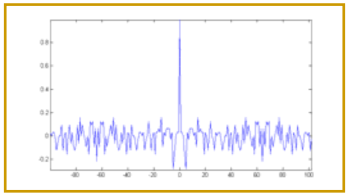
ECE 5660 – Spread Spectrum Communications
Spring 2008



Instructor: R. Michael Buehrer

Lecture #1: Course Overview and Review of Digital Communications

Today

- Overview of Course Mechanics
- Overview of Digital Communications
- Current Materials (e-mailed previously):
  - Course Syllabus
  - Lecture #1
- Available on Web Site:
  - Syllabus
  - Lectures #1 and #2
  - Chapter 1 of Course Text

Course Mechanics

- CRN 16577
  - Meeting Time: TR 3:30-4:45pm
  - Room: RAND 316
- Please check your calendars now!
  - Examine the dates on the syllabus today
  - Of particular importance is the presentation date (April 12)
  - If you have conflicts due to religious observances or other immovable, important events, please see me before the end of the second week of class. After that time, I will not consider making special arrangements except in the case of an emergency.

Instructor: R. Michael Buehrer

- Position: Associate Professor
- Office: Durham 433
- Phone (during office hours): 231-1898
- e-mail: buehrer@vt.edu
- Office Hours:
  - T 10:00-12:00; R 1-2
  - Alternate hours available by appointment
- I work in the field of wireless communications with the MPRG laboratory (*Wireless @ Virginia Tech*)
- To learn more about my work, see my website:
  - http://www.mprg.org/people/buehrer

Instructor: R. Michael Buehrer

- Personal:
  - Married
  - Five children: Faith (12), JoHannah (10), Noah (7), Gabrielle (5), Ruthie (2)
  - Hobbies: hiking, running, photography, philosophy, skiing and star-gazing
  - Deacon/teacher at Blacksburg Christian Fellowship
    - I would be more than happy to talk to anyone interested in learning more about Church history, Old Testament Studies, New Testament Studies, General Christianity, or Christian Thought/Philosophy
    - Currently co-teaching a class on Church History

Web Site for Course Documents

- http://www.mprg.org/people/buehrer/5660/ece_5660.htm
- What will be available in ".pdf" format:
  - Lecture Notes
  - Handouts
  - Mini-project descriptions
  - Useful references
  - Access to many things is password protected
    - Username: spread_spectrum
    - Password: 20spring04
- In order to read .pdf files you will need Adobe Acrobat Reader (available free - instructions on website)
- I will also occasionally use Blackboard as a backup.
  - www.learn.vt.edu

Required Course Materials

- **Textbook:**
  - R.M Buehrer, Spread Spectrum Communications, *unpublished manuscript*. Available for download on the course website.
  - R.M. Buehrer, Code Division Multiple Access (CDMA) *Morgan-Claypool Publishers*. Available for free download for VT students. A hard copy can also be purchased for $40.
- Other 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
  - Note: All are on reserve at the Library.
- **Software:**
  - Preferred – Matlab for Windows (release 13 or later)
  - Acceptable – any programming language that will allow you to simulate various components of spread spectrum communications system

CDMA Text

- The text for the second half of the class is available for free download at
  - http://dx.doi.org/10.2200/S00017ED1V01Y200508COM002 or
  - http://www.morganclaypool.com/doi/abs/10.2200/S00017ED1V01Y200508COM002.

- This site is IP authenticated. Thus, students who are not on campus can access this material two possible ways*:

- (1) Off Campus Sign In Link
  - http://www.lib.vt.edu/ [right side of the page]
  - This link takes the person to a proxy server which asks for PID and password to verify that the person is a VT affiliate. This will work most of the time.

- (2) Set up a VPN. Please see:
  - http://www.computing.vt.edu/internet_and_web/internet_access/vpn.html
  - This is necessary if you are trying to access from a corporation or apartment complex where a firewall or proxy server is installed.

