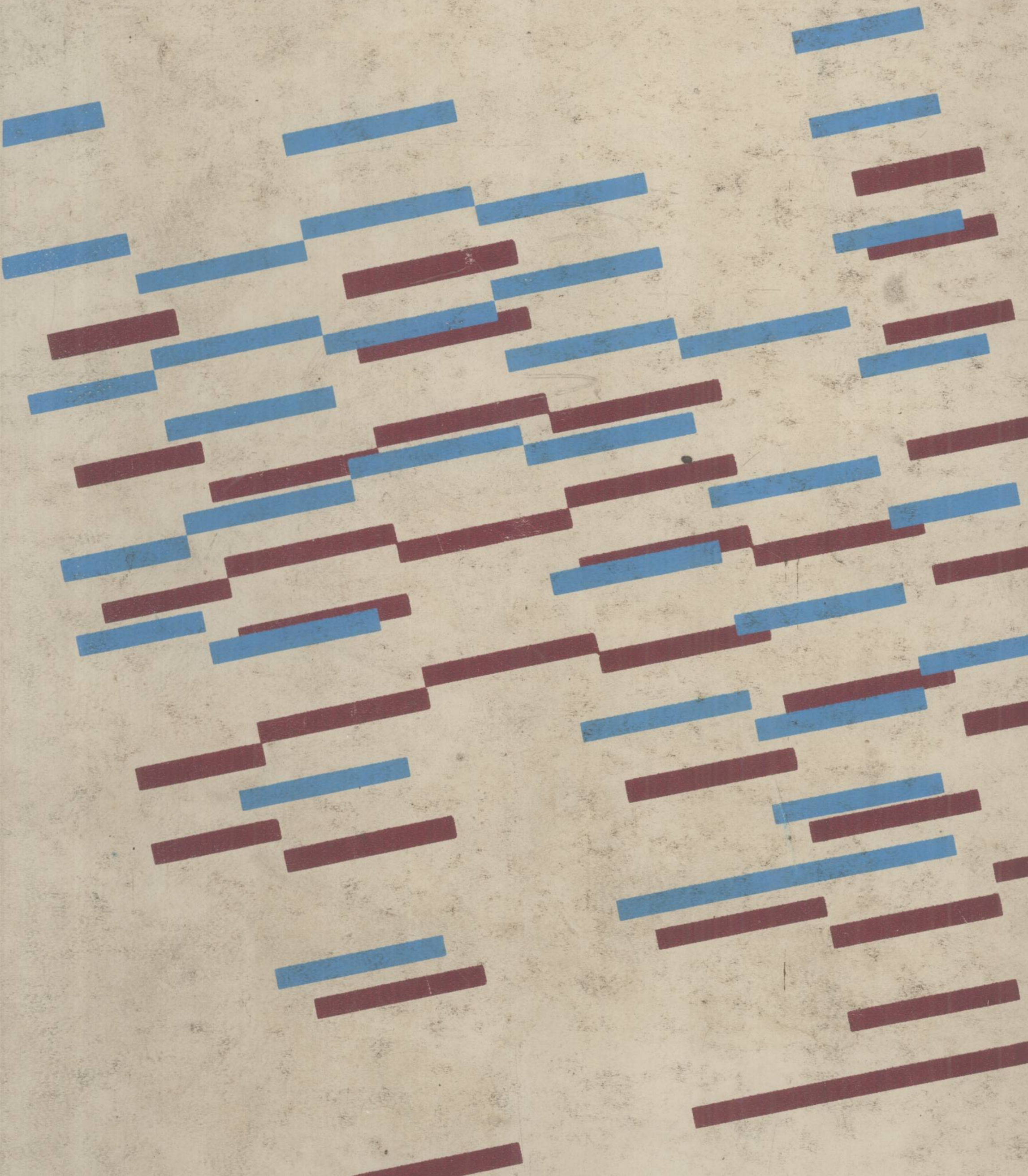
Principles of Communications

Systems, Modulation, and Noise

Second Edition

Ziemer/Tranter



Principles of Communications

SYSTEMS, MODULATION, AND NOISE

second edition

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To our students

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Preface

The appearance of yet another book dealing with communication systems requires a few words of justification. Our aim in writing this book is to provide a broad treatment of communication theory, beginning with signal, system, and noiseless modulation theory, proceeding through a treatment of the effects of noise in analog and digital communication systems, and ending with introductory treatments of detection, estimation, and information theory. Thus we have tried to provide in a single volume a basic introduction to what is commonly referred to as "communication theory." Yet the material is modularized so that the instructor is not committed to covering the entire book, but may select from several possible course options, ranging in length from one quarter to two semesters. We have suggested several possibilities in the table included in this preface.

