ELEC 7073 Digital Communication III

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Date & Time: Tuesday: 7:00-9:30pm

Place: CYC Lecture Room A

Notes can be obtained from: Intranet - MSc Course Materials

https://www.eee.hku.hk/~sdma/elec7073/
Contents

Introduction to digital communications
- Overview of digital communications
- A brief historical review of the development of digital communications
- Model of a digital communication system, elements in the systems
- Communication channel model
- Performance evaluation

Channel coding
- Block codes
- Convolutional codes
- Turbo codes
- Error detection coding: Cyclic Redundancy Check (CRC)
Contents

Modulation

- Basic modulation method: PAM, PSK, QAM
- Coded modulation: Trellis coded modulation
- Adaptive modulation and coding

Automatic Repeat reQuest (ARQ)

- Fundamental ARQ schemes: SAW, Go-Back-N, SR
- Hybrid ARQ: combining channel coding with ARQ
- Advanced HARQ: chase combining, incremental redundancy
Contents

*Multiple antenna techniques*
- Transmit diversity
- Receiver diversity
- Multiple input multiple output (MIMO)
- Space time coding

*Orthogonal Frequency Division Multiplexing (OFDM)*
- Basic structure
- OFDM in multi-path channels
- Time and frequency synchronization
References


• Journal and magazine articles as appropriate
Assessment

• Assignments: 30% (15% x 2)
• Final Examination: 70%
Lecture Notes

- Part 1: Introduction
- Part 2: Channel coding
- Part 3: Modulation
- Part 4: ARQ
- Part 5: Multiple antenna techniques
- Part 6: OFDM
Part 1. Introduction
Historical Perspective in the Development of Digital Communications (1)

- First telegraph --- Samuel Morse in 1837, variable-length binary code (*Morse code*) ➔ source coding

- 1875 --- Emile Baudot, fixed-length binary code (*Baudot code*)

- 1924 --- Nyquist, maximum signaling rate over a band-limited channel without inter-symbol interference (ISI) (*Nyquist rate*)

- 1928 --- Hartley, maximum reliable transmission rate over a band-limited channel with fixed signal power constraint and multiple signal amplitude level
Historical Perspective in the Development of Digital Communications (2)

- **1939 & 1942 --- Kolmogorov & Wiener**, the optimum linear filter whose output is the best mean-square approximation of the desired signal in the presence of additive noise (*Kolmogorov-Wiener filter*)

- **1947 --- Kotelnikov**, a coherent analysis of the various digital communication systems based on a geometrical approach
Historical Perspective in the Development of Digital Communications (3)

1948 --- Shannon

✓ **Sampling theorem**: a signal of bandwidth W can be reconstructed from samples taken at the Nyquist rate of 2W samples/s using the interpolation formula:

\[
s(t) = \sum_{n} s\left(\frac{n}{2W}\right) \frac{\sin\left[2\pi W (t - n/2W)\right]}{2\pi W (t - n/2W)}
\]

✓ **Channel capacity**: reliable (error-free) transmission of information, for example, AWGN channel with bandwidth W has a capacity of

\[
C = W \log_2\left(1 + \frac{P}{WN_0}\right) \text{ bits/s}
\]
Historical Perspective in the Development of Digital Communications (4)

1950 --- *Hamming*, error-detecting and error-correcting codes to combat the detrimental effects of channel noise

Notable advances

- *New block codes* by Muller (1954), Reed (1954), Reed and Solomon (1960), Bose and Ray-Chaudhuri (1960), and Goppa (1970, 1971)
- *Concatenated codes* by Forney (1966)
- *Computationally efficient decoding of BCH codes*, e.g., the Berlekamp-Massey algorithm
- *Trellis-coded modulation* by Ungerboeck (1982), Forney et al. (1984) and others
- *Efficient source encoding algorithms*, such as Ziv and Lempel (1977, 1978)...
- *Turbo codes and iterative decoding* by Berrou et al. (1993)
- *Low density parity check (LDPC) codes* by Gallager (1961), Mackay, Neal and Wiberg [1996]

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Digital Communication System

Transmitter

Information Source & Input Transducer

Source Encoding → Channel Encoding → Digital Modulation

Physical Channel

Digital Domain

Analog Waveform

Receiver

Output Transducer & Information Sink

Source Decoding ← Channel Decoding ← Digital Demodulation
Elements of Digital Communication Systems (1)

➢ **Information source:**
  – Analog signal, such as an audio or video signal
  – Digital signal, such as the output of a teletype machine, internet data

➢ **Source coding:**
  – To remove redundancy in source signals before transmission.
  – *Transmission efficiency* is improved.
  – Also known as data compression.
  – Examples: code excited linear prediction (CELP), MPEG.
A Simple Example of Source Coding