* For additional help please contact Larry Thompson larryt@vt.edu

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 – Graduate-level Digital Communications
  - 4634 – Senior-level Digital Communications or equivalent is required prerequisite
- **Working knowledge of 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

Grading – Mini-Projects (75%)

- Three mini-project assignments
- Typically two-week assignments (see syllabus for schedule)
- These are in lieu of homework and exams
- These projects will typically be simulation-based and will require you to implement key concepts of spread spectrum systems in Matlab (or other programming language), verifying main results from the course.
- The mini-projects are to be your own work and **are NOT group projects**. If you have questions, please see me rather than discussing with your classmates.

Grading – Research Project (25%)

- The course will include a group “research” project.
- You will carry-out a semester-long project
  - 25% of Final Grade
- Topic – On the use of spread spectrum principles (e.g, interference averaging, frequency diversity) in 4G and emerging systems. Examples:
  - WiMax
  - 3GPP2 Long Term Evolution (LTE)
  - Other emerging standards
- Should be a combination of literature/standard survey and computer simulation (preferably Matlab or C) and analysis
- Work as individual or in small groups (1-3 people)

Important Project Info

- January 29: Project Proposals Due
- April 12: Oral Project Presentations (NOTE: Saturday)
  - Spread spectrum "Mini-Conference"
- April 22: Written Projects Due
- Project Grading
  - Communication skills (oral and written) 25%
    - 10% from presentation and 15% from report
  - Technical accuracy 25%
    - 5% from presentation and 20% from report
  - Completeness in results (based on proposal) 30%
    - 10% from presentation and 20% from report
  - Conclusion (what do your results show?) 20%
    - 5% from presentation and 15% from report

Project Format

- The goal of the presentation (and the report) is to present to the class a tutorial overview of how spread spectrum principles are being exploited in emerging standards
- Thus, they *should not* focus on
  - basic ideas in digital comm. or spread spectrum
  - too much of the fine details of the standard (unless absolutely necessary)
- They *should* focus on
  - how concepts presented in the course are being used either explicitly or implicitly in the new system
  - how the performance or capacity is enhanced (analysis or simulation should be used here)
  - how the system differs from the systems studied in class
- Format of the report can follow the format of the class text

Grading – Extra Credit

- Every semester I get requests for extra credit assignments
- Available extra credit for this class:
  - Create (and provide solution for) homework assignments to be used in the course textbook
  - Should not duplicate examples or derivations already in the text
  - Submission must be in LaTeX format (easy to learn)
  - 5 points per problem added to your project grade

Course Objectives

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

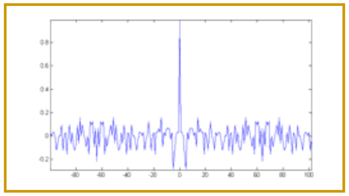
- Describe the differences between standard narrowband communication systems and spread spectrum systems.
- Describe the types and advantages of spread spectrum modulation formats.
- Perform analysis on the performance of spread spectrum modulation formats.
- Describe the differences and benefits of different types of spreading codes.
- Analyze the performance of spread spectrum systems in the presence of interference.

Course Objectives (cont.)

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

- 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.

