COMMUNICATION SYSTEMS ENGINEERING

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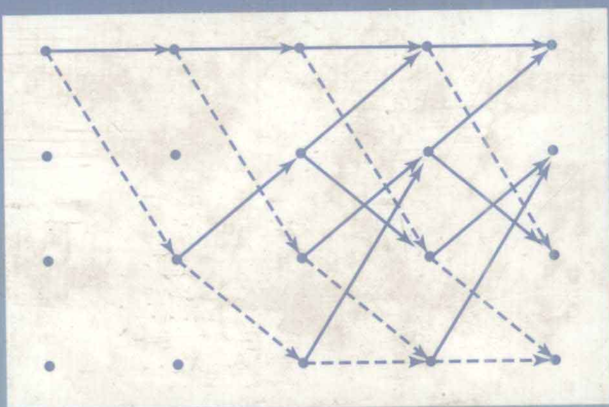

John G. Proakis
Masoud Salehi

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2nd Ed.

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To Felia, George, and Elena.
—John G. Proakis

To Fariba, Omid, Sina, and my parents.
—Masoud Salehi

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Preface

The objective of this book is to provide an introduction to the basic principles in the analysis and design of communication systems. It is primarily intended for use as a text for a first course in communications, either at a senior level or at a first-year graduate level.

BROAD TOPICAL COVERAGE

Although we have placed a very strong emphasis on digital communications, we have provided a review of important mathematical foundational topics and a solid introduction to analog communications. The major topics covered are:

- A review of frequency domain analysis of signals and systems, and the characterization of random processes (*Chapters 2 and 4*)
- An introduction to analog signal transmission and reception (*Chapters 3 and 5*)
- An introduction to digital communications (*Chapters 6–10*)

EMPHASIS ON DIGITAL COMMUNICATIONS

Our motivation for emphasizing digital communications is due to the technological developments that have occurred during the past five decades. Today, digital communication systems are in common use and generally carry the bulk of our daily information transmission through a variety of communications media, such as wireline telephone channels, microwave radio, fiber optic channels, and satellite channels. We are currently witnessing an explosive growth in the development of personal communication systems and ultrahigh speed communication networks, which are based on digital transmission of the information, whether it is voice, still images, or video. We anticipate that, in the near future, we will witness a replacement of the current analog AM and FM radio and television broadcast by digital transmission systems.

The development of sophisticated, high-speed digital communication systems has been accelerated by concurrent developments in inexpensive high speed integrated circuits (IC) and programmable digital signal processing chips. The developments in Microelectronic IC fabrication have made possible the implementation of high-speed, high precision A/D converters, of powerful error-correcting coders/decoders, and of complex digital modulation techniques. All of these technological developments point to a continuation in the trend toward increased use of digital communications as a means for transmitting information.

OVERVIEW OF THE TEXT

It is assumed that students using this book have a basic understanding of linear system theory, both continuous and discrete, including a working knowledge of Fourier series and Fourier transform techniques. Chapter 2 provides a review of basic material on signals and systems and establishes the necessary notation used in subsequent chapters. It is also assumed that students have had a first course in probability. Such courses are currently required in many undergraduate electrical engineering and computer engineering programs. Chapter 4 provides a review of probability and random processes to the extent that is necessary for a first course in communications.

Chapter 3 treats modulation and demodulation of analog signals. This treatment includes *amplitude modulation (AM), frequency modulation (FM),* and *phase modulation (PM).* Radio and television broadcasting and mobile radio cellular systems are discussed as examples of analog communication systems. Chapter 5 continues the treatment of analog communication systems by analyzing the effect of additive noise in the demodulation of AM, FM, and PM signals. The phase-locked loop, which is used for estimating the phase of a sinusoidal carrier in both analog and digital communication systems is also described in Chapter 5. The chapter concludes with a treatment of the effect of transmission losses and the characterization of noise sources in communication systems.

A logical beginning in the introduction of digital communication systems analysis and design is the characterization of information sources and source encoding. Chapter 6 is devoted to this topic. In this chapter we introduce the reader to the modeling of information sources, both discrete and continuous (analog), and the basic mathematical concepts of entropy and mutual information. Our discussion of source encoding for discrete sources includes the Huffman coding algorithm and the Lempel-Ziv algorithm. For the case of analog sources, we treat both scalar and vector quantization and describe the common waveform-coding techniques, namely, PCM, DPCM, and DM. We also describe the LPC-based source modeling method. As practical examples of the source-coding methods described in this chapter we cite the digital speech transmission systems in the telephone plant, the digital audio recording systems as embodied in the compact disc (CD) player and the JPEG image-coding standard.

Digital modulation and demodulation techniques are described in Chapter 7. Binary and nonbinary modulation methods are described based on a geometric representation of signals, and their error-rate performance is evaluated and compared. This chapter also describes symbol synchronization methods for digital communication systems.

Chapter 8 treats digital transmission through bandlimited AWGN channels. In this chapter we derive the power-spectral density of linearly modulated baseband signals and consider the problem of signal design for a bandlimited channel. We show that the effect of channel distortion is to introduce intersymbol interference (ISI), which can be eliminated or minimized by proper signal design. The use of linear and nonlinear adaptive equalizers for reducing the effect of ISI is also described.