Our basic objective when we were preparing the first edition of this text was to present a broad treatment of communications. This goal is still valid. In preparing the second edition, we took care to ensure that the basic theme and style of the first edition were retained. Those sections of the book that our students accepted well, and that are essential to a basic understanding of communication theory, were retained intact. The main changes made in the second edition include: (1) the addition of numerous example problems, (2) the inclusion of a number of circuit-related implementation examples, (3) the addition of a number of new problems at the end of each chapter, and (4) the inclusion of those topics that have become fundamental communication techniques since the publication of the first edition, such as minimum-shift keying and spread-spectrum communications.

We were strongly tempted to add sections on the many new applications that have become important during the last ten years, such as computer networking, cellular radio, fiber optic systems, and so forth. We resisted the temptation for two basic reasons. First, this would have increased the length and cost of the book significantly and would have resulted in a volume too long to be covered in a sequence of two three-semester-hour courses. Second, the main purpose of our courses is to stress basic analysis techniques and not to present all possible areas of application. Some applications are, of course, essential for both understanding and motivation. We have tried to choose those that are the most fundamental and that yield significant insight.

The outline of the book remains unchanged from the first edition. The historical perspective of modern communications is in Chapter 1. Chapter 2 presents the basic ideas of signal and system theory for those students who have not previously been exposed to them. Chapter 3 treats noiseless modulation theory. This chapter features the noiseless phase-lock loop and its application in modern communication systems, a topic that has become increasingly important with the availability of low-cost integrated-circuit phase-lock loops. (Appendix A, which deals with physical noise sources and calculations of system noise, is so written that it can be covered any time after Chapter 3. Its purpose is to expose students to noise effects and calculations without requiring the tools of probability theory.) Chapters 4 and 5 constitute a brief course in probability and random processes. No previous knowledge of probability is assumed. The effects of noise on analog systems is the subject of Chapter 6. After a unified treatment of linear modulation, Chapter 6 turns attention to phase, frequency, and pulse modulation. Chapter 7 is a broad treatment of digital communication systems, beginning with the analysis of several techniques of basic digital modulation and continuing through a consideration of systems for synchronization and the effects of multipath in digital communications. Chapter 8 deals with the basic ideas of detection and estimation theory and their applications. It introduces ideas of signal space to provide a unifying structure for understanding the tradeoffs available between bandwidth and noise performance. In addition, the theoretical basis of the phase-lock loop as a phase-estimation device is illustrated by example. Chapter 9 is an elementary treatment of information theory and error-correcting codes. Chapters 8 and 9 serve to tie together the system performance results of earlier chapters as well as to lead into more advanced courses in communication theory.

To compare the first and second editions of this book in detail, let us take it chapter by chapter. The basic changes in Chapter 2 are few. We expanded the material on the relationship between risetime and bandwidth, added a section on the transmission of sample data through bandlimited channels, and expanded the material on Hilbert transforms to include the frequency-domain representation of analytic signals.

Chapter 3, which covers basic modulation techniques, has been expanded significantly by the addition of a number of example problems and implementation techniques. We added sections on mixers, balanced discriminators, and applications to television receivers, and we expanded the section on superheterodyne receivers. All of these additions were made to give the student insight into practical methods of implementation. Also, we expanded both the section on delta modulation to include a discussion on slope-overload and adaptive techniques and the section on pulse-width and pulse-position modulation to illustrate the basic relationship between these modulation techniques.

We changed Chapters 4 and 5, which cover probability and random processes, less than any of the other chapters from the first edition. We felt that the existing material was both concise and teachable. An example to illustrate the concept of conditional expectation was added. In addition, we prepared a new appendix, supporting Chapter 4, that introduces the matrix representation of jointly Gaussian random variables. In Chapter 5, we introduced a discussion of the random telegraph waveform, as well as a section on the quantization of random processes.

