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# DIGITAL COMMUNICATIONS

## Fundamentals and Applications

Second Edition

**BERNARD SKLAR**

*Communications Engineering Services, Tarzana, California  
and  
University of California, Los Angeles*



Prentice Hall P T R  
Upper Saddle River, New Jersey 07458  
[www.phptr.com](http://www.phptr.com)



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# Preface

This second edition of *Digital Communications: Fundamentals and Applications* represents an update of the original publication. The key features that have been updated are:

- The error-correction coding chapters have been expanded, particularly in the areas of Reed-Solomon codes, turbo codes, and trellis-coded modulation.
- A new chapter on fading channels and how to mitigate the degrading effects of fading has been introduced.
- Explanations and descriptions of essential digital communication concepts have been amplified.
- End-of-chapter problem sets have been expanded. Also, **end-of-chapter** question sets (and where to find the answers), as well as end-of-chapter CD exercises have been added.
- A compact disc (CD) containing an educational version of the design software **System View** by ELANIX® accompanies the textbook. The CD contains a workbook with over 200 exercises, as well as a concise tutorial on digital signal processing (DSP). CD exercises in the workbook reinforce material in the textbook; concepts can be explored by viewing waveforms with a windows-based PC and by changing parameters to see the effects on the overall system. Some of the exercises provide basic training in using **System View**; others provide additional training in DSP techniques.



The teaching of a one-semester university course proceeds in a very different manner compared with that of a short-course in the same subject. At the university, one has the luxury of **time—time** to develop the needed skills and mathematical tools, time to practice the ideas with homework exercises. In a short-course, the treatment is almost backwards compared with the university. Because of the time factor, a short-course teacher must "jump in" early with essential concepts and applications. One of the vehicles that I found useful in structuring a short course was to start by handing out a check list. This was not merely an outline of the curriculum. It represented a collection of concepts and nomenclature that are not clearly documented, and are often misunderstood. The short-course students were thus initiated into the course by being challenged. I promised them that once they felt comfortable describing each issue, or answering each question on the list, they would be well on their way toward becoming knowledgeable in the field of digital communications. I have learned that this list of essential concepts is just as valuable for teaching full-semester courses as it is for short courses. Here then is my "check list" for digital communications.

1. What mathematical dilemma is the cause for there being several definitions of bandwidth? (See Section 1.7.2.)
2. Why is the ratio of bit energy-to-noise power spectral density,  $E_b/N_0$ , a natural figure-to-merit for digital communication systems? (See Section 3.1.5.)
3. When representing timed events, what dilemma can easily result in confusing the most-significant bit (MSB) and the least-significant bit (LSB)? (See Section 3.2.3.1.)
4. The error performance of digital signaling suffers primarily from two degradation types. a) loss in signal-to-noise ratio, b) distortion resulting in an irreducible bit-error probability. How do they differ? (See Section 3.3.2.)
5. Often times, providing more  $E_b/N_0$  will not mitigate the degradation due to intersymbol interference (ISI). Explain why. (See Section 3.3.2.)
6. At what location in the system is  $E_b/N_0$  defined? (See Section 4.3.2.)
7. Digital modulation schemes fall into one of two classes with opposite behavior characteristics. a) orthogonal signaling, b) phase/amplitude signaling. Describe the behavior of each class. (See Sections 4.8.2 and 9.7.)
8. Why do binary phase shift keying (BPSK) and quaternary phase shift keying (QPSK) manifest the same bit-error-probability relationship? Does the same hold true for **-ary** pulse amplitude modulation ( $M$ -PAM) and  $M^2$ -ary quadrature amplitude modulation ( $M^2$ -QAM) bit-error probability? (See Sections 4.8.4 and 9.8.3.1.)
9. In orthogonal signaling, why does error-performance improve with higher dimensional signaling? (See Section 4.8.5.)
10. Why is *free-space loss* a function of wavelength? (See Section 5.3.3.)
11. What is the relationship between received signal to noise ( $S/N$ ) ratio and carrier to noise ( $C/N$ ) ratio? (See Section 5.4.)
12. Describe four types of trade-offs that can be accomplished by using an error-correcting code. (See Section 6.3.4.)

