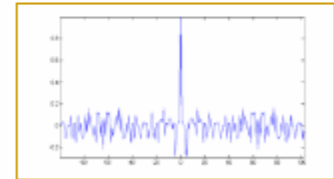


# ECE 5660 – Spread Spectrum Communications

Fall 2006



**Dr . Mohab Mangoud**

**Lecture # 1: Course Overview**

**Review of Digital Communications**

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# Today

- Overview of Course Mechanics
- Overview of Digital Communications
  
- Available on Web Site: +VT blackboard
  - Syllabus
  - Lecture #1
  
  - Chapter 1 “textbook”

[www.aast.edu/~mangoud/ECE5660](http://www.aast.edu/~mangoud/ECE5660)

# Required Course Materials

- **Textbook:**

- **R. Michael Buehrer, Spread Spectrum communications and CDMA Manuscript. Will be available on course website**
- Good references are:
  - A.J. Viterbi, CDMA: Principles of Spread Spectrum Communication,
  - R.L. Peterson, R.E. Ziemer, and D.E. Borth, Introduction to Spread Spectrum Communications
  - S. Verdu, Multiuser Detection

- **Access to Networked PC or Workstation**

- **Software:**

- Student Edition of Matlab for Windows
- Version: 5.3 newer is preferred. Other versions of Matlab are acceptable, but may not be completely compatible with \*.m files which we distribute. (Although there won't be many of these)

# Prerequisites

- **Background in digital communications**
  - A good test: Do you understand the bandwidth/performance trade-off between  $M$ -PSK, QAM, and FSK modulation schemes?
  - Good prerequisite or co-requisite: 5654 – Digital Communications
  - 4634 - Analog and Digital Communications or equivalent is required prerequisite
- **You should be comfortable with basic probability and random process theory**
  - A good test: How is the autocorrelation function of a random process related to the power spectral density?
  - One course which provides this background: EE 5605 - Stochastic Processes I

## Course Objectives:

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- To develop a fundamental understanding of spread spectrum communication systems.
  - Show the ability of spread spectrum to combat jamming and prevent intercept.
  - We will also examine the use of these properties in the context of commercial systems.
  - Code Division Multiple Access or CDMA.
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# **(MMLLO) Major, Measurable Learning Objectives**

Having successfully completed this course, the student will be able to:

- Describe the types and advantages of spread spectrum modulation formats.
- Perform analysis on the performance of spread spectrum modulation formats.
- Describe the differences and benefits of different types of spreading codes.
- Describe the differences between standard narrowband communication systems and spread spectrum systems.
- Analyze the performance of spread spectrum systems in the presence of interference.
- Analyze the performance of spread spectrum signals in the presence of multiple access interference (CDMA context).
- Describe techniques for reducing the impact of interference on spread spectrum signals.
- Analyze the performance of spreading code acquisition and tracking circuits.
- Analyze the performance of multiple access techniques based on spread spectrum (i.e., CDMA).
- Describe the major factors influencing the capacity of CDMA wireless networks.

## Justification • Reasons for Studying the course:

- ❑ Spread spectrum communications is a core technology for wireless systems.
- ❑ Future cellular systems are virtually all being designed using spread spectrum techniques.
- ❑ A large number of wireless LAN products are being designed using spread spectrum.
- ❑ Many military systems use spread spectrum. In fact the techniques were originally a military application only.
- ❑ In short, wireless communication engineers will almost certainly work on spread spectrum systems during their career.
- ❑ Since the design methods for spread spectrum and the principles behind them are significantly different from other communication systems, it is important to devote a course to the topic.



## Prerequisites and Co-requisites

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- This course requires basic communication theory as well as a basic knowledge of stochastic processes. Spread spectrum communications will build on an understanding of basic modulation formats and receiver analyses. These prerequisites are satisfied by
- **ECE 4634 (Analog and Digital Communications)** or an equivalent course at another university.
- The course will also deal with fading processes, noise sources, and the design of random sequence generators. This requires an understanding of random variables and stochastic processes which can be satisfied by **ECE 5605 (Stochastic Processes)**.

