

ECE 5520: Digital Communications  
Lecture Notes  
Spring 2009

---

## Lecture 1

Today: (1) Syllabus (2) Intro to Digital Communications

### 1 Class Organization

**Textbook** Few textbooks cover solely digital communications (without analog) in an introductory communications course. But graduates today will almost always encounter / be developing solely *digital* communication systems. So half of most textbooks are useless; and that the other half is sparse and needs supplemental material. For example, the past text was the ‘standard’ text in the area for an undergraduate course, Proakis & Salehi, J.G. Proakis and M. Salehi, *Communication Systems Engineering*, 2nd edition, Prentice Hall, 2001. Students didn’t like that I had so many supplemental readings. This year’s text covers primarily digital communications, and does it in depth. Finally, I find it to be very well-written. And, there are few options in this area. I will provide additional readings solely to provide another presentation style or fit another learning style. Unless specified, these are optional.

**Lecture Notes** I type my lecture notes. I have taught ECE 5520 previously and have my lecture notes from past years. I’m constantly updating my notes, even up to the lecture time. These can be available to you at lecture, and/or after lecture online. However, you must accept these conditions:

1. **Taking notes is important:** I find most learning requires some writing on your part, not just watching. Please take your own notes.
2. **My written notes do not and cannot reflect everything said during lecture:** I answer questions and understand your perspective better after hearing your questions, and I try to tailor my approach during the lecture. If I didn’t, you could just watch a recording!

### 2 Introduction

A digital communication system conveys discrete-time, discrete-valued information across a physical channel. Information sources

might include audio, video, text, or data. They might be continuous-time (analog) signals (audio, images) and even 1-D or 2-D. Or, they may already be digital (discrete-time, discrete-valued). Our object is to convey the signals or data to another place (or time) with as faithful representation as possible.

In this section we talk about what we'll cover in this class, and more importantly, what we won't cover.

## 2.1 "Executive Summary"

Here is the one sentence version: We will study how to efficiently encode digital data on a noisy, bandwidth-limited analog medium, so that decoding the data (*i.e.*, reception) at a receiver is simple, efficient, and high-fidelity.

The keys points stuffed into that one sentence are:

1. Digital information on an analog medium: We can send waveforms, *i.e.*, real-valued, continuous-time functions, on the channel (medium). These waveforms are from a discrete set of possible waveforms. What set of waveforms should we use? Why?
2. Decoding the data: When receiving a signal (a function) in noise, none of the original waveforms will match exactly. How do you make a decision about which waveform was sent?
3. What makes a receiver difficult to realize? What choices of waveforms make a receiver simpler to implement? What techniques are used in a receiver to compensate?
4. Efficiency, Bandwidth, and Fidelity: Fidelity is the correctness of the received data (*i.e.*, the opposite of error rate). What is the tradeoff between energy, bandwidth, and fidelity? We all want high fidelity, and low energy consumption and bandwidth usage (the costs of our communication system).

You can look at this like an impedance matching problem from circuits. You want, for power efficiency, to have the source impedance match the destination impedance. In digital comm, this means that we want our waveform choices to match the channel and receiver to maximize the efficiency of the communication system.

## 2.2 Why not Analog?

The previous text used for this course, by Proakis & Salehi, has an extensive analysis and study of analog communication systems, such as radio and television broadcasting (Chapter 3). In the recent past, this course would study both analog and digital communication systems. Analog systems still exist and will continue to exist;

however, development of new systems will almost certainly be of digital communication systems. Why?

- Fidelity
- Energy: transmit power, and device power consumption
- Bandwidth efficiency: due to coding gains
- Moore's Law is decreasing device costs for digital hardware
- Increasing need for digital information
- More powerful information security

### 2.3 Networking Stack

In this course, we study digital communications from bits to bits. That is, we study how to take ones and zeros from a transmitter, send them through a medium, and then (hopefully) correctly identify the same ones and zeros at the receiver. There's a lot more than this to the digital communication systems which you use on a daily basis (*e.g.*, iPhone, WiFi, Bluetooth, wireless keyboard, wireless car key).