In Chapter 6, we expanded the discussion of thresholding in angle modulation systems and also added an approximate analysis of PCM.

We made a number of significant changes in Chapter 7. We included new sections on offset QPSK and on techniques of bandwidth-efficient digital modulation, as well as a section on digital signaling through band-limited channels. The section on equalization was expanded to include the concept of zero-forcing equalization and minimum mean-square-error equalization. A section of spread-spectrum systems was added.

We added a new section to Chapter 8 to introduce minimum mean-square estimators and the orthogonality principle. We considered this chapter to be otherwise complete, and a good overview of detection and estimation theory.

To Chapter 9, we added a number of examples on information theory and coding. One significant example shows the effect of various channel models on the performance of repetition codes and illustrates the relationship between the repetition code and diversity transmission. Also, the section on convolutional coding was expanded to include a brief discussion of the Viterbi algorithm.

A large number of basic concepts are introduced in Chapters 2 through 5. For this reason, the summaries of these chapters are presented in a style that provides the student with a quick review of the chapter by delineating the most important concepts introduced in the chapter. Chapters 2 and 3 may seem rather long. However, each chapter is divided into a sequence of blocks of material; the problems are keyed to these blocks, so that each block can be treated as an individual chapter.

In some cases, we provided double coverage of a topic. We did this for two reasons. First, a cursory treatment of some topics is followed by a later, more complete treatment to allow the text to be "modularized," so that several possible course sequences can be taught from it. An example is the initial treatment in Chapter 2 of the power spectral density of a signal based on purely deterministic ideas, which is followed by a more rigorous treatment in Chapter 5 using a probabilistic approach. A second example is the introduction of the noiseless phase-lock loop in Chapter 3, followed by several treatments later in the text that deal with applications and the effect of noise in phase-lock loops. Another reason for double coverage of some areas is to give students extra exposure to topics that we know from experience are difficult for them. The sections on the correlation function in Chapters 2 and 5 are examples. An instructor may elect to teach such sections consecutively.

Wherever possible, we have tried to present material that emphasizes state-of-the-art techniques and practical means for implementing systems. Thus, for example, the treatment of the transmission of digital data does not conclude with the matched filter receiver, but continues with elementary discussions of systems for coherent demodulation, synchronization, and system performance in multipath. For another example, the material on information theory and coding does not end with the usual elementary discussions of information measure and channel capacity, but continues with coverage of basic coding techniques, examples of their implementation, and comparison of their performance. We have been able to make the text up to date and practical for two reasons. First, the text as a whole provides a unified treatment of the basic theory, from elementary signal and system theory to the more abstract ideas of signal space, information theory, and coding. In addition, we have provided in our developments only the level of rigor necessary for a basic understanding of the principles involved. The student who wants advanced study in a specific area is referred to one or more of the many well-written, more advanced books available. Using this philosophy, we have included many topics not generally treated in other texts of comparable level.

We have used this text for a two-semester course sequence for a number of years. The first course is a first-semester senior-level one covering Chapters 1, 2, 3, and Appendix A. The second course is a one-semester senior-level one covering Chapters 4 and 5 and selected topics from the remainder of the book. Some good students who have had a previous course in signal and system theory have successfully taken the second course without the first. Typically, we cover the material in Chapter 2 in a three-hour lecture course in about five weeks and the material in Chapters 4 and 5 (excluding the last section of Chapter 5) in a similar period. Thus, students who have had a previous systems course would be able to cover Chapters 3, 4, and 5 in one semester. A logical three-course sequence for schools on the quarter system would be Chapters 1 to 3 for the first course, 4 to 6 for the second course, and 7 to 9 for the third course, with some topics from Chapters 6 to 9 omitted at the instructor's discretion.

Although the text was designed primarily for a two-semester sequence, we included sufficient material to allow considerable flexibility in structuring many different course sequences based on the text. The table illustrates various possible options. The sections in parentheses are those that could be omitted.

