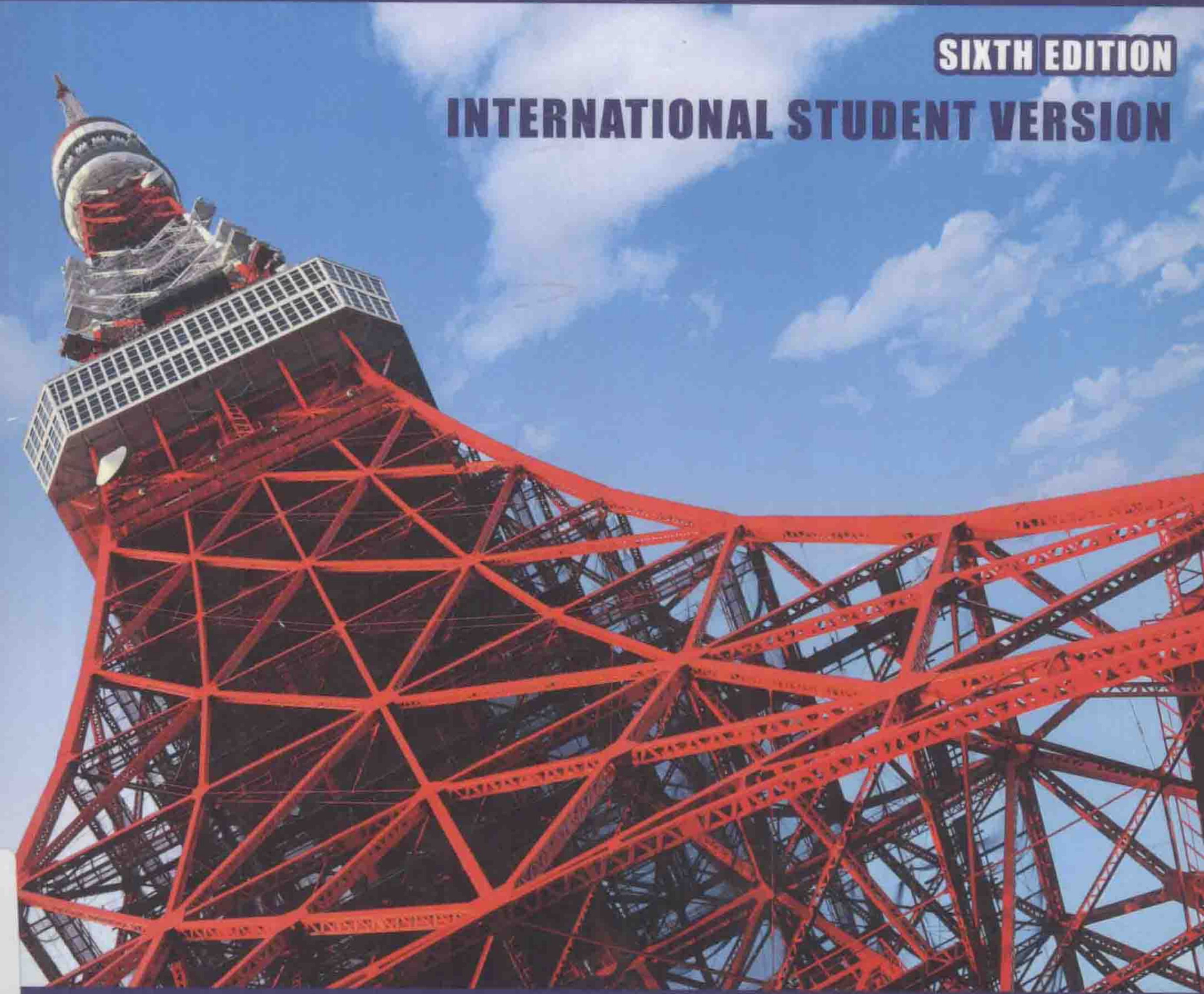
Principles of

COMMUNICATIONS

Systems, Modulation, and Noise

SIXTH EDITION

INTERNATIONAL STUDENT VERSION



RODGER E. ZIEMER • WILLIAM H. TRANTER

PRINCIPLES OF COMMUNICATIONS

Systems, Modulation, and Noise

SIXTH EDITION

INTERNATIONAL STUDENT VERSION

RODGER E. ZIEMER
University of Colorado at Colorado Springs

WILLIAM H. TRANTER
Virginia Polytechnic Institute and State University

WILEY

John Wiley & Sons, Inc.

ISBN: 978-0-470-39878-4

Printed in Asia

10 9 8 7 6 5 4 3 2

To our families.