To manage complexity, we (engineers) don't try to build a system to do everything all at once. We typically start with an application, and we build a layered network to handle the application. The 7-layer OSI stack, which you would study in a CS computer networking class, is as follows:

- Application
- Presentation (\*)
- Session (\*)
- Transport
- Network
- Link Layer
- Physical (PHY) Layer

(Note that there is also a 5-layer model in which \* layers are considered as part of the application layer.) ECE 5520 is part of the bottom layer, the physical layer. In fact, the physical layer has much more detail. It is primarily divided into:

- Multiple Access Control (MAC)
- Encoding
- Channel / Medium

We can control the MAC and the encoding chosen for a digital communication.

## 2.4 Channels and Media

We can choose from a few media, but we largely can't change the properties of the medium (although there are exceptions). Here are some media:

- EM Spectra: (anything above 0 Hz) Radio, Microwave, mm-wave bands, light
- Acoustic: ultrasound
- Transmission lines, waveguides, optical fiber, coaxial cable, wire pairs, ...
- Disk (data storage applications)

## 2.5 Encoding / Decoding Block Diagram

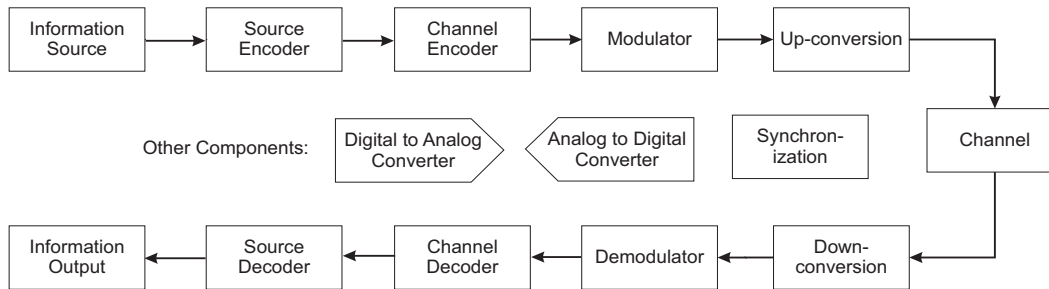


Figure 1: Block diagram of a single-user digital communication system, including (top) transmitter, (middle) channel, and (bottom) receiver.

Notes:

- Information source comes from higher networking layers. It may be continuous or packetized.
- Source Encoding: Finding a compact digital representation for the data source. Includes sampling of continuous-time signals, and quantization of continuous-valued signals. Also includes compression of those sources (lossy, or lossless). What are some compression methods that you're familiar with? We present an introduction to source encoding at the end of this course.
- Channel encoding refers to redundancy added to the signal such that any bit errors can be corrected. A channel decoder, because of the redundancy, can correct some bit errors. We will not study channel encoding, but it is a topic in the (ECE 6520) Coding Theory.

- Modulation refers to the digital-to-analog conversion which produces a continuous-time signal that can be sent on the physical channel. It is analogous to impedance matching - proper matching of a modulation to a channel allows optimal information transfer, like impedance matching ensured optimal power transfer. Modulation and demodulation will be the main focus of this course.
- Channels: See above for examples. Typical models are additive noise, or linear filtering channel.

Why do we do both source encoding (which compresses the signal as much as possible) and also channel encoding (which adds redundancy to the signal)? Because of Shannon's source-channel coding separation theorem. He showed that (given enough time) we can consider them separately without additional loss. And separation, like layering, reduces complexity to the designer.

## 2.6 Channels

A channel can typically be modeled as a linear filter with the addition of noise. The noise comes from a variety of sources, but predominantly:

1. Thermal background noise: Due to the physics of living above 0 Kelvin. Well modeled as Gaussian, and white; thus it is referred to as additive white Gaussian noise (AWGN).
2. Interference from other transmitted signals. These other transmitters whose signals we cannot completely cancel, we lump into the 'interference' category. These may result in non-Gaussian noise distribution, or non-white noise spectral density.

The linear filtering of the channel result from the physics and EM of the medium. For example, attenuation in telephone wires varies by frequency. Narrowband wireless channels experience fading that varies quickly as a function of frequency. Wideband wireless channels display multipath, due to multiple time-delayed reflections, diffractions, and scattering of the signal off of the objects in the environment. All of these can be modeled as linear filters.