# Syllabus

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## □ Topic Percent of Course

- Introduction to Spread Spectrum 5%
  - Review of Digital Communications 5%
  - Direct Sequence Spread Spectrum 10%
  - Frequency Hopping 10%
  - Pseudo-random sequence generation 10%
  - Synchronization Issues for Spread-Spectrum 10%
  - Performance of Direct-Sequence Spread Spectrum 10%
  - Performance of Frequency-Hopped Spread-Spectrum 10%
  - CDMA 15%
  - Interference Rejection for DS/SS 10%
  - Other Wideband Techniques 5%
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# Course Grading

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- ❑ HW and mini-project assignments+Midterm (40%)
- ❑ Final Exam (20%)
- ❑ Class Project (40%)

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“The instructor reserves the right to change the grading scheme”

# Class Project

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- You will propose and carry-out a semester-long project
- 40% of Final Grade
- Will require computer simulation (preferably Matlab but you
- Work as individual

## Purpose

- Provide you with research experience
  - Improve communication skills
  - Provide examples of the kinds of problems in Digital Communications
  - Publish a paper
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# Proposal

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- All project topics are up to the student to decide. However, they must be approved.
  - In order to obtain approval there must be a project proposal.
  - Due date - **Sunday 9/3/2006**
  - Format
    - 1-2 pages
    - Topic ( 1 paragraph background) ,
    - Objective (what do you plan to examine?)
    - Approach (how will you attack the problem?)
    - References
    - Expected results (what key results will determine your outcome?)
-

# Topics

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- Below are some suggested topics
- You can choose other topics which are relevant to spread spectrum communications, but they must be approved

## **1. Multi-user detection**

**Successive Interference Cancellation**

**Parallel interference cancellation**

## **2. Smart antennas for CDMA systems.**

## **3. Multicode CDMA systems performance.**

## **4. UWB :**

**Frequency vs. Time Domain UWB**

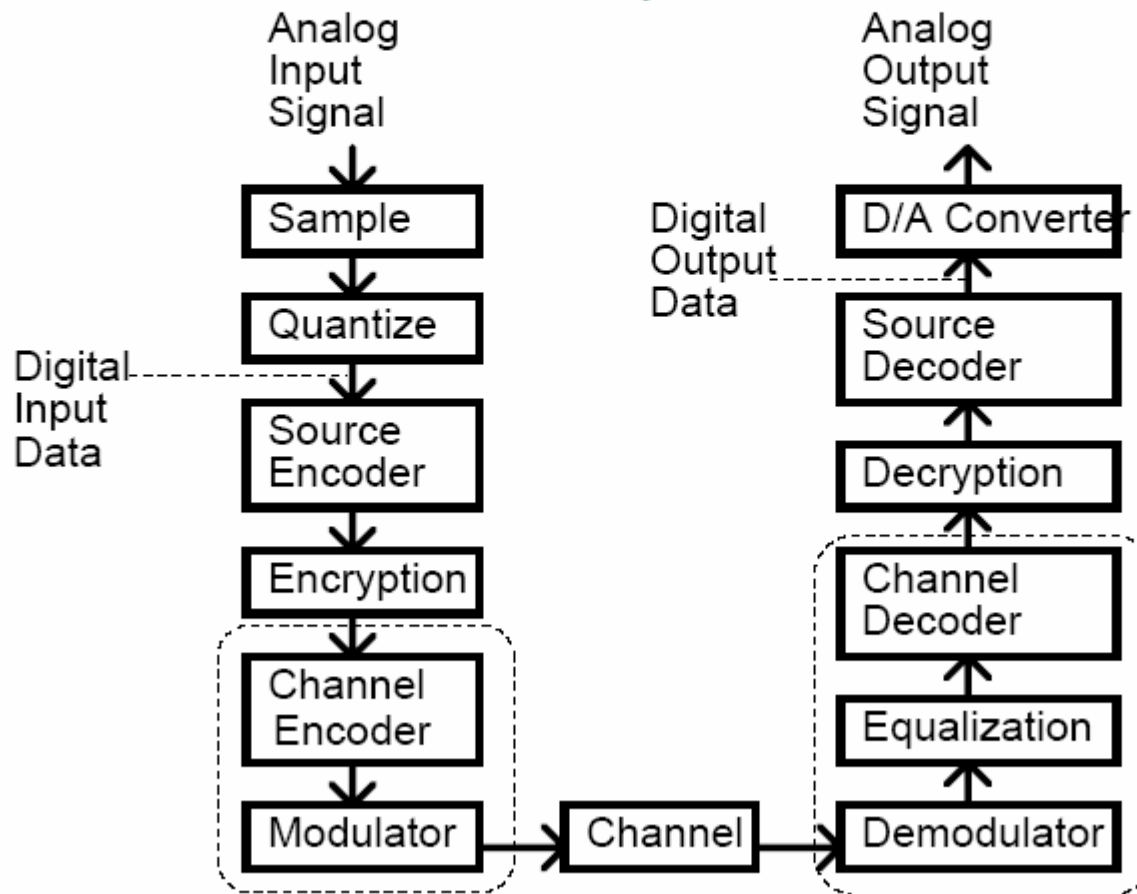
**Position Location in NLOS environments using UWB**