Rodger Ziemer and Bill Tranter

PREFACE

As in previous editions, the objective of this book is to provide, in a single volume, a thorough treatment of the principles of communication systems, both analog and digital, at the physical layer. As with the previous five editions of this book, the sixth edition targets both senior-level and beginning graduate students in electrical and computer engineering. Although a previous course on signal and system theory would be useful to students using this book, an overview of this fundamental background material is included early in the book (Chapter 2). A significant change in the sixth edition is the addition of a new chapter (Chapter 4) covering the principles of baseband data transmission. Included in this new chapter are line codes, pulse shaping and intersymbol interference, zero-forcing equalization, eye diagrams, and basic ideas on symbol synchronization without the complicating factor of noise. Following overview chapters on probability and random processes (Chapters 5 and 6), the book turns to the central theme of characterizing the performance of both analog (Chapter 7) and digital (Chapters 8–11) communication systems in the presence of noise. Significant additions to the book include an expanded treatment of phase-locked loops, including steady-state tracking errors of first-order, second-order, and third-order loops, the derivation and comparative performances of M-ary digital modulation systems, an expanded treatment of equalization, and the relative bit error rate performance of BCH, Reed-Solomon, Golay, and convolutional codes. Each chapter contains a number of worked examples as well as several computer examples, a summary delineating the important points of the chapter, references, homework problems, and computer problems.

Enabled by rapid and continuing advances in microelectronics, the field of communications has seen many innovations since the first edition of this book was published in 1976. The cellular telephone is a ubiquitous example. Other examples include wireless networks, satellite communications including commercial telephone, television and radio, digital radio and television, and GPS systems, to name only a few. While there is always a strong desire to include a variety of new applications and technologies in a new edition of a book, we continue to believe that a first course in communications serves the student best if the emphasis is placed on fundamentals. We feel that application examples and specific 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. As examples, sections on currently important areas such as spread spectrum techniques, cellular communications, and orthogonal frequency-division multiplexing are provided. Reactions to previous editions have shown that emphasizing fundamentals, as opposed to specific technologies, serve the user well while keeping the length of the book reasonable. This strategy appears to have worked well for advanced 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 feature of the previous edition of *Principles of Communications* was the inclusion of several computer examples within each chapter. (MATLAB was chosen for these examples because of its widespread use in both academic and industrial settings, as well as for MATLAB's rich graphics library.) These computer examples, which range from programs for computing performance curves to simulation programs for certain types of communication systems and algorithms, allow the student to observe the behavior of more complex systems without the need for extensive computations. These examples also expose the student to modern computational tools for analysis and simulation in the context of communication systems. Even though we have limited the amount of this material in order to ensure that the character of the book is not changed, the number of computer examples has been increased for the sixth edition. In addition to the in-chapter computer examples, a number of "computer exercises" are included at the end of each chapter. The number of these has also been increased in the sixth edition. These exercises follow the end-of-chapter problems and are designed to make use of the computer in order to illustrate basic principles and to provide the student with additional insight. A number of new problems are included at the end of each chapter in addition to a number of problems that were revised from the previous edition.

The publisher maintains a web site from which the source code for all in-chapter computer examples may be downloaded. The URL is www.wiley.com/go/global/ziemer. We recommend that, although MATLAB code is included in the text, students download MATLAB code of interest from the publisher website. The code in the text is subject to printing and other types of errors and is included to give the student insight into the computational techniques used for the illustrative examples. In addition, the MATLAB code on the publisher website is periodically updated as need justifies. This web site also contains complete solutions for the end-of-chapter problems and computer exercises. (The solutions manual is password protected and is intended only for course instructors.)

In order to compare the sixth edition of this book with the previous edition, we briefly consider the changes chapter by chapter.

In Chapter 1, the tables have been updated. In particular Table 1.1, which identifies major developments in communications, includes advances since the last edition of this book was published. The role of the ITU and the FCC for allocating spectrum has been reworked. References to turbo codes and to LDPC codes are now included.

Chapter 2, which is essentially a review of signal and system theory, remains basically unchanged. However, several examples have been changed and two new examples have been added. The material on complex envelopes has been clarified.

Chapter 3, which is devoted to basic modulation techniques, makes use of complex envelope notation in the presentation of frequency modulation in order to build upon the ideas presented in Chapter 2. In addition, Chapter 3 has been expanded to include significantly more material on phase-locked loops operating in both the acquisition and tracking modes. The phase-locked loop is a key building block of many communication system components including frequency and phase demodulators, digital demodulators, and carrier and symbol synchronizers.

Chapter 4, which is a new chapter for the sixth edition, covers basic digital transmission techniques including line codes, pulse shaping and filtering, intersymbol interference, equalization, eye diagrams, and basic synchronization techniques. Covering this material early in the book allows the student to appreciate the differences between analog and digital transmission techniques. This material is also presented without considering the complicating effects of noise.

Chapters 5 and 6, which deal with basic probability theory and random processes, have not been significantly changed from the previous edition. Some of the material has been rearranged to increase clarity and readability.