The filter may be constant, or time-invariant, if the medium, the TX and RX do not move or change. However, for mobile radio, the channel may change very quickly over time. Even for stationary TX and RX, in real wireless channels, movement of cars, people, trees, etc. in the environment may change the channel slowly over time.

In this course, we will focus primarily on the AWGN channel, but we will mention what variations exist for particular channels, and how they are addressed.

## 2.7 Topic: Random Processes

Random things in a communication system:

- Noise in the channel
- Signal (bits)
- Channel filtering, attenuation, and fading
- Device frequency, phase, and timing offsets

These random signals often pass through LTI filters, and are sampled. We want to build the best receiver possible despite the impediments. Optimal receiver design is something that we study using probability theory.

We have to tolerate errors. Noise and attenuation of the channel will cause bit errors to be made by the demodulator and even the channel decoder. This may be tolerated, or a higher layer networking protocol (eg., TCP-IP) can determine that an error occurred and then re-request the data.

## 2.8 Topic: Frequency Domain Representations

To fit as many signals as possible onto a channel, we often split the signals by frequency. The concept of sharing a channel is called *multiple access* (MA). Separating signals by frequency band is called frequency-division multiple access (FDMA). For the wireless channel, this is controlled by the FCC (in the US) and called spectrum allocation. There is a tradeoff between frequency requirements and time requirements, which will be a major part of this course. The Fourier transform of our modulated, transmitted signal is used to show that it meets the spectrum allocation limits of the FCC.

## 2.9 Topic: Orthogonality and Signal spaces

To show that signals sharing the same channel don't interfere with each other, we need to show that they are *orthogonal*. This means, in short, that a receiver can uniquely separate them. Signals in different frequency bands are orthogonal.

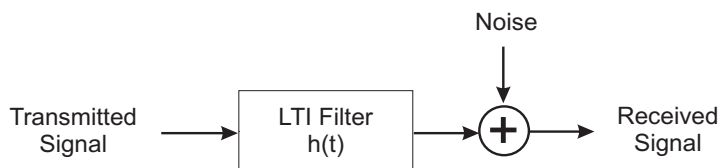


Figure 2: Linear filter and additive noise channel model.

We can also employ multiple orthogonal signals in a single transmitter and receiver, in order to provide multiple independent means (dimensions) on which to modulate information. We will study orthogonal signals, and learn an algorithm to take an arbitrary set of signals and output a set of orthogonal signals with which to represent them. We'll use signal spaces to show graphically the results, as the example in Figure 3.

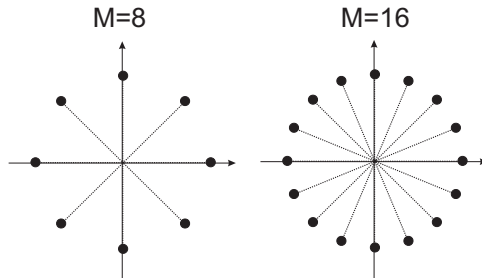


Figure 3: Example signal space diagram for  $M$ -ary Phase Shift Keying, for (a)  $M = 8$  and (b)  $M = 16$ . Each point is a vector which can be used to send a 3 or 4 bit sequence.

## 2.10 Related classes

1. Pre-requisites: (ECE 5510) Random Processes; (ECE 3500) Signals and Systems.
2. Signal Processing: (ECE 5530): Digital Signal Processing
3. Electromagnetics: EM Waves, (ECE 5320-5321) Microwave Engineering, (ECE 5324) Antenna Theory, (ECE 5411) Fiber-optic Systems
4. Breadth: (ECE 5325) Wireless Communications
5. Devices and Circuits: (ECE 3700) Fundamentals of Digital System Design, (ECE 5720) Analog IC Design
6. Networking: (ECE 5780) Embedded System Design, (CS 5480) Computer Networks
7. Advanced Classes: (ECE 6590) Software Radio, (ECE 6520) Information Theory and Coding, (ECE 6540): Estimation Theory