13. Why do traditional error-correcting codes yield error-performance degradation at low values of  $N_0$ ? (See Section 6.3.4.)
14. Of what use is the *standard array* in understanding a block code, and in evaluating its capability? (See Section 6.6.5.)
15. Why is the Shannon limit of -1.6 dB not a useful goal in the design of real systems? (See Section 8.4.5.2.)
16. What are the consequences of the fact that the Viterbi decoding algorithm does not yield *a posteriori* probabilities? What is a more descriptive name for the Viterbi algorithm? (See Section 8.4.6.)
17. Why do binary and 4-ary orthogonal frequency shift keying (FSK) manifest the same bandwidth-efficiency relationship? (See Section 9.5.1.)
18. Describe the subtle energy and rate transformations of received signals: from data-bits to channel-bits to symbols to chips. (See Section 9.7.7.)
19. Define the following terms: Baud, State, Communications Resource, Chip, Robust Signal. (See Sections 1.1.3 and 7.2.2, Chapter 11, and Sections 12.3.2 and 12.4.2.)
20. In a fading channel, why is signal dispersion independent of fading rapidity? (See Section 15.1.1.1.)

I hope you find it useful to be challenged in this way. Now, let us describe the purpose of the book in a more methodical way. This second edition is intended to provide a comprehensive coverage of digital communication systems for senior level undergraduates, first year graduate students, and practicing engineers. Though the emphasis is on digital communications, necessary analog fundamentals are included since analog waveforms are used for the radio transmission of digital signals. The key feature of a digital communication system is that it deals with a finite set of discrete messages, in contrast to an analog communication system in which messages are defined on a continuum. The objective at the receiver of the digital system is not to reproduce a waveform with precision; it is instead to determine from a noise-perturbed signal, which of the finite set of waveforms had been sent by the transmitter. In fulfillment of this objective, there has arisen an impressive assortment of signal processing techniques.

The book develops these techniques in the context of a unified structure. The structure, in block diagram form, appears at the beginning of each chapter; blocks in the diagram are emphasized, when appropriate, to correspond to the subject of that chapter. Major purposes of the book are to add organization and structure to a field that has grown and continues to grow rapidly, and to insure awareness of the "big picture" even while delving into the details. Signals and key processing steps are traced from the information source through the transmitter, channel, receiver, and ultimately to the information sink. Signal transformations are organized according to nine functional classes: Formatting and source coding, Baseband signaling, Band-pass signaling, Equalization, Channel coding, Multiplexing and multiple access, Spreading, Encryption, and Synchronization. Throughout the book, emphasis is placed on system goals and the need to trade off basic system parameters such as signal-to-noise ratio, probability of error, and bandwidth expenditure.

## ORGANIZATION OF THE BOOK

Chapter 1 introduces the overall digital communication system and the basic signal transformations that are highlighted in subsequent chapters. Some basic ideas of random variables and the *additive white Gaussian noise* (AWGN) model are reviewed. Also, the relationship between power spectral density and autocorrelation, and the basics of signal transmission through linear systems are established. Chapter 2 covers the signal processing step, known as *formatting*, in order to render an information signal compatible with a digital system. Chapter 3 emphasizes *baseband signaling*, the detection of signals in Gaussian noise, and receiver optimization. Chapter 4 deals with *bandpass signaling* and its associated modulation and demodulation/detection techniques. Chapter 5 deals with *link analysis*, an important subject for providing overall system insight; it considers some subtleties that are often missed. Chapters 6, 7, and 8 deal with *channel coding*—a cost-effective way of providing a variety of system performance trade-offs. Chapter 6 emphasizes *linear block codes*, Chapter 7 deals with *convolutional codes*, and Chapter 8 deals with *Reed-Solomon codes* and *concatenated codes* such as *turbo codes*.

Chapter 9 considers various modulation/coding system *trade-offs* dealing with probability of bit-error performance, bandwidth efficiency, and signal-to-noise ratio. It also treats the important area of coded modulation, particularly *trellis-coded modulation*. Chapter 10 deals with *synchronization* for digital systems. It covers phase-locked loop implementation for achieving carrier synchronization. It covers bit synchronization, frame synchronization, and network synchronization, and it introduces some ways of performing synchronization using digital methods.