Original Picture (2M TIF file)  
Highly compressed picture (177k JPEG file)
Elements of Digital Communication Systems (2)

➢ **Channel coding:**

- To add redundancy in the information sequence so that the sequence can be recovered at the receiver even in the presence of noise and interference.
- **Transmission reliability** is improved.
- Examples:
  - Block code
    - Repetition code, Hamming code, Maximum-length code, BCH code, Reed-Solomon code
  - Convolutional code
  - Cyclic redundancy check (CRC) code
  - Turbo code
  - LDPC code
Examples of Channel Coding (1)

- Convolutional Code used for IS95 Forward Links

![Convolutional Code Diagram]

Data → Coded symbols

Forward link; rate = 1/2; constraint length = 9

Coded symbols
Examples of Channel Coding (2)

- Convolutional Code used for IS95 Reverse Links

Reverse link; rate = 1/3; constraint length = 9
Example of Channel Coding: Coding Gains of the Convolutional Code used for IS95

Good for voice communications

Good for video transmission

Figure 8.52 Dependence of realizable coding gains on constraint length for rate $\frac{1}{2}$ convolutional codes.

Figure 8.53 Dependence of realizable coding gains on constraint length for rate $\frac{1}{3}$ convolutional codes.

Elements of Digital Communication Systems (3)

Digital modulation and demodulation:

- Modulation (demodulation) maps (retrieves) the digital information into (from) an analog waveform appropriate for transmission over the channel.

- Generally involve translating (recovering) the baseband digital information to (from) a bandpass analog signal at a carrier frequency that is very high compared to the baseband frequency.

- **Binary modulation and M-ary modulation**
  - Given the channel bit rate $R$, the waveform period corresponding to a $b$-bit sequence is $b$ times the waveform period in a system using binary modulation.

- Examples: QPSK, $\pi/4$-DQPSK, 16QAM
Examples of Digital Modulations

- BPSK
- QPSK
- 16-QAM
- 64-QAM

Popular for mobile communications (IS-95, WCDMA)
Elements of Digital Communication Systems (4)

- Communication channels:
  - The physical medium used to send the signal from the transmitter to the receiver.
  - *Essential feature: the transmitted signal is corrupted in a random manner*
  - Examples: atmosphere, wire lines, optical fiber cables, etc.
Communication channels and their characteristics (1)

➢ Signal degradation caused by the channels
  - Additive noise
  - Interference
  - Signal attenuation
  - Amplitude and phase distortion
  - Multi-path distortion

➢ Communication channels
  - Wireline channels
  - Fiber-optic channels
  - Wireless electromagnetic channels
  - Underwater acoustic channels
  - Storage channel

Practical constrains limiting channel capacity
- Transmission power
- Channel Bandwidth
Communication channels and their characteristics (2)

Wireline channels
- Twisted-pair wire lines: a bandwidth of several hundred KHz
- coaxial cable: a bandwidth of several MHz
- Amplitude and phase distortion, additive noise and crosstalk interference

Fiber-optic channels
- Bandwidth: several orders of magnitude larger than coaxial cable channel
- The intensity of the light source is varied (modulated) with the information signal.
- Low signal attenuation

Frequency range for wire channel

Copied from Proakis's Digital Communications
Wireless electromagnetic channels (1)

- Electromagnetic energy is coupled to the propagation medium by an antenna.
- The physical size and the configuration of the antenna depend primarily on the operation frequency.
- Generally, the antenna should be longer than 1/10 of the wavelength.
  - \( f_\text{c} = 1 \text{MHz}, \ \lambda = c/f_\text{c} = 300 \text{m}, \) the minimum length of antenna: 30m
Communication channels and their characteristics (4)

➢ Wireless electromagnetic channels (2)

- Propagation mode
  - *Ground-wave propagation*: MF band
  - *Sky-wave propagation*:
    - HF band
    - *Signal multi-path* occurs when the transmitted signals arrives at the receiver via multiple propagation paths at different delays
    - The signal components arriving via different propagation paths may add destructively, resulting in *signal fading*
  - *Line-of-sight (LOS) propagation*: VHF, UHF and SHF bands
Communication channels and their characteristics (5)

- **Underwater acoustic channels**
  - Multi-path channel due to signal reflections from the surface and bottom of the sea
  - Signal fading, frequency-dependent attenuation

- **Storage channels**
  - Magnetic tape, magnetic and optical disks
  - The process of storing data → Signal transmission
  - The readback process → Signal recovering at the receiver
  - The amount of data limited by the size and the density
  - The processing speed limited by the mechanical and electrical subsystems
Mathematical models for communication channels (1)

