ECE 5654 – Advanced Digital Communications

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Lecture 1.2 - Review of Digital Communications

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Learning Objectives

- After completing this lecture the student should be able to
  - Define digital communications and list several reasons digital communication systems are implemented instead of analog communication systems
  - List and describe the functions of the major blocks in a communications system
  - Describe the fundamental trade-offs in the design of a digital communications system

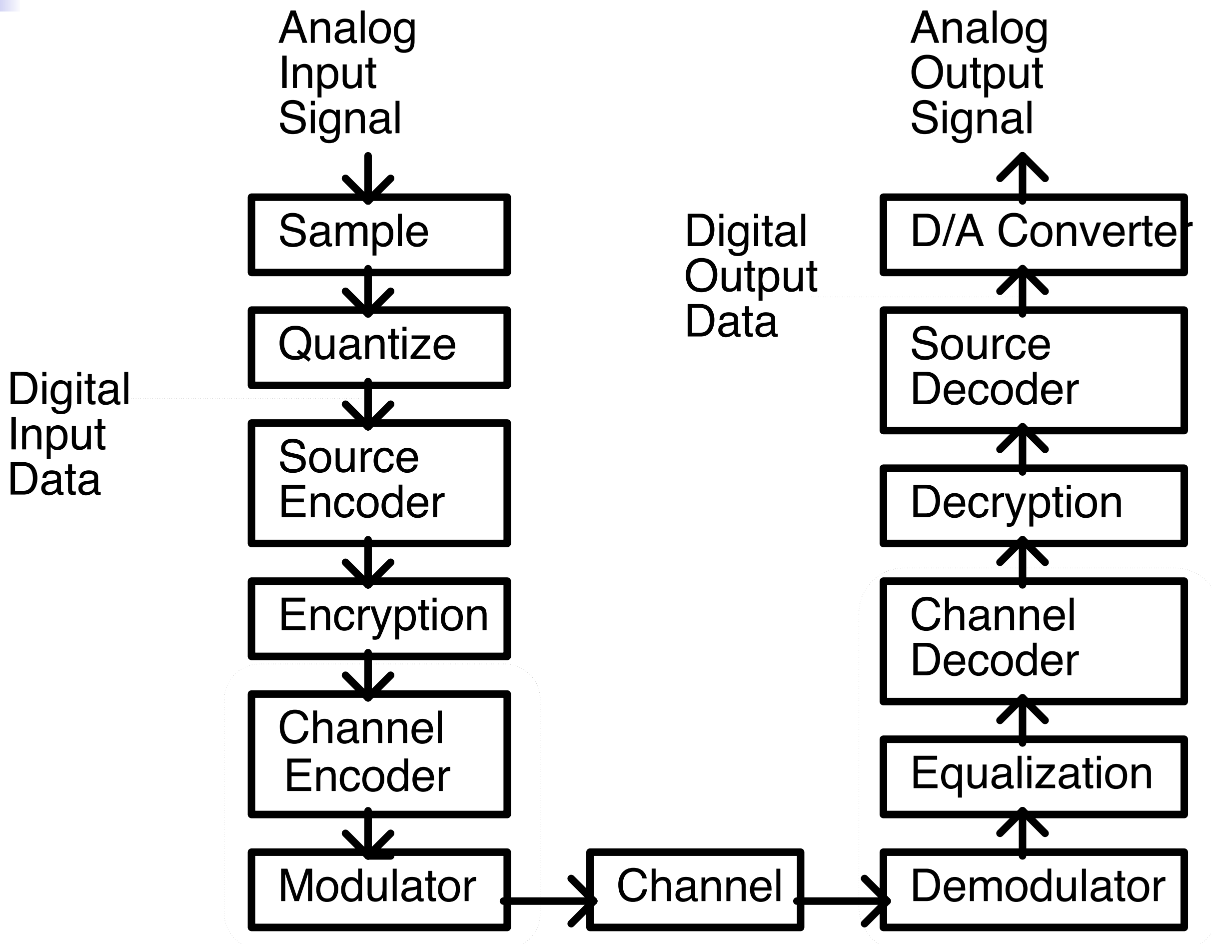
What is digital communications?

- Digital communications is the transfer of digital information (i.e., discrete messages) from one place/time to another place/time
- The discrete messages are in the form of binary information (i.e., bits)

Why digital communications?