A complete solutions manual for the problems is available from the publisher as an aid to the instructor. Also included in the solutions manual are a classification of each problem (drill problem, more difficult problem, extension to text material) and suggested extensions to several problems. A computer program for evaluating error-correcting codes is given as an appendix to the solutions manual.

Possible Course Sequences

Chapter 2, or previous course on signals and systems
(Topics for possible omission: Sections 2.7, 2.11 if SSB omitted)

Topics in Comm. Theory	*Modulation Theory & Noise Calculations*	*Digital Communications in Noise*	*Analog Communications in Noise*	*Probability, Random Processes, and Optimum Signal Reception*	*Analog and Digital Communications in Noise*
Chap. 3 (3.3; 3.4; 3.5; 3.6)	**Chap. 3** (3.3; 3.6)	**Chap. 4**	**Chap. 3**	**Chap. 4**	**Chap. 3**
Chap. 4	**Appendix A** Sec. 3.6	**Chap. 5**	**Chap. 4**	**Chap. 5**	**Chap. 4**
Chap. 5 (5.6 if 6.4 omitted)		**Chap. 7**	**Chap. 5**	**Chap. 7**	**Chap. 5**
Chap. 6 (6.2; 6.4; 6.5)		**Chap. 9**	**Chap. 6**	**Chap. 8**	**Chap. 6**
Chap. 7 (7.3; 7.6–7.12)					**Chap. 7**
Chap. 8 8.1 and 8.4 stand on own					
Chap. 9 (9.2; 9.3—last half; 9.4)					

(Can be covered in any order) [Chaps. 6–9 of Topics in Comm. Theory]

We wish to thank the many people who contributed to the development of this textbook and who suggested improvements for the second edition. Our colleagues at the University of Missouri–Rolla who have taught from the first edition—Drs. D. R. Cunningham, G. E. Carlson, J. Stuller, J. R. Betten, J. Liebetreu, and M. Wickert—have provided many useful comments and suggestions. We also wish to express thanks to the many colleagues who have written to us or talked to us at technical meetings to offer helpful suggestions. The agencies that have supported our research deserve special

mention, since, by working on these projects, we have expanded our knowledge and insight significantly. These agencies include the National Aeronautics and Space Administration; the National Science Foundation; Motorola, Incorporated; Emerson Electric Company; Naval Electronics Laboratory Center; Battelle Memorial Institute; and the McDonnell Douglas Corporation. Thanks are also owed to R. S. Simpson of Texaco USA, who will find many of his examples incorporated into Chapter 9, and to Saul Fast of McDonnell Douglas, who has contributed significantly through many hours of stimulating discussion.

We also wish to thank our reviewers of both the first and second editions of this book. The reviewers of the first edition were: Richard F. J. Filipowsky of the University of South Florida, William C. Davis of Ohio State University, Robert R. Boorstyn of the Polytechnic Institute of New York, and Bruce A. Eisenstein of Drexel University. The reviewers of the second edition were Jerome K. Butler of Southern Methodist University, L. J. Giacoletto of Michigan State University, Herbert Hacker, Jr., and Robert Kerr of Duke University, Vijay K. Jain of the University of South Florida, Lawrence B. Milstein of the University of California at San Diego, and Rao Yarlagadda of Oklahoma State University. Both sets of reviewers provided many valuable suggestions, comments, and criticisms.

Our students have provided encouragement for this project, as well as many suggestions for improvements. It is to them that we dedicate this book.

Finally, our wives, Sandy and Judy, deserve much more than a simple thanks for the patience they have shown throughout this task.

R. E. Z.
W. H. T.

Contents

1

Introduction

As we enter the fifth decade after the close of World War II, we live in a world in which electrical communication is so commonplace that we pick up our cordless telephones without a second thought. Yet the importance of such communication in today's world is so crucial that we cannot imagine modern society without it. We are entering an era of change, which some people refer to as the information age, much like the era—more than 100 years ago—when the world underwent drastic changes because of the industrial revolution. From now on, the prosperity and continued development of modern nations will depend primarily on the originating and disseminating of *information*, rather than of manufactured goods. For example, a hotel in Saudi Arabia might well be designed by an architectural firm in the United States, built with steel produced in Japan, and constructed by workers from Korea. All phases of such a project depend for their successful completion on rapid world-wide communications.