Review of Digital Communications

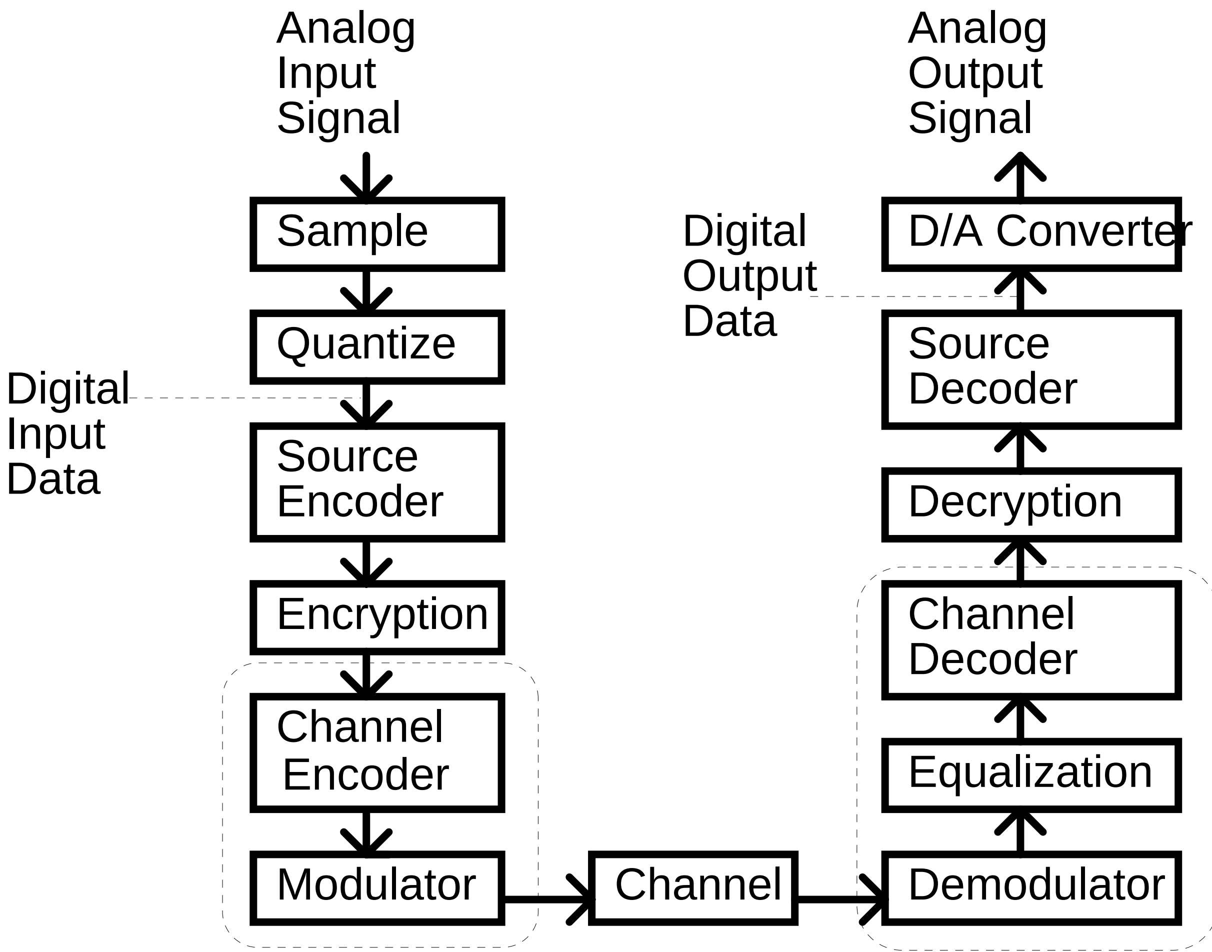


Text – Chapter 1

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 mater 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

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

Encryption

- Encryption techniques can ensure data privacy
- Encryption is what we think of when we think of spies and secret decoder rings –
  - Communications engineers typically use the word "coding" for other concepts
- We will not talk about encryption in detail
- Spread spectrum can provide some amount of privacy through the use of scrambling codes and by keeping a low power spectral density

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

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 usually study modulation in terms of complex baseband (using a signal space approach)

Examples of Modulation

- Amplitude Shift Keying (ASK) or On/Off Keying (OOK):

$$1 \Rightarrow A\cos\left(2\pi f_c t\right)$$

$$0 \Rightarrow 0$$

- Frequency Shift Keying (FSK):

$$1 \Rightarrow A\cos\left(2\pi f_1 t\right)$$

$$0 \Rightarrow A\cos\left(2\pi f_0 t\right)$$

- 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 *often* assume a very simple channel – additive Gaussian noise (AWGN)
  - However, mitigation of fading is one motivation for the use of spread spectrum and will thus be considered

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

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: $\eta_B = R_b / W$
- Typically, we want large bandwidth efficiency η_B
- However, in spread spectrum we sacrifice bandwidth efficiency for performance benefits in certain types of channels

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 η_E

- Note that in other types of channels (e.g., interference) E_b/I_o may be a more appropriate measure

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 PSK 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.

