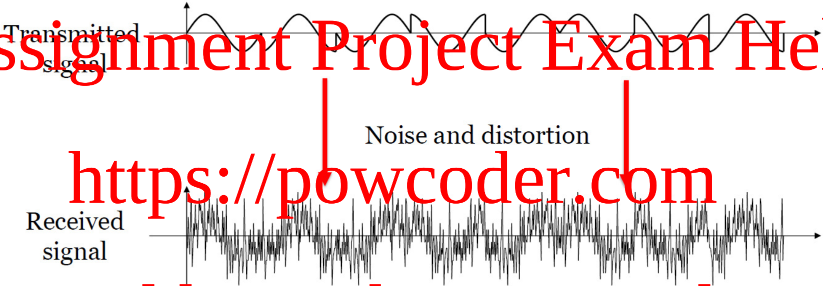
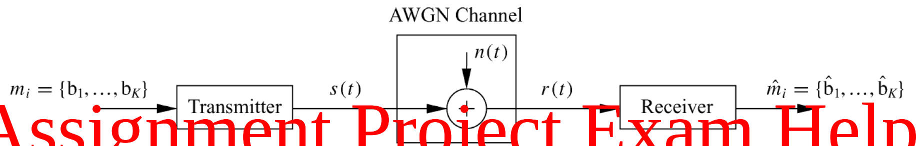


Figure 4: Phase-Shift Keying (PSK) digital modulation $s(t) = A\cos(2\pi f_c t + \theta)$.

Digital modulation/demodulation



- 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



1. Over a time interval of T_s, the system sends $K = \log_2(M)$ bits.
2. Data rate is $R = K/T$ bits per second (bps).
3. For M-ary Tx, there are $M = 2^K$ possible sequences of K bits.
4. Each bit sequence of length K comprises a message m_i.

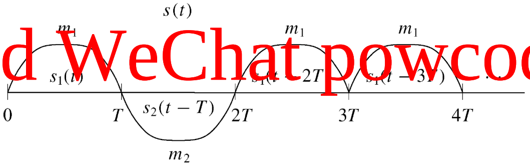


Figure 5: $s(t) = s_1(t) + s_2(t-T) + s_1(t-2T) + s_1(t-3T)$

How do we represent $s(t)$ for a large signal set $s_i(t) \in S = \{s_1(t), \cdots, s_M(t)\}$?

1. Gram–Schmidt orthogonalization procedure: Any set of M real signals $S = \{s_1(t), \cdots, s_M(t)\}$ defined on $[0, T_s)$ with finite energy can be represented as a linear combination of $N \leq M$ real orthonormal basis functions $\{\phi_1(t), \cdots, \phi_N(t)\}$.

$$\int_0^{T_s} \phi_i(t)\phi_j(t)\,dt = 0;\ i \neq j \tag{1}$$

2. Basis function representation:

$$s_i(t) = \sum_{j=1}^{N} s_{ij}\phi_j(t),\ 0 \leq t \leq T_s \text{ where } s_{ij} = \int_0^{T_s} s_i(t)\phi_j(t)\,dt \tag{2}$$

s_{ij} is a real coefficient representing the projection of $s_i(t)$ onto the basis function $\phi_j(t)$.

Receiver structure

- Matched Filter (MF) receiver: If a given input signal is passed through a filter matched to that signal then the output SNR is maximized.

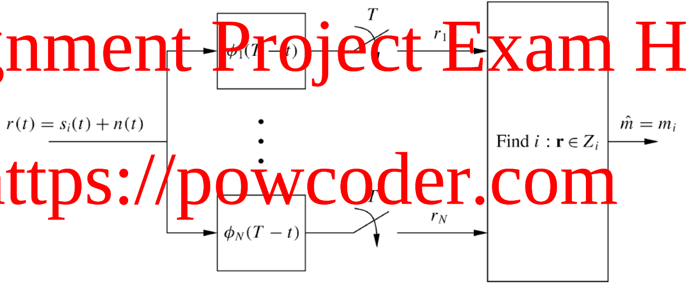


Figure 6: Matched Filter (MF) receiver structure.