Chapter 11 treats *multiplexing* and *multiple access*. It explores techniques that are available for utilizing the communication resource efficiently. Chapter 12 introduces *spread spectrum* techniques and their application in such areas as multiple access, ranging, and interference rejection. This technology is important for both military and commercial applications. Chapter 13 deals with *source coding* which is a special class of data formatting. Both formatting and source coding involve digitization of data; the main difference between them is that source coding additionally involves data redundancy reduction. Rather than considering source coding immediately after formatting, it is purposely treated in a later chapter so as not to interrupt the presentation flow of the basic processing steps. Chapter 14 covers basic *encryption/decryption* ideas. It includes some classical concepts, as well as a class of systems called public key cryptosystems, and the widely used E-mail encryption software known as *Pretty Good Privacy* (PGP). Chapter 15 deals with *fading channels*. Here, we deal with applications, such as mobile radios, where characterization of the channel is much more involved than that of a nonfading one. The design of a communication system that will withstand the degradation effects of fading can be much more challenging than the design of its nonfading counterpart. In this chapter, we describe a variety of techniques that can mitigate the effects of fading, and we show some successful designs that have been implemented.

It is assumed that the reader is familiar with Fourier methods and convolution. Appendix A reviews these techniques, emphasizing those properties that are

particularly useful in the study of communication theory. It also assumed that the reader has a knowledge of basic probability and has some familiarity with random variables. Appendix B builds on these disciplines for a short treatment on statistical decision theory with emphasis on hypothesis testing—so important in the understanding of detection theory. A new section, Appendix E, has been added to serve as a short tutorial on  $s$ -domain,  $z$ -domain, and digital filtering. A concise DSP tutorial also appears on the CD that accompanies the book.

If the book is used for a two-term course, a simple partitioning is suggested; the first seven chapters can be taught in the first term, and the last eight chapters in the second term. If the book is used for a one-term introductory course, it is suggested that the course material be selected from the following chapters: 1, 2, 3, 4, 5, 6, 7, 9, 10, 12.

## ACKNOWLEDGMENTS

It is difficult to write a technical book without contributions from others. I have received an abundance of such assistance, for which I am deeply grateful. For their generous help, I want to thank Dr. Andrew Viterbi, Dr. Chuck Wheatley, Dr. Ed Tiedeman, Dr. Joe Odenwalder, and Serge Willingeger of Qualcomm. I also want to thank Dr. Dariush Divsalar of Jet Propulsion Laboratory (JPL), Dr. Bob Bogusch of Mission Research, Dr. Tom Stanley of the Federal Communications Commission, Professor Larry Milstein of the University of California, San Diego, Professor Ray Pickholtz of George Washington University, Professor Daniel Costello of Notre Dame University, Professor Ted Rappaport of Virginia Polytechnic Institute, Phil Kossin of Lincom, Les Brown of Motorola, as well as Dr. Bob Price and Frank Amoroso.

I also want to acknowledge those people who played a big part in helping me with the first edition of the book. They are: Dr. Maurice King, Don Martin and Ned Feldman of The Aerospace Corporation, Dr. Marv Simon of JPL, Dr. Bill Lindsey of Lincom, Professor Wayne Stark of the University of Michigan, as well as Dr. Jim Omura, Dr. Adam Lender, and Dr. Todd Citron.

I want to thank Dr. Maurice King for contributing Chapter 10 on Synchronization, and Professor Fred Harris of San Diego State University for contributing Chapter 13 on Source Coding. Also, thanks to Michelle Landry for writing the sections on Pretty Good Privacy in Chapter 14, and to Andrew Guidi for contributing end-of-chapter problems in Chapter 15.

I am particularly indebted to my friends and colleagues Fred Harris, Professor Dan Bukofzer of California State University at Fresno, and Dr. Maury Schiff of Elanix, who put up with my incessant argumentative discussions anytime that I called on them. I also want to thank my very best teachers—they are my students at the University of California, Los Angeles, as well as those students all over the world who attended my short courses. Their questions motivated me and provoked me to write this second edition. I hope that I have answered all their questions with clarity.

I offer special thanks for technical clarifications that my son, Dean Sklar, suggested; he took on the difficult role of being his father's chief critic and "devil's advocate." I am particularly indebted to Professor Bob Stewart of the University of Strathclyde, Glasgow, who contributed countless hours of work in writing and preparing the CD and in authoring Appendix E. I thank Rose Kernan, my editor, for watching over me and this project, and I thank Bernard Goodwin, Publisher at Prentice Hall, for indulging me and believing in me. His recommendations were invaluable. Finally, I am extremely grateful to my wife, Gwen, for her encouragement, devotion, and valuable advice. She protected me from the "slings and arrows" of everyday life, making it possible for me to complete this second edition.

BERNARD SKLAR

*Tarzana, California*