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 matched filter and *maximum likelihood detector*
- The probability of bit error is

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

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 ρ 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

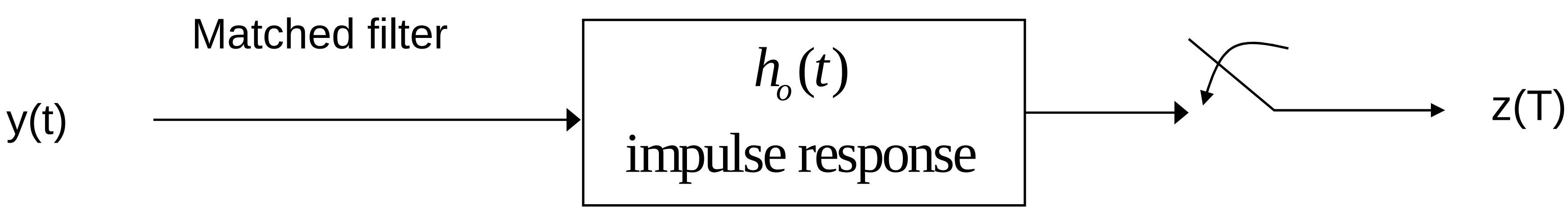
Performance of Binary Digital Modulation

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

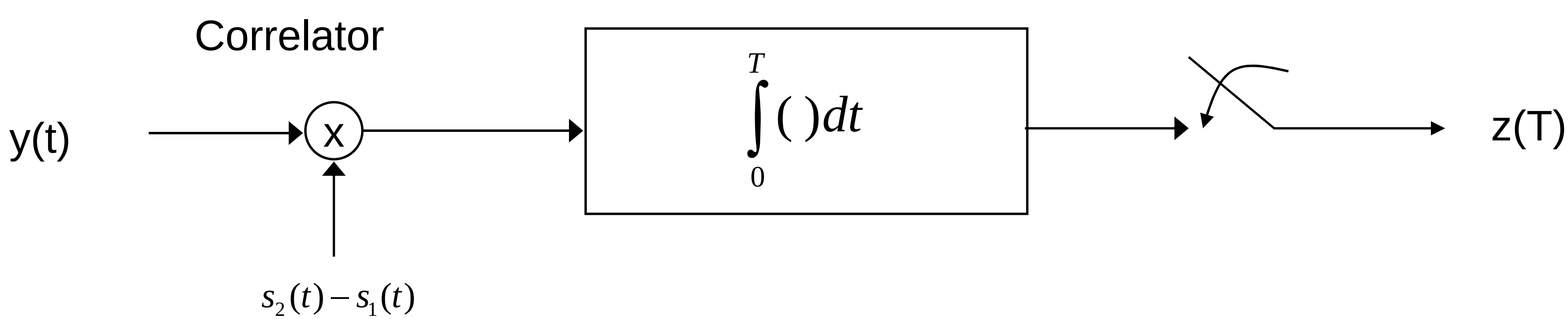
- Specific cases:
  - $\rho = 0$
    - orthogonal modulation (e.g., BFSK, BASK)
  - $\rho = -1$
    - Antipodal signaling (e.g., BPSK)
    - Best performance for binary modulation
  - $\rho > 0$ results in worse performance than either case