- Maximum likelihood receiver: Decision depends only on distances.

$$\hat{s} = \arg \min_{s_i, \forall i} ||r - s_i|| \tag{3}$$

- Decision regions $\{Z_1, ..., Z_M\}$ are subsets of the signal space $\mathbb{R}^N$.
- When known CSI at Rx, MF does: $h' \cdot r$

Pulse Amplitude Modulation (MPAM)

1. All of the information is encoded into the signal amplitude A_i.

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

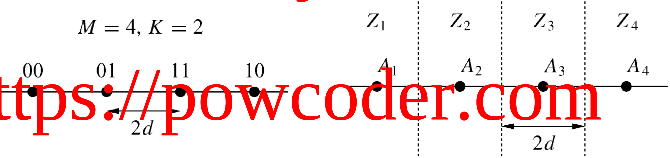


Figure 7: Gray encoding and decision regions for MPAM

2. The minimum distance: $d_{min} = \min_{i,j} |A_i - A_j| = 2d$.
3. The ith constellation has energy $E_{si} = A_i^2$, and the average energy is

$$\bar{E}_s = \frac{1}{M}\sum_{i=1}^{M} A_i^2 \tag{4}$$

Phase-Shift Keying (MPSK)

1. All of the information is encoded in the phase of the transmitted signal.

$$s_i(t) = \Re\{Ag(t)e^{j2\pi(i-1)/M}e^{j2\pi f_c t}\},\ i = 1, \ldots, M$$

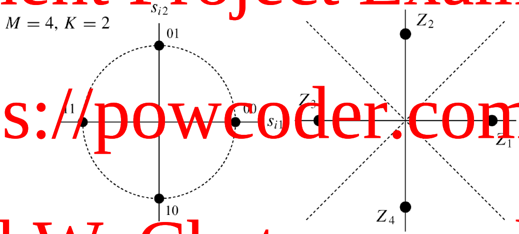


Figure 8: Gray encoding and decision regions for MPSK.

2. The minimum distance: $d_{min} = \min_{i,j} |A_i - A_j| = 2A\sin(\pi/M)$.
3. All possible transmitted signals $s_i(t)$ have equal energy:

$$\bar{E}_s = \frac{1}{M}\sum_{i=1}^{M} A^2 = A^2 \quad (5)$$

Quadrature Amplitude Modulation (MQAM)

1. The information bits are encoded in both the amplitude and phase of the transmitted signal:

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

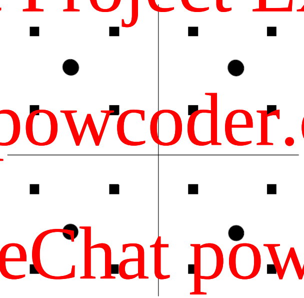


Figure 9: 4-QAM and 16-QAM constellations.

2. $\bar{E}_s = \frac{1}{M}\sum_{i=1}^{M} A_i^2$.
3. The distance between any pair of symbols:
$d_{ij} = ||\mathbf{s}_i - \mathbf{s}_j|| = \sqrt{(s_{i1} - s_{j1})^2 + (s_{i2} - s_{j2})^2}$; and $d_{min} = 2d$.

Average power

$$\bar{P} = \frac{1}{M}\sum_{i=1}^{M} A_i^2 \tag{6}$$

- For BPSK:

$$\bar{P} = \frac{1}{2} 2A^2 = A^2 \Rightarrow A = \sqrt{\bar{P}} \tag{7}$$

- For 4-QAM:

$$\bar{P} = \frac{1}{4} 4(2A^2) = 2A^2 \Rightarrow A = \sqrt{\frac{\bar{P}}{2}} \tag{8}$$

- Signal model (kth sample):

$$r_k = \sqrt{P_t}\left(\frac{1}{\sqrt{\bar{P}}} x_k\right) h + n_k \tag{9}$$

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

Decision regions

$$\textit{Received signal}: r = h\,s_i + n \tag{10}$$

$$\textit{AWGN channel}: r = s_i + n \tag{11}$$

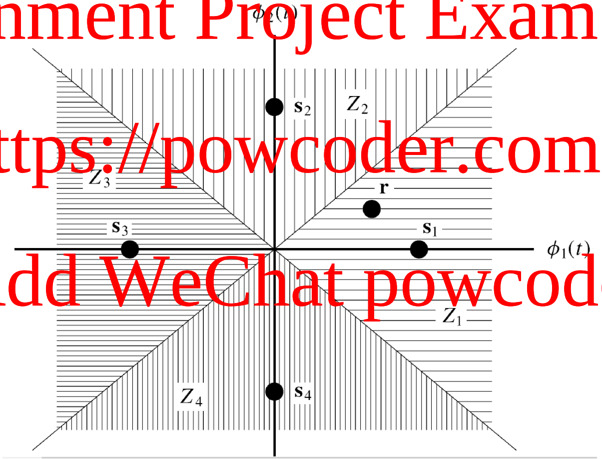


Figure 10: Decision regions for 4-PSK.

References

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

Thank You!

See you again ☺