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# Why *digital* communications?

- Any noise introduces distortion to an analog signal. Since a digital receiver need only distinguish between two waveforms it is possible to exactly recover digital information.
- Many signal processing techniques are available to improve system performance: source coding, channel (error-correction) coding, equalization, encryption
- Digital ICs are inexpensive to manufacture. A single chip can be mass produced at low cost, no matter how complex
- Digital communications allows integration of voice, video, and data on a single system
- Digital communication systems provide a better tradeoff of bandwidth efficiency and energy efficiency than analog

# Block Diagram of Typical Digital Communications System





# Sampling

- Sampling makes signal discrete in time
- Sampling Theorem says that a band-limited signal can be sampled without introducing distortion
- Baseband sampling theorem
  - $f_s \geq 2B$ 
    - $B$  - absolute bandwidth
- Bandpass sampling theorem
  - $f_s \geq 2B_T = 4B$  ( $2B$  if complex baseband is purely real)
    - $B_T$  - transmission bandwidth

# Quantization

- Quantizer makes signal discrete in amplitude
- Unlike sampling, quantization introduces some distortion
- Data rate out of quantizer dependent on sampling rate and number of quantization levels
- Good quantizers are able to use few bits and introduce small distortion

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# Source Coding

- Quantization – method of converting analog message to digital message
  - Digital Source coding (compression) – method of removing the redundancy from the digital data
    - e.g., Huffman coding
  - Analog source coding – combination of quantization and compression
    - Takes advantage of the redundant information in the analog source
    - e.g., vocoders
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# Encryption

- Encryption techniques can ensure data privacy
  - Encryption is what we think of when we think of spies and secret decoder rings - Communications engineers use the word "coding" for other ideas
  - Very good "public key" encryption algorithms exist - this worries the folks at NSA
  - We will not talk about encryption in detail
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# Channel Encoder

- Provides protection against transmission errors by selectively inserting redundant data
- Note that quantizer and source encoder work to squeeze out redundant information. The channel encoder inserts redundant information in a very selective manner to protect against transmission errors
- Also called Forward Error Correction (FEC) coding
- Error correction coding plays an important role in digital communications, especially spread spectrum systems

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# Modulator

- Converts digital data to a continuous waveform suitable for transmission over channel - usually a sinusoidal wave
  - Information is transmitted by varying one or more parameters of waveform:
    - Amplitude
    - Phase
    - Frequency
  - Although we modulate a high frequency sinusoid, we will study the modulation in terms of complex baseband (using a signal space approach)
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# Examples of Modulation

- Amplitude Shift Keying (ASK) or On/Off Keying (OOK):  
 $1 \Rightarrow A \cos(2\pi f_c t)$   
 $0 \Rightarrow 0$
- Frequency Shift Keying (FSK):  
 $1 \Rightarrow A \cos(2\pi f_1 t)$   
 $0 \Rightarrow A \cos(2\pi f_0 t)$
- Phase Shift Keying (PSK):  
 $1 \Rightarrow A \cos(2\pi f_c t)$   
 $0 \Rightarrow A \cos(2\pi f_c t + \pi) = -A \cos(2\pi f_c t)$

# Channel

- Carries signal - could be a telephone wire, free space
- Presents distorted signal to demodulator. Effects include attenuation, noise, fading.
- Fading is very important - studied in Cellular and Personal Communications class
  - Rayleigh fading
  - Ricean fading
  - Log-normal “shadowing”
- We will *usually* assume a very simple channel - additive Gaussian noise (AWGN)



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# What Makes a Good Communication System?

