Principles of Communications Systems, Modulation, and Noise

PRINCIPLES OF COMMUNICATIONS

Systems, Modulation, and Noise

Fourth Edition

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PREFACE

In the fourth edition of this book we have maintained the objectives of the previous three editions. For the past 20 years we have attempted to provide in a single book a relatively complete treatment on the principles of communications suitable for seniors and beginning graduate students in electrical engineering. In addition to topics in communications, sections have been included on signals, systems, probability, and random processes, so that all of the necessary background is included within the pages of a single book. This has worked well for undergraduates, for new graduate students who may have forgotten some of the fundamentals, and for the working engineer who may use the book as a reference or who may be taking a course after hours.

A significant feature of the fourth edition of *Principles of Communications* is the inclusion of a number of "computer exercises" at the end of each chapter. These exercises are designed to make use of a computer in order to illustrate the principles involved. They follow the end-of-chapter problems in a section marked by a computer symbol. There are a number of motivations for the inclusion of these problems. The computer is now accepted as a valuable tool in engineering education and is becoming integrated into engineering curricula. Computer usage allows students to work more complex problems and to gain important insights through the working of these problems. While these problems can all be worked by writing programs in FORTRAN, Pascal, or C, we strongly recommend the use of scientific problem-solving programs such as MATLAB®, Mathcad® and Mathematica® to name only a few. Through the use of these tools, the programming time for the student is significantly minimized. In addition, the graphing support provided by these tools allows the student to plot waveforms and performance characteristics with ease. We also feel that it is important for students to be familiar with these tools and to use them in their day-to-day problem solving efforts.

The past twenty years have seen many new applications for communication systems and a number of new technologies have been developed for the implementation of these systems. While there is always a strong desire to include a wide variety of new applications and technologies in a new edition of a book, we strongly feel that a first course in communications serves the student best if the emphasis is placed on fundamentals. We feel that applications and technologies, which often have short lifetimes, are best treated in subsequent courses after students have mastered the basic theory and analysis techniques. We have, however, been sensitive to new techniques that are fundamental in nature and have added material as appropriate. A new section on trellis-coded modulation is an example. Other new sections are discussed in later paragraphs. In addition, a number of new problems and in-chapter examples have been added. Several less-useful sections have been deleted, resulting in a fourth edition that is actually a few pages shorter than the previous edition.

In order to compare the fourth edition of this book with the previous edition, we briefly consider the changes chapter by chapter. In Chapter 1, the tables have been updated and a brief discussion on atmospheric characteristics has been added. Chapter 2, which is essentially a review of signal and system theory, has been tightened by deleting several examples that seemed superfluous and a brief discussion of the decimation-in time FFT algorithm has been added.

Chapter 3, which is devoted to basic modulation methods, has been significantly expanded. A number of examples have been added which illustrate the effect of modulation in the time domain. Students usually find it much easier to visualize the effect of modulation in the frequency domain than in the time domain and therefore a number of waveforms corresponding to different modulation techniques have been added. In addition, the effect of interference in linear and nonlinear modulation has been combined into a single section. This section has also been expanded to include a discussion on spike noise resulting from origin encirclement in FM systems due to signal-tone interference. An understanding of this simple deterministic process will significantly help the student understand the origin encirclement phenomenon in the presence of additive Gaussian noise in Chapter 5 and thresholding in FM systems, studied in Chapter 6.

Chapters 4 and 5, which deal with probability and stochastic processes, have changed little from previous editions of this book. The most significant change in Chapter 4 is the use of the probability Q-function rather than the error function, erf(x), to represent probabilities of events in a Gaussian environment. While this really represents only a notational change, it recognizes that the probability Q-function is now used extensively in communications engineering. In edition four, a table has been added that gives the most common probability density functions along with the means and variances of the random variables described by the density functions. Chapter 5 has been shortened slightly, and a short section has been added illustrating the determination of the system equivalent-noise bandwidth from the impulse response.

In Chapter 6, which treats the noise performance of various modulation schemes, the section on threshold extension has been rewritten so that the results are more general. The thresholding characteristics of an FM discriminator with a sinusoidal message signal are presented as a special case in an example problem.

Binary digital data transmission is the subject of Chapter 7. A new section has been added to this chapter dealing with fading channels. This is an important subject in today's world because of the rapidly expanding use of mobile communication systems. Chapter 8 treats more advanced topics in data communication systems including M-ary systems, bandwidth efficiency, synchronization, spread-spectrum systems and satellite links.

Chapter 9, which deals with optimum receivers and signal-space concepts is little changed from the previous edition. The chapter has been tightened, however, by deleting the topics of Weiner filtering and nonlinear estimation.

Chapter 10 provides the student with a brief introduction to the subjects of information theory and coding. As mentioned previously, an addition to this chapter is a brief discussion of the important subject of trellis-coded modulation, a very useful technique for the implementation of bandwidth and power efficient communication systems.