Chapter 9 treats the topic of channel coding and decoding. The capacity of a communication channel is first defined, and the capacity of the Gaussian channel is determined. Linear block codes and convolutional codes are introduced and appropriate decoding algorithms are described. The benefits of coding for bandwidth constrained channels are also described. The final section of this chapter presents three practical applications of coding.

The last chapter of this book treats topics in wireless communications. First, we consider the characterization of fading multipath channels and describe the effects of such channels on wireless digital communication systems. The design of signals that are effective in mitigating this type of channel distortion is also considered. Second, we describe the class of continuous-phase modulated signals, which are especially suitable for digital communication in wireless channels. Finally, we treat the class of spread-spectrum signals, which are suitable for multi-user wireless communication systems.

EXAMPLES AND HOMEWORK PROBLEMS

We have included a large number of carefully chosen examples and homework problems. The text contains over 180 worked-out examples and over 480 problems. Examples and problems range from simple exercises to more challenging and thought-provoking problems. A Solutions Manual is available free to all adopting faculty, which is provided in both typeset form and as a diskette formatted in LaTeX. Solutions are not available for sale to students. This will enable instructors to print out solutions in any configuration easily.

COURSE OPTIONS

This book can serve as a text in either a one- or two-semester course in communication system. An important consideration in the design of the course is whether or not the students have had a prior course in probability and random processes. Another important consideration is whether or not analog modulation and demodulation techniques are to be covered. Here, we outline three scenarios. Others are certainly possible.

1. A one-term course in analog and digital communication: Selected review sections from Chapters 2 and 4, all of chapters 3, 5, 7, and 8, and selections from chapters 6, 9, and 10.
2. A one-term course in digital communication: Selected review sections from Chapters 2 and 4, and Chapters 6–10.
3. A two-term course sequence on analog and digital communications:
   (a) Chapters 2–6 for the first course.
   (b) Chapters 7–10 for the second course.

We wish to thank Gloria Doukakis for her assistance in the preparation of the manuscript.

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1

Introduction

Every day, in our work and in our leisure time, we come in contact with and use a variety of modern communication systems and communication media, the most common being the telephone, radio, television, and the Internet. Through these media we are able to communicate (nearly) instantaneously with people on different continents, transact our daily business, and receive information about various developments and events of note that occur all around the world. Electronic mail and facsimile transmission have made it possible to rapidly communicate written messages across great distances.

Can you imagine a world without telephones, radio, and TV? Yet, when you think about it, most of these modern-day communication systems were invented and developed during the past century. Here, we present a brief historical review of major developments within the last two hundred years that have had a major role in the development of modern communication systems.

1.1 HISTORICAL REVIEW

Telegraphy and Telephony. One of the earliest inventions of major significance to communications was the invention of the electric battery by Alessandro Volta in 1799. This invention made it possible for Samuel Morse to develop the electric telegraph, which he demonstrated in 1837. The first telegraph line linked Washington with Baltimore and became operational in May 1844. Morse devised the variable-length binary code given in Table 1.1, in which letters of the English alphabet were represented by a sequence of dots and dashes (code words). In this code, more frequently occurring letters are represented by short code words, while letters occurring less frequently are represented by longer code words.

TABLE 1.1 MORSE CODE

A	·—	N	—·
B	—···	O	———
C	—·—·	P	·——·
D	—··	Q	——·—
E	·	R	·—·
F	··—·	S	···
G	——·	T	—
H	····	U	··—
I	··	V	···—
J	·———	W	·——
K	—·—	X	—··—
L	·—··	Y	—·——
M	——	Z	——··

(a) Letters

1	·————
2	··———
3	···——
4	····—
5	·····
6	—····
7	——···
8	———··
9	————·
0	—————

(b) Numbers

Period (·)	·—·—·—	Wait sign (AS)	·—···
Comma (,)	——··——	Double dash (break)	—···—
Interrogation (?)	··——··	Error sign	········
Quotation Mark (")	·—··—·	Fraction bar (/)	—··—·
Colon (:)	———···	End of message (AR)	·—·—·
Semicolon (;)	—·—·—·	End of transmission (SK)	···—·—
Parenthesis ( )	—·——·—		

(c) Punctuation and Special Characters

The *Morse code* was the precursor to the variable-length source-coding methods that are described in Chapter 6. It is remarkable that the earliest form of electrical communications that was developed by Morse, namely *telegraphy,* was a binary digital communication system in which the letters of the English alphabet were efficiently encoded into corresponding variable-length code words having binary elements.

Nearly forty years later, in 1875, Émile Baudot developed a code for telegraphy in which each letter was encoded into fixed-length binary code words of length 5. In the *Baudot code* the binary code elements have equal length and are designated as mark and space.

An important milestone in telegraphy was the installation of the first transatlantic cable in 1858 that linked the United States and Europe. This cable failed after about four weeks of operation. A second cable was laid a few years later and became operational in July 1866.

Telephony came into being with the invention of the telephone in the 1870s. Alexander Graham Bell patented his invention of the telephone in 1876, and in 1877 established the Bell Telephone Company. Early versions of telephone communication systems were relatively simple and provided service over several hundred miles. Significant advances in the quality and range of service during the first two decades of the twentieth century resulted from the invention of the carbon microphone and the induction coil.