- Large data rate (measured in bits/sec)
  - Small bandwidth (measured in Hertz)
  - Small signal power (measured in Watts or dBW)
  - Low distortion (measured in  $S/N$  or bit error rate)
  - Low cost - with digital communications, large complexity does not always result in large cost
  - In practice, there must be tradeoffs made in achieving these goals
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# Tradeoffs in System Design:

## Data Rate vs. Bandwidth

- Increased data rate leads to shorter data pulses which leads to larger bandwidth.
- This tradeoff cannot be avoided - however, some systems use bandwidth more efficiently than others.
- We will define Bandwidth Efficiency as the ratio of data rate  $R_b$  to bandwidth  $W$ :  $\eta_B = R_b/W$
- We want large bandwidth efficiency  $\eta_B$

# Tradeoffs in System Design:

## Fidelity vs. Signal Power

- One way to get an error free signal would be to use huge amounts of power to blast over the noise.
- Some types of modulation achieve relative error free transmission at lower powers than others.
- We define Energy Efficiency:  $\eta_E = E_b / N_o \big|_{P_b = \text{target error rate}}$
- We desire small  $\eta_E$

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## Tradeoffs in System Design:

### Bandwidth Efficiency vs. Energy Efficiency

- It is possible for a system design to trade between bandwidth efficiency and energy efficiency.
  - Examples:
    - Binary modulation sends only one bit per use of the channel.  $M$ -ary modulation can send multiple bits, but is more vulnerable to errors.
    - Error correction coding: inserting redundant bits improves bit error rate, but increases bandwidth.
  - This is a fundamental tradeoff in digital communications.
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# Performance of Digital Modulation

- Let us first consider the case of binary signaling with *coherent* detection in an AWGN channel
- For equally likely symbols the minimum probability of error is obtained using a *maximum likelihood receiver*
- The probability of symbol (and equivalently bit) error is

$$P_b = Q\left(\sqrt{\frac{E_b}{N_o}(1-\rho)}\right)$$

$P_b$  = bit err. prob.  
 $P_s$  = sym. err. prob.

- Where  $Q(x) = \int_x^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{u^2}{2}} du$  is the standard Q-function
- $E_b/N_o$  is the *average* energy per bit divided by the one sided power spectral density  $N_o$
- and  $\rho$  is correlation coefficient between symbols:

$$\rho = \frac{1}{\sqrt{E_1 E_2}} \int_0^T s_1(t) s_2(t) dt$$

$E_1$  = energy in symbol 1  
 $E_2$  = energy in symbol 2  
 $T$  = symbol duration

# Performance of Binary Digital Modulation

$$P_b = Q\left(\sqrt{\frac{E_b}{N_o}(1-\rho)}\right)$$

## ■ Specific cases:

□  $\rho = 0$

- orthogonal modulation (e.g., BFSK, BASK)