Almost every day we hear about, or read about, concepts such as electronic mail, wired cities, overnight stock-market quotes fed into our home computers, teleconferencing, and a host of space and military applications of electrical communication. This book is concerned with the theory of systems for the conveyance of information. A *system* is a combination of circuits and devices put together to accomplish a desired result, such as the transmission of intelligence from one point to another. A characteristic of communication systems is the presence of uncertainty. This uncertainty is due in part to the inevitable presence in any system of unwanted signal perturbations, broadly referred to as *noise*, and in part to the unpredictable nature of information itself. Systems analysis in the presence of such uncertainty requires the use of probabilistic techniques.

Table 1.1 A Brief History of Communications

TIME PERIOD	YEAR	EVENT
	1826	Ohm's law
	1838	Samuel F. B. Morse demonstrates telegraph
80 years	1864	James C. Maxwell predicts electromagnetic radiation
	1876	Alexander Graham Bell patents the telephone
	1887	Heinrich Hertz verifies Maxwell's theory
	1897	Marconi patents a complete wireless telegraph system
	1904	Fleming invents the diode
	1906	Lee DeForest invents the triode amplifier
	1915	Bell System completes a transcontinental telephone line
40 years	1918	B. H. Armstrong perfects the superheterodyne radio receiver
	1920	J. R. Carson applies sampling to communications
	1937	Alec Reeves conceives pulse-code modulation (PCM)
	1938	Television broadcasting begins
	World War II	Radar and microwave systems are developed; statistical methods are applied to signal extraction problems
20 years	1948	The transistor is invented; Claude Shannon's "A Mathematical Theory of Communications" is published
	1950	Time-division multiplexing is applied to telephony
	1956	First transoceanic telephone cable
10 years	1960 to 1970	Laser demonstrated by Maiman (1960) First communication satellite, Telstar I, launched (1962) Live television coverage of moon exploration; experimental PCM systems; experimental laser communications; integrated circuits; digital signal processing; color TV
10 years	1970 to 1980	Commercial relay satellite communications (voice and digital); gigabit signaling rates; large-scale integration; integrated circuit realization of communications circuits; intercontinental computer communication nets; low-loss light fibers; off-the-shelf optical communication systems; packet-switched digital data systems

Noise has been an ever-present problem since the early days of electrical communication, but it was not until the 1940s that probabilistic systems-analysis procedures were used to analyze and optimize communication systems operating in its presence [Wiener 1949; Rice 1944, 1945].* It is also somewhat surprising that the unpredictable nature of information was not widely recognized until the publication of Claude Shannon's mathematical theory of communications [Shannon 1948] in the late 1940s. This work

* References in brackets [ ] refer to Historical References in the Bibliography.

was the beginning of the science of information theory, a topic that will be considered in some detail later.

A better appreciation of the accelerating pace at which electrical communication is developing can perhaps be gained by the historical outline of selected communications-related events given in Table 1.1.

With this brief introduction and history, we now look in more detail at the various components that make up a typical communication system.

1.1 THE BLOCK DIAGRAM OF A COMMUNICATION SYSTEM

Figure 1.1 shows a commonly used model for a communication system. Although it suggests a system for communication between two remotely located points, this block diagram is also applicable to remote sensing systems, such as radar or sonar, in which the system input and output may be located at the same site. Regardless of the particular application and configuration, all information transmission systems invariably involve three major subsystems—a transmitter, the channel, and a receiver. In this book we will usually be thinking in terms of systems for transfer of information between remotely located points. It is emphasized, however, that the techniques of systems analysis developed are not limited to such systems.

We will now discuss in more detail each functional element shown in Figure 1.1.

Input Transducer. The wide variety of possible sources of information results in many different forms for messages. Regardless of their exact form, however, messages may be categorized as *analog* or *digital*. The former may be modeled as functions of a continuous-time variable (for example, pressure, temperature, speech, music), whereas the latter consist of discrete symbols (for example, written text, punched holes in a computer card). Almost invariably, the message produced by a source must be converted by a transducer to a form suitable for the particular type of communication system

Figure 1.1 Block diagram of a communication system