- **Additive noise channel**
  - The transmitted signal is corrupted by an additive random noise process, generally *Gaussian noise process ➔ AWGN channel*

  \[ r(t) = s(t) + n(t) \]

- Taking channel attenuation into account

  \[ r(t) = \alpha s(t) + n(t) \]

  The attenuation factor
Mathematical models for communication channels (2)

- **Linear filter channel**
  - The signal goes through a linear filter and is also corrupted by additive noise.
  - Example: filters for bandwidth limitation in *wireline telephone channels*

\[
r(t) = s(t) * c(t) + n(t)
\]

**Channel impulse response:**
- Is used to characterize the channel.
- Can be measured (though not conveniently) by sending a pulse to the channel and recording the channel output by a receiver.
Mathematical models for communication channels (3)

- Linear time-variant filter channel (1)
  - The signals undergoes time-variant multi-path propagation
  - Examples: underwater acoustic and mobile cellular radio channels
  - $c(\tau; t)$: the response of the channel at time t due to an impulse applied at time $(t-\tau)$

$$r(t) = s(t) * c(\tau; t) + n(t)$$
$$= \int_{-\infty}^{\infty} c(\tau; t) s(t - \tau) d\tau + n(t)$$
Mathematical models for communication channels (4)

- **Linear time-variant filter channel (2)**
  - A model of $c(\tau; t)$ in mobile cellular radio channels

  $$c(\tau; t) = \sum_{k=1}^{L} \alpha_k(t) \delta(\tau - \tau_k)$$

  - $\{\alpha_k(t)\}$ represents the time-variant attenuation factor for the L multi-path propagation paths
  - $\{\tau_k\}$ are the corresponding time delays

  $$r(t) = s(t) * c(\tau; t) + n(t)$$
  $$= \sum_{k=1}^{L} \alpha_k(t) s(t - \tau_k) + n(t)$$
Mathematical models for communication channels (5)

- **Linear time-variant filter channel (3)**
  - An example of the time-variant channel impulse response

\[
c(\tau; t) = \sum_{k=1}^{L} \alpha_k(t) \delta(\tau - \tau_k)
\]

*Figure 5.4*  An example of the time varying discrete-time impulse response model for a multipath radio channel. Discrete models are useful in simulation where modulation data must be convolved with the channel impulse response [Tra02].

Copied from *Rappaport’s Wireless Communications: Principle and Practice*
Performance evaluation (1)

- **Bit error rate (BER)**
  - BER means Bit Error Rate, however some people refer to it as the Bit Error Ratio
  - Strictly speaking, it is the Probability that *a single Bit Error will occur*
  - BER is usually given as a power exponent, e.g. $10^{-6}$, which means one error in $10^6$ bits

- **Symbol error rate (SER)**
  - A symbol is the fundamental unit that is used to modulate the carrier waveform. For example, in QPSK, two bits constitute a symbol, and this symbol is used to control the phase shift of the carrier frequency
  - SER is the Probability that *a symbol error will occur*
  - SER can be converted into an equivalent BER. For example, M-ary PSK (Gray encoded)+coherent detection, $P_b \approx P_s / \log_2 M$
Performance evaluation (2)

What cause changes in BER or SER?

- BER/SER is determined by *Signal-to-Noise-ratio (SNR)*. Change in BER/SER is caused either by
  - Changes in S (i.e. signal power level)
    - Antenna loses track
    - Signal attenuation
  - Changes in N (i.e. noise power level)
    - Interference
    - Enhanced noise input
  - Varieties of SNR
    - SNR per bit: \( \gamma_b = \varepsilon_b / N_0 \) \((\varepsilon_b \rightarrow \text{bit energy})\)
    - SNR per symbol: \( \gamma_s = \varepsilon_s / N_0 \) \((\varepsilon_s \rightarrow \text{symbol energy})\)
Examples of BER

Figure 5.2-4 BER for binary signals

\[
\text{Probability of error, } P_b \\
\rho_r = 0 \quad \text{Orthogonal signals} \\
\rho_r = -1 \quad \text{Antipodal signals} \\
P_b = Q(\sqrt{\gamma_b})
\]

Figure 5.2-5 BER for coherent detection of orthogonal signals

\[
\text{Probability of a bit error} \\
\text{SNR per bit, } \gamma_b \text{ (dB)}
\]

\[
M = 64, \quad M = 32, \quad M = 16, \quad M = 8, \quad M = 2
\]

Copied from Proakis’s Digital Communications

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Examples of SER

Figure 5.2-8 SER for PAM

Figure 5.2-10 SER for PSK signals

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