Maximum Likelihood Receiver

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



$$h_o(t) = s_2(T-t) - s_1(T-t) \quad 0 \le t \le T$$



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

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

Non-coherent modulation

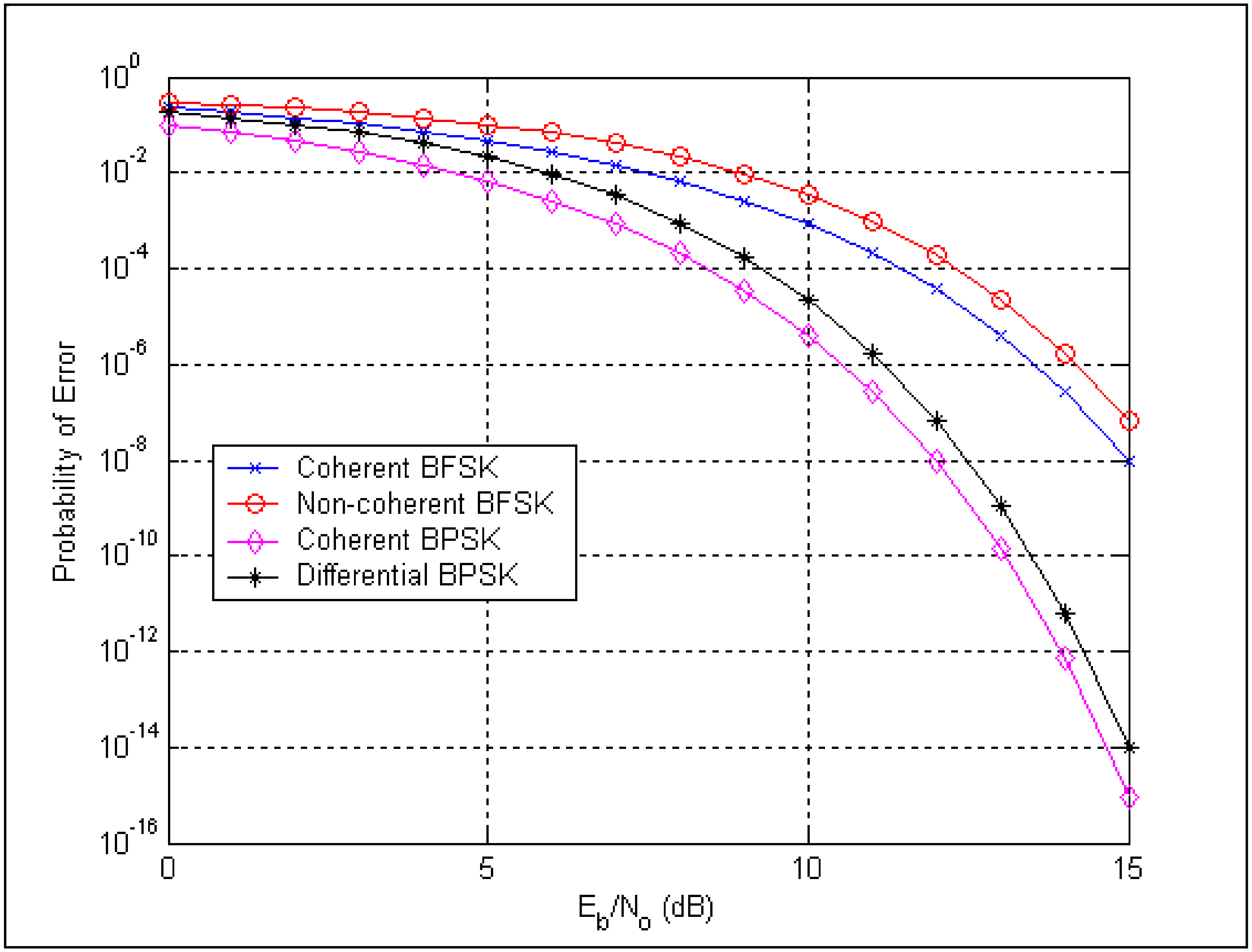
- BPSK inherently requires phase information.
- However, coherent detection can be avoided by encoding information into phase *changes* rather than the absolute phase
- Again, there is a performance penalty
- The bit error rate for DPSK is

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

Compare this to coherent BPSK which has a performance of

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_o}}\right) \approx \frac{1}{\sqrt{4\pi E_b / N_o}} e^{-\frac{E_b}{N_o}}$$

Coherent vs. Non-coherent Demodulation



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

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 modulated 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

Modulation Type	Bandwidth Efficiency (b/s/Hz)
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

M-ary Modulation

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

Performance of *M*-ary Modulation

- *M*-PSK

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

Performance degrades with increasing *M*

- *M*-FSK

$$P_s \le (M-1)Q\left(\sqrt{\frac{E_b}{N_o}\log_2(M)}\right)$$

Performance improves with increasing *M*

- *QAM (assuming M is power of 4 and square constellation)*

$$P_s = 1-\left(1-2\left(1-\frac{1}{\sqrt{M}}\right)Q\left(\sqrt{\frac{3\log_2 M}{M-1}\frac{E_b}{N_o}}\right)\right)^2$$

Performance degrades with increasing *M*

Non-coherent *M*-ary Modulation Performance

- DPSK

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

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_o 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)

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