Digital Communication Techniques

Signal Design and Detection

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Dedication

Marvin K. Simon would like to dedicate this book to his wife Anita in appreciation for her consultation at every step of the way through the preparation of this manuscript. Indeed this author could have never completed his portion of this book nor for that matter any of his previous books without the support, encouragement, guidance, and sharing in the many anxieties that accompany a project of this magnitude. This book is also dedicated to his children Brette and Jeff who have made him very proud through their development and accomplishments both as human beings and in their respective fields of interest.

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William C. Lindsey would like to dedicate this book to Dorothy, my wife, and to John, my son, for the support system they have provided me throughout by professional career. Also, to Corinne Leslie, my secretary for 27 years, for her loyal, continuous, and dedicated support; and to my sisters, Loretta and Jean for their lifelong inspiration and encouragement.

Preface

Future applications of **Digital Communication Techniques** to architecting and implementing global information transportation and computing systems have never been brighter. This outlook is driven by social, economical, political, and technological reasons. From a technical perspective, it is recognized by most communication engineers that communications is required to accomplish computing while computers are required to accomplish communications. From a technology viewpoint, this technical perspective is rapidly being accomplished using emerging digital microelectronic technologies (DSP and VLSI) to implement digital communication systems.

Digital Communication Techniques are exciting and are of vital importance to all societies. Countries have failed to be competitive simply because they did not succeed in establishing good communication infrastructures. Consequently, one major purpose of this textbook is to present, in a unique and innovative way, a functional architecture and a theory for use in the design of uncoded and coded digital communication systems. The system architecture is pyramidal and the theoretical development is unique in that it is presented, for the first time, from a **Systems Engineering** perspective for both bandlimited and power limited communication channels. This perspective adopts the point of view that **coding** and **modulation** are both components of the **signal design** problem and that **demodulation** and **decoding** are both components of the **signal detection** problem. Beginning with Chapter 1, the subject matter progresses top down and systematically in a hierarchial way. The geometric concepts, first introduced by Shannon and Kotelnikov, and later documented by Wozencraft and Jacobs in their book *Principles of Communication Engineering*, are used in Chapter 3 to set the foundations for signal design and detection. Starting with Chapter 4 and ending in Chapter 8, **coherent, noncoherent, partially coherent, and differentially coherent** detection techniques are treated for numerous uncoded modulation techniques, such as BPSK, QPSK, MPSK, and MFSK. In Chapter 10, these same detection techniques are applied to more advanced forms of uncoded modulation such as QAM, CPFSK, MSK, QFPM, and CPQFPM. As opposed to the M-ary error probability criterion used in designing uncoded systems, the R_0-criterion is introduced for use in optimizing the design of coded systems. Since R_0 is a function of the codec and modem choice, this criterion leads to a combined codec-modem design that employs the most effective coding and modulation technique. In fact, soft-decision demodulators can be systematically designed using R_0. Chapters 11, 12, and 13 consider **block**, **convolutional**, and **concatenated coding** techniques from the systems perspective. In addition, the counterparts of maximum-likelihood (ML) decoding and ML decoding using the Viterbi algorithm are given. A variety of **interleaving-deinterleaving** techniques (block, convolutional, helical, hybrid) are presented. To understand the connection among the various coding techniques presented, a Venn diagram for error correcting codes is constructed; emphasis is placed on presenting the communciations efficiency achieved using **Hamming, Golay, Bose-Chaudhuri-Hocquenghem (BCH), Reed Solomon (RS),** and **convolutional** codes.

There are a vast number of textbooks on the market today that deal with the subject of digital communications. In fact, in a quick survey of the textbook literature, we were able to come up with at least ten books that *include* the words "digital communications" in their titles. At least three bear these words as their *entire* title implying, somewhat, that they are an all-inclusive treatment of the subject. Many of these books are quite broad in scope, but also quite shallow in detail. Striking a proper balance between these two attributes, yet maintaining a high level of readability, is no simple task. We believe that our book accomplishes this important goal and sets it apart from all other digital communication texts currently on the market. Several key features that distinguish our book from the others are as follows:

- A top-down perspective of digital communication system design, using a pyramid structure to describe the system functional architecture.
- A top-down presentation of the theory needed to perform uncoded and coded system design.
- Includes R_0 criterion for use in the design of coded systems.
- Includes more recent developments in the field that have occurred over the last 20 or 30 years.
- A universal appeal to graduate students as well as system architects and engineers.
- Written by authors whose combined industrial and university experience exceeds 60 years.