- Digital communications allows integration of voice, video, and data on a single system
- Any noise introduces distortion to an analog signal. Since a digital receiver need only distinguish between a finite number of waveforms it is possible to recover digital information without corruption a large percentage time.
- 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 systems provide a more flexible tradeoff between bandwidth efficiency and energy

Block Diagram of Digital Communications System



Analog Input Signal

- Note that digital transmission can be used even for information that is inherently analog
- Analog information is continuous in time and amplitude
  - Examples: voice, video
- Need to convert analog information to binary information for digital transmission
  - Make discrete in time – sampling
  - Make discrete in amplitude - quantization
- Goal is to minimize distortion of the analog signal while minimizing the amount of digital information sent

Sampling

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

Note: Bandwidth is usually defined over a positive frequency range

Quantization

- Quantizer makes signal discrete in amplitude
- Unlike sampling, quantization introduces some distortion
- Data rate of a quantizer is dependent on sampling rate f_s and number of quantization levels $L=2^b$
- Good quantizers are able to use a small number of bits and while introducing a small amount of distortion

Source Coding

- Source Coding removes redundancy in digital data to reduce the data rate requirements
  - Ex: 000000000000111110000000001111
  - Example Compression:

    0 1100 1 0101 0 1001 1 0100

    bit 12 bit 5 bit 9 bit 4

    - only 20 bits instead of 30
- Can be done on digital information or combined with sampling/quantization for analog information

Encryption

- Encryption techniques can ensure data privacy
- Encryption is the ‘code’ many people envision when we think of spies and secret decoder rings - Communications engineers typically use the word "coding" for other ideas
- Very good "public key" encryption algorithms
- We will not talk about encryption in detail

Channel Encoder

- Provides protection against transmission errors by selectively inserting redundant data
- Note that source encoding works 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
- We will study the role that error correction coding plays in system design, including block codes, convolutional codes, and turbo codes
- This is different from error detection codes (e.g., redundancy checks) which are used with retransmission techniques

Modulator

- Converts digital data to a continuous waveform suitable for transmission over channel - usually a modulated sinusoidal wave
  - Exception: Impulse Radio or UWB
- Information is transmitted by varying one or more parameters of the waveform such as
  - Amplitude
  - Phase
  - Frequency
- Although we modulate a high frequency sinusoid, we will study modulation in terms of the 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):

$$1 \Rightarrow A\cos\left(2\pi f_c t\right)$$
$$0 \Rightarrow A\cos\left(2\pi f_c t + \pi\right) = -A\cos\left(2\pi f_c t\right)$$

Notes on Modulation

- Choice of modulation greatly effects system performance
- Channel coding and modulation can be combined as a single operation. This results in "trellis coded modulation".
- We will study modulation extensively
  - Signal space representation
  - Spectral characteristics
  - Optimum receiver structures

Mapping

- Modulation is sometimes referred to as "mapping" since it maps a finite number of bits (k) to one of $M=2^k$ symbols
- While the transmit waveform is continuous and analog, the messages are discrete and thus the communication is digital

Channel

- Carries signal - could be a telephone wire, free space
- Presents distorted version of the signal to the receiver.
  - Possible effects include attenuation, additive noise, amplitude fading and temporal or spectral dispersion.
- Fading is very important concept - studied in depth in the Cellular and Personal Communications class
  - Rayleigh fading
  - Ricean fading
  - Log-normal "shadowing"
- We will *initially* assume a very simple channel model - additive white Gaussian noise (AWGN)
- Will later address Rayleigh. Ricean, and Nakagami fading channels

Demodulator

- The demodulator converts the received signal into samples that represent the transmitted symbols at complex baseband
- The received symbols are distorted and must be "equalized" before a decision is made on which symbol was sent
- In order for proper demodulation to take place several operations must be performed
  - Demodulation to baseband
  - Sampling
  - Time synchronization
  - Frequency synchronization

Equalizer

- Due to temporal and frequency distortion, the received signal cannot be accurately “demapped” to the proper symbols
- Equalization is the generic term used to describe the process of removing that distortion
- Generally requires pilot symbols or some other a priori signal knowledge

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 bit error rate)
- Low 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 (symbols) which leads to larger bandwidth.
- The tradeoff between symbol duration and bandwidth 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 η_B

Tradeoffs in System Design: Fidelity vs. Signal Power

- One way to get an error free signal would be to use incredibly large 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: $\eta_E = E_b/N_o\big|_{\text{target } P_b}$
- We desire small η_E

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 but is fairly robust to noise. *M*-ary modulation can send multiple bits, but is more vulnerable to noise-induced errors.
  - Error correction coding: inserting redundant bits improves bit error rate, but increases bandwidth.
- This is a fundamental tradeoff in digital communications.

Conclusions

- In this lecture we have reviewed
  - The major components of a digital communication system
  - The fundamental trade-offs in digital communication system design
- This course will examine in detail many aspects of digital communications systems including
  - Digital modulation
  - Forward error correction coding
  - Equalization
  - The impact of fading and its mitigation