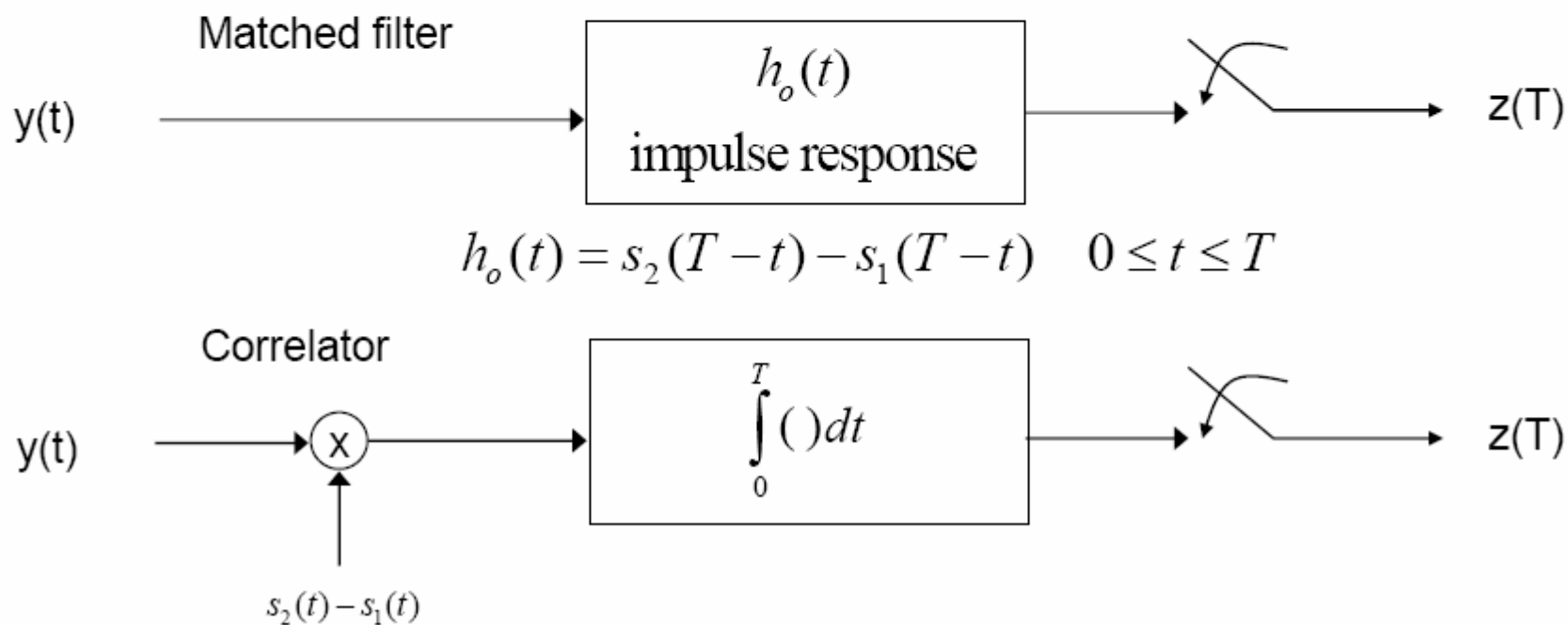
□  $\rho = -1$

- Antipodal signaling (e.g., BPSK)
- Best performance for binary modulation

- $\rho > 0$  results in worse performance than either case

# Maximum Likelihood Receiver

- The ML receiver can be implemented as either a *correlator* or a *matched filter*



# Non-coherent modulation

- FSK and ASK do not encode information in the phase of the carrier, thus we do not need to demodulate coherently.
- Most simply, we use an envelope detector
- However, there is a performance penalty
- The bit error rate for non-coherent BASK and BFSK is