There are many specific features that make this book unique and beneficial to its readers. With the advent of today's advances in the solid state microelectronic technologies, a variety of novel digital communication systems are appearing on the market and are serving as motivation for the introduction of new telecommunication and information services. Chapter 1 of this book provides the reader with examples of such services and top level system architectures thereby indicating the highly complex nature of these systems. We believe that Chapter 2, which discusses the computation of power spectral density of digital modulations, is the best treatment of spectrum efficiency evaluation found anywhere. This computation is essential to assessing the bandwidth (spectral) occupancy requirement of a digital modulation, yet it is ignored in many books. Another key feature of this book is the organization and order of presentation of the material in Chapters 3 through 7. By first describing coherent detection and then successively following with noncoherent, partially coherent, and differentially coherent detection, the reader is provided with a logical flow starting with the conceptually simplest technique and proceeding top down to the more complex techniques. The discussion of double differentially coherent detection in Chapter 8 is unique to our book.[1] Here the reader will learn how to design differentially coherent communication systems that are robust to frequency offsets due, for example, to Doppler and oscillator instabilities. Chapter 9 treats the voluminous subject of bandlimited communications in a condensed and unified way. Included here are the important subjects of Nyquist

1. There are a few Russian-authored textbooks that discuss double differentially coherent detection, but as yet, they have not been translated into English.

and partial response signaling, maximum-likelihood detection in the presence of intersymbol interference, and equalization. To the authors' knowledge, Chapter 10 of this book is the most complete and up-to-date treatment of advanced modulation techniques. It guides the reader through the most recent modulation techniques described in the literature and how they compare in terms of such properties as modulation type, pulse shaping, continuity of phase, variation of envelope, I and Q channel data rates, and parameter offsets. Still another key feature is the proper identification of the important link (mapping function) between the modulation and coding functions in coded digital communication systems. Most books that discuss both modulation and coding treat these two functions as separate and independent entities. In some books where modulation and coding are treated as combined, the treatment is strictly limited to trellis coded modulation. This book is unique in that it presents a general formulation for coded communication systems by properly defining the key parameters and interfaces between the various modulation and coding functions. This discussion is presented in Chapter 11 which includes many examples to clearly elucidate this often overlooked but all important aspect of system design. Chapter 12 discusses the use of the R_0 criterion in the design of coded systems. Finally, Chapter 13 presents a compact yet authoritative discussion of the design of convolutionally-coded communication systems, a subject that, by itself, can occupy an entire textbook.

We recognize that a complete study of reliable and efficient communication of information requires a full and detailed treatment of the two important disciplines: information theory and communication theory. Since the main focus in this book is on the latter, we do not treat the problem of efficient packaging of information (data compression of text, voice, video, etc.) nor do we treat the important problem of designing the ultimate error control coding-decoding technique which achieves the ultimate transmission speed (channel capacity). The solution to these problems are best treated in separate books on information theory and error control coding, and, indeed, there are such books available.

This book has been written for use as a textbook at universities involved in teaching Communication Sciences. It has also been designed to accommodate certain needs of the systems architect, systems engineer, the professor, and communication sciences researcher. The lecture material has been organized and written in a form whereby theory and practice are continuously emphasized. Most of the problems suggested at the conclusion of each chapter have evolved from teaching graduate level courses to students at the University of Southern California and the California Institute of Technology. Through homework assignments, most of the problems have been field tested, corrected, and enhanced over the years.

The architecture for this book is predicated upon two graduate level Communication Theory courses (EE564 and EE664) taught at the University of Southern California's Communication Sciences Institute over the past 25 years. In this sense, two semesters are required to cover its contents. The organization and presentation of the material is largely based upon the academic and course design work of Professors William C. Lindsey and Robert A. Scholtz. The authors' approach to presenting the solution to the problem of vector communications in the presence of colored noise and the representation of bandpass random processes are largely due to Professor Scholtz. The Digital Communication System architecture presented in the pyramids of Chapter 1 was created by Professor Lindsey. In addition, certain exercises given in and at the conclusion of Chapters 1, 3, 4, 5, and 6 were taken with permission from problems created and used by Professors Robert M. Gagliardi, Vijay Kumar, William C. Lindsey, Andreas Polydoros, Charles L. Weber, and Robert A. Scholtz all of the University of Southern California's Communication Sciences Institute. The authors wish to thank these individuals for permission to use these challenging problems as homework exercises.

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