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 on signal and system theory have successfully taken the second course without the first. A previous course on signal and system theory also allows the material in Chapter 2 to be reviewed rather than covered in detail. Hence, more material from Chapter 3 can be covered; for example, the coverage of the phase-lock loop can be expanded. Similarly, a previous course on probability allows the material in Chapters 4 and 5 to be reviewed, thereby allowing more topics on communications to be covered.

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. A solutions manual is available from the publisher. This manual contains complete solutions to all odd-numbered problems and answers to all even-numbered problems. Partial solutions are given to even-numbered problems in those cases in which we felt that some extra guidance would be helpful. In addition, complete solutions to all computer exercises are given in the solutions manual.

We wish to thank the many persons who have contributed to the development of this textbook and who have suggested improvements for the fourth edition. We especially thank our colleagues and students at the University of

Colorado at Colorado Springs and at the University of Missouri-Rolla for their comments and suggestions. We also express our thanks to the many colleagues who have offered suggestions to us by correspondence or verbally at technical conferences. The industries and agencies that have supported our research deserve special mention since, by working on these projects, we have expanded our knowledge and insight significantly. These include the National Aeronautics and Space Administration, the Office of Naval Research, the National Science Foundation, GE Aerospace, Motorola, Inc., Emerson Electric Company, Battelle Memorial Institute, and the McDonnell Douglas Corporation.

We also thank the reviewers of all editions of this book. The reviewers for the fourth edition deserve special mention. They were:

Derald Cummings, Penn State
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Dr. Ronald Iltis, from the University of California at Santa Barbara, deserves special mention. He provided a very helpful checkout review by reading the entire manuscript in page-proof form. All reviewers have contributed significantly to the fourth edition of this book. All remaining shortcomings are solely the responsibility of the authors.

Our students have provided continuing encouragement for our writing projects, and 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 that they have shown throughout our seemingly endless writing projects.

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

PRINCIPLES OF COMMUNICATIONS

CONTENTS

INTRODUCTION 1

As we approach the close of the twentieth century, 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 in 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. The prosperity and continued development of modern nations will depend more on the originating and disseminating of *information,* rather than of manufactured goods. Examples illustrating that the value of information is often more than that of goods and services are provided by the fact that many portable computers are equipped with modems so that persons traveling on business are linked with their offices; by the number of motorists using cellular telephones in metropolitan areas; and by the fact that more and more mail transactions are now accomplished through computer, or electronic, mail.*

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.

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 sys-

* For more on this fascinating subject, see the *IEEE Communications Magazine,* Vol. 30, Oct. 1992 (special issue on "Realizing Global Communications").

tems 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 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). 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 employed. For example, in electrical communications, speech waves are converted by a microphone to voltage variations. Such a converted message is referred to as the *message signal*. In this book, therefore, a *signal* can be interpreted as the variation of a quantity, often a voltage or current, with time.

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

TABLE 1.1 A Brief History of Communications

Time Period	Year	Event
80 years	1826	Ohm's law
	1838	Samuel F. B. Morse demonstrates telegraph
	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
40 years	1904	Fleming invents the diode
	1906	Lee De Forest invents the triode amplifier
	1915	Bell System completes a transcontinental telephone line
	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
20 years	World War II	Radar and microwave systems are developed; statistical methods are applied to signal extraction problems
	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; time-shared computing
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; interplanetary grand tour launched (1977)—communications accomplished from Jupiter, Saturn, Uranus, and Neptune (encounter in August, 1989); microprocessor, computed tomography, and supercomputers developed
	1980	Satellite "switchboards in the sky"; mobile, cellular telephone systems; multifunction digital displays; 2 gigasample/s digital oscilloscopes; desktop publishing systems; programmable digital signal processors; digitally tuned receivers with autoscan;

(continued)

TABLE 1.1 *(continued)*

Time Period	Year	Event
10 years	to	cryptography on a chip; single-chip digital encoders and decoders; infrared data/control links; compact disk audio players; 200,000-word optical storage media; Ethernet developed; Bell system disbands, allowing competing long-haul telephone services;
	1990	digital signal processors developed
	1990's	Global positioning system (GPS) completed; high-definition television, very small antenna aperture satellites (VSATs), global satellite–based cellular telephones and integrated services digital network (ISDN) developed; personal communications systems come of age

Transmitter The purpose of the transmitter is to couple the message to the channel. Although it is not uncommon to find the input transducer directly coupled to the transmission medium, as for example in some intercom systems, it is often necessary to *modulate* a carrier wave with the signal from the input transducer. *Modulation* is the systematic variation of some attribute of the carrier, such as amplitude, phase, or frequency, in accordance with a function of the message signal. There are several reasons for using a carrier and modulating it. Important ones are (1) for ease of radiation, (2) to reduce noise and interference, (3) for channel assignment, (4) for multiplexing or transmission of several messages over a single channel, and (5) to overcome equipment limitations. Several of these reasons are self-explanatory; others, such as the second, will become more meaningful later.

In addition to modulation, other primary functions performed by the

FIGURE 1.1 Block diagram of a communication system