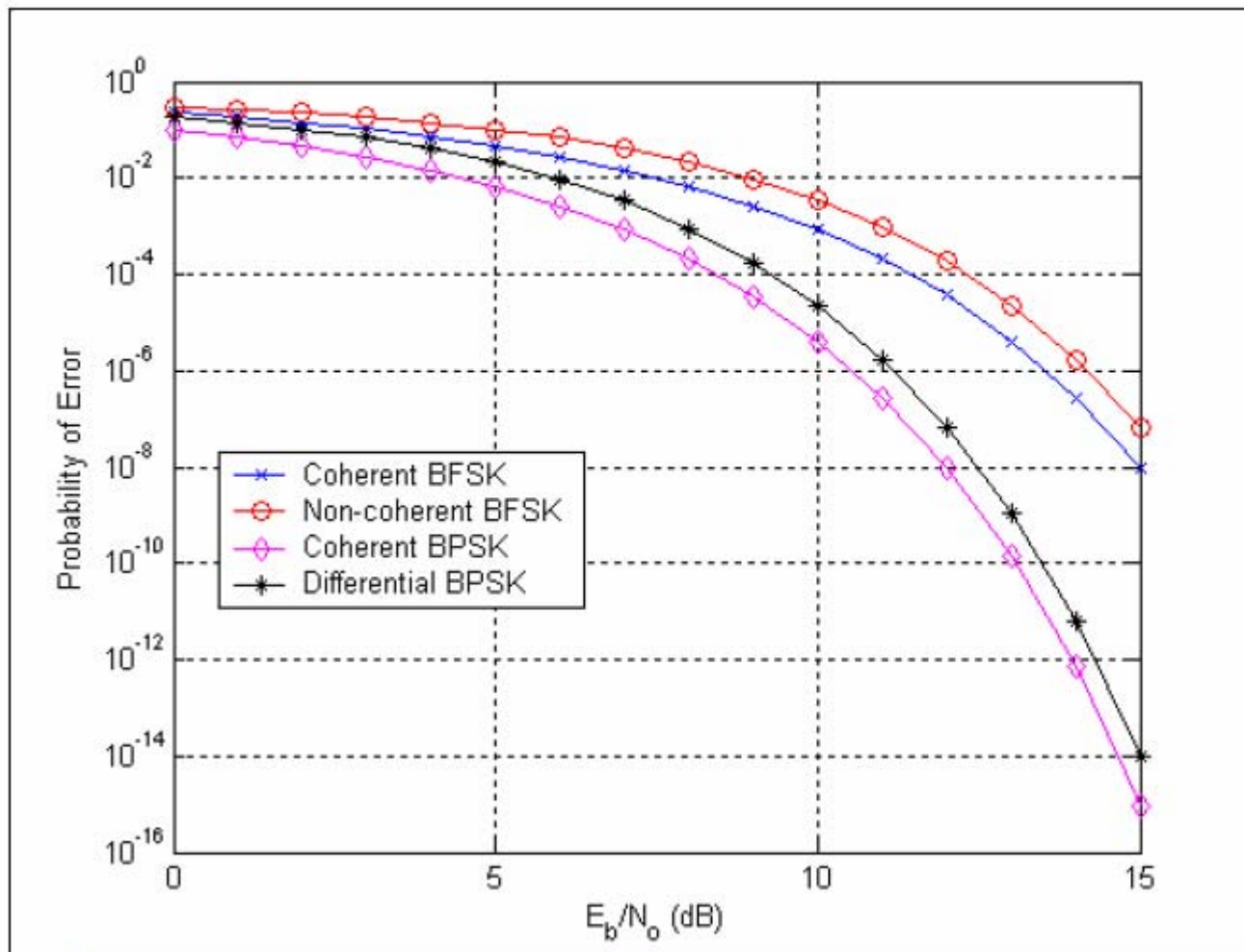
$$P_b \approx \frac{1}{2} e^{-\frac{1}{2} \frac{E_b}{N_o}}$$

Compare this to coherent BASK/BFSK which has a performance of

$$P_b = Q\left(\sqrt{\frac{E_b}{N_o}}\right) \approx \frac{1}{\sqrt{2\pi E_b/N_o}} e^{-\frac{1}{2} \frac{E_b}{N_o}}$$



# Coherent vs. Non-coherent Demodulation



- Approximately 1dB loss for non-coherent demodulation
- Approximately 3dB loss going from PSK to FSK/ASK

**HW1**

# Bandwidth Efficiency

- For rectangular pulses, the spectrum of PSK and ASK is a *sinc* function. The bandwidth of this signal is usually specified as *null-to-null* bandwidth

$$W = 2R_s$$

- For FSK, the minimum spacing between phase synchronous carriers for coherent demodulation is

$$\Delta f_{\min} = \frac{1}{2T_s} = \frac{R_s}{2}$$

- Since the individual carriers are modulation by square pulses, the null-to-null bandwidth is  $R_s + R_s/2 + R_s$  or

$$W = 2.5R_s$$

Note: For non-phase synchronous carriers  
 $W=3R_s$

# Bandwidth Efficiency

<b>Modulation Type</b>	<b>Bandwidth Efficiency (b/s/Hz)</b>
BPSK	0.5
BASK	0.5
BFSK	0.4

- The bandwidth efficiency of binary modulation is not very good. Thus, we typically use  $M$ -ary modulation schemes to improve spectral efficiency
- Pulse shaping is also used to control bandwidth

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## *M*-ary Modulation

- *M*-PSK  $\rightarrow \log_2(M)$  bits are transmitted per symbol by sending one of *M* carrier phases
  - *M*-FSK  $\rightarrow \log_2(M)$  bits are transmitted per symbol by sending one of *M* carrier frequencies
  - QAM  $\rightarrow \log_2(M)$  bits are transmitted per symbol by sending one of *M* combinations of amplitudes and phases
-