Chapter 7 treats the noise performance of various analog modulation schemes and also contains a brief discussion of pulse-code modulation. The introduction to this chapter has been expanded to reflect the importance of noise and the sources of noise. This also serves to better place Appendix A in context. In addition, this material has been reorganized so that it flows better and is easier for the student to follow.

Binary digital data transmission in the presence of noise is the subject of Chapter 8. A section on the noise performance of M-ary PAM systems has been added. The material dealing with the noise performance of zero-ISI systems has been expanded as well as the material on equalization. An example has been added which compares various digital transmission schemes.

Chapter 9 treats more advanced topics in data communication systems including M-ary systems, synchronization, spread-spectrum systems, multicarrier modulation and OFDM, satellite links, and cellular radio communications. Derivations are now provided for the error probability of M-ary QAM and NCFSK. A figure comparing PSK, DPSK, and QAM has been added as well as a figure comparing CFSK and NCFSK. The derivation of the power density for quadrature modulation schemes has been expanded as well as the material on synchronization. The treatment of multicarrier modulation has also been expanded and information on 3G cellular has been added.

Chapter 10, which deals with optimum receivers and signal-space concepts, is little changed from the previous edition.

Chapter 11 provides the student with a brief introduction to the subjects of information theory and coding. Our goal at the level of this book is not to provide an in-depth treatment of information and coding but to give the student an appreciation of how the concepts of information theory can be used to evaluate the performance of systems and how the concepts of coding theory can be used to mitigate the degrading effects of noise in communication systems. To this end we have expanded the computer examples to illustrate the performance of BCH codes, the Golay code, and convolutional codes in the presence of noise.

We have used this text for various types of courses for a number of years. This book was originally developed for a two-semester course sequence, with the first course covering basic background material on linear systems and noiseless modulation (Chapters 1–4) and the second covering noise effects on analog and digital modulation systems (Chapters 7–11). With a previous background by the students in linear systems and probability theory, we know of several instances where the book has been used for a one-semester course on analog and digital communication system analysis in noise. While probably challenging for all but the best students, this nevertheless gives an option that will get students exposed to modulation system performance in noise in one semester. In short, we feel that it is presumptuous for us to tell instructors using the book what material to cover and in what order. Suffice it to say we feel that there is more than enough material included in the book to satisfy almost any course design at the senior or beginning graduate levels.

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

University of Science and Technology, and Virginia Tech for their comments and suggestions. The help of Dr. William Ebel at St. Louis University is especially acknowledged. We also express our thanks to the many colleagues who have offered suggestions to us by correspondence or verbally. The industries and agencies that have supported our research deserve special mention since, by working with them on various 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, DARPA, Raytheon, and the LGIC Corporation. The expert support of Cyndy Graham, who worked through many of the LaTeX-related problems and who contributed significantly to the development of the solutions manual is gratefully acknowledged.

We also thank the reviewers of this and all previous editions of this book. The reviewers for the sixth edition deserve special thanks for their help and guidance. They were:

Larry Milstein, University of California – San Diego

Behnam Kamali, Mercer University

Yao Ma, Iowa State University

Michael Honig, Northwestern University

Emad Ebbini, University of Minnesota

All reviewers, past and present, contributed significantly to this book. They caught many errors and made many valuable suggestions. The authors accept full responsibility for any remaining errors or shortcomings.

Finally, our families deserve much more than a simple thanks for the patience and support that they have given us throughout more than thirty years of seemingly endless writing projects. It is to them that this book is dedicated.

Rodger E. Ziemer
William H. Tranter

CONTENTS

CHAPTER 1

OVERVIEW AND HISTORICAL PERSPECTIVES

We are said to live in an era called the intangible economy, driven not by the physical flow of material goods but rather by the flow of information. If we are thinking about making a major purchase, for example, chances are we will gather information about the product by an Internet search. Such information gathering is made feasible by virtually instantaneous access to a myriad of facts about the product, thereby making our selection of a particular brand more informed. When one considers the technological developments that make such instantaneous information access possible, two main ingredients surface: a reliable, fast means of communication and a means of storing the information for ready access, sometimes referred to as the *convergence* of communications and computing.

This book is concerned with the theory of systems for the conveyance of information. A *system* is a combination of circuits and/or devices that is assembled to accomplish a desired task, such as the transmission of intelligence from one point to another. Many means for the transmission of information have been used down through the ages ranging from the use of sunlight reflected from mirrors by the Romans to our modern era of electrical communications that began with the invention of the telegraph in the 1800s. It almost goes without saying that we are concerned about the theory of systems for *electrical* communications in this book.

A characteristic of electrical 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 systems operating in its presence (Wiener, 1949; Rice 1944, 1945).[1] 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.

Major historical facts related to the development of electrical communications are given in Table 1.1.

[1]Refer to Historical References in the Bibliography.