# Performance of $M$ -ary Modulation

■  $M$ -PSK      $P_s \leq 2Q\left(\sqrt{\frac{2E_b}{N_o} \log_2(M)} \sin\left(\frac{\pi}{M}\right)\right)$      Performance degrades with increasing  $M$

■  $M$ -FSK      $P_s \leq (M-1)Q\left(\sqrt{\frac{E_b}{N_o} \log_2(M)}\right)$      Performance improves with increasing  $M$

■ QAM (assuming  $M$  is power of 4)

$$P_s = 1 - \frac{1}{M} \left[ (\sqrt{M} - 2)^2 \left( 1 - 2Q\left(\sqrt{\frac{6 \log_2(M) E_b}{2(M-1) N_o}}\right) \right)^2 + 4(\sqrt{M} - 2) \left( 1 - 2Q\left(\sqrt{\frac{6 \log_2(M) E_b}{2(M-1) N_o}}\right) \right) \left( 1 - Q\left(\sqrt{\frac{6 \log_2(M) E_b}{2(M-1) N_o}}\right) \right) + 4 \left( 1 - Q\left(\sqrt{\frac{6 \log_2(M) E_b}{2(M-1) N_o}}\right) \right)^2 \right]$$

Performance degrades with increasing  $M$

# Non-coherent $M$ -ary Modulation Performance

## ■ DPSK

$$P_s \leq \pi \frac{\cos(\pi / 2M)}{\sqrt{\cos(\pi / M)}} Q\left(2 \sqrt{\frac{E_b}{N_o} \log_2(M)} \sin\left(\frac{\pi}{M}\right)\right)$$

Performance degrades with increasing  $M$

## ■ Non-coherent $M$ -FSK

$$P_s = \sum_{k=1}^{M-1} \binom{M-1}{k} \frac{(-1)^{k+1}}{k+1} \exp\left(-\frac{k}{k+1} \frac{E_b}{N_o} \log_2(M)\right)$$

Performance improves with increasing  $M$

# Bandwidth Efficiency

Modulation Type	Bandwidth Efficiency (b/s/Hz)
MPSK/MDPSK/MQAM	$\frac{\log_2(M)}{2}$
BASK	0.5
Coherent MFSK	$\frac{2\log_2(M)}{M+3}$
Non-coherent MFSK	$\frac{\log_2(M)}{M+1}$

- Bandwidth efficiency increases with  $M$  for PSK and QAM. It decreases with  $M$  for FSK.
- Pulse shape also heavily influences bandwidth

# Power Efficiency

Modulation Type	Power Efficiency ( $E_b/N_0$ for $P_e = 10^{-5}$ )
BPSK/QPSK (DBPSK)	9.5dB (10.5dB)
8-PSK (8-DPSK)	13.5dB (16.5dB)
16-PSK (16-DPSK)	18dB (21dB)
32-PSK (32-DPSK)	23dB (26dB)
Coherent BFSK (Non-coherent)	12.5dB (13.5dB)
Coherent 4-FSK (Non-coherent)	10dB (11dB)
Coherent 8-FSK (Non-coherent)	8dB (9dB)
Coherent 16-FSK (Non-coherent)	7dB (8dB)
4-QAM	9.5dB
16-QAM	13dB
64-QAM	17.5dB

- Note: For PSK/QAM we can use Gray coding and thus  $P_b = \frac{P_s}{\log_2 M}$
- For FSK  $P_b = \frac{MP_s}{2(M-1)}$
- For PSK/QAM BER increases with  $M$
- For FSK BER decreases with  $M$
- Non-coherent demodulation suffers 1-3dB penalty for PSK but little penalty for FSK (at low error rates)



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# Conclusions

- Today we briefly reviewed digital communication systems with an emphasis on modulation schemes
  - In general we can increase bandwidth (spectral) efficiency by increasing the order of the modulation scheme (opposite is true for FSK)
  - In general the power efficiency is degraded by increasing modulation order (opposite is true for FSK)
  - Thus, we have a classic trade-off in communication systems between bandwidth and energy efficiency
    - Note that bandwidth efficiency is not the primary concern for spread spectrum as we will see
  - Non-coherent demodulation allows us to trade off complexity for energy efficiency
-