CHAPTER 1

INTRODUCTION

1.1 WHY THIS BOOK?

This book is intended for practicing engineers in the digital communication field. It can be used as a textbook for master's level courses (e.g., for part-time professional education programs) or self-study. As such, the book has some unique characteristics comparing a typical textbook on the same subject.

A typical textbook strives to provide comprehensive and pedagogically sophisticated coverage of the concepts and theories. Such treatment makes it easier for the students to grasp key knowledge points. However, practicing engineers already have good general engineering knowledge and powerful self-learning skills. They need information sources that can be digested quickly. This book selects concepts and technologies that are most relevant to today's communication systems and presents them concisely and intuitively.

Instead of becoming well-versed in the entire field of digital communications, practicing engineers are more interested in getting knowledge on the specific subfields of their work. This book is organized as self-contained chapters. One can choose to read one or several relevant chapters, instead of the entire book.

Practicing engineers are more interested in applying existing techniques to their particular problems, rather than inventing new techniques. This book focuses on the pros and cons of broadly used techniques, rather than detailed mathematical analyses that may lead to discoveries. For example, on adaptive filtering, this book discusses in detail the tradeoff between performance and complexity of various methods and the tradeoff between convergence speed and final accuracy based on parameter choices.

Advanced topics such as orthogonal frequency division multiplexing (OFDM) and multiple-input multiple-output (MIMO), which are enabling technologies for modern communication systems such as WiFi and LTE-Advanced, are covered in more detail than usual (Chapters 10 and 11). This book also briefly describes other emerging technologies, some of which are adopted in the 5G cellular standards. These contents help practicing engineers follow the current technology trend.

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This book also covers some contents that are usually out of scope for textbooks, such as cyclostationary symbol timing recovery (Chapter 7), adaptive self-interference canceller (Chapter 8), and Tomlinson–Harashima precoder (Chapter 9). These techniques are used in many popular communications systems and are therefore useful to practicing engineers.

In addition to practicing engineers, regular students of digital communications can benefit from this book's unique perspective and treatment, by using it as a primary or supplementary textbook.

1.2 HOW TO USE THIS BOOK

A textbook typically strikes a balance between details and suspense. Omitting some details in derivation and leaving some open questions help to keep the readers engaged and inspired. On the other hand, narrative gaps increase the difficulty in understanding. Since its targeted readers are likely to be self-studying without professors or peers available to answer questions, this book biases to providing more details and leaving fewer gaps. Some of the homework problems provide leads for further exploration and contemplation.

Another balance is between conceptual discourses and mathematical details. Since the book is designed for self-study, it is important to provide detailed derivations to important conclusions. On the other hand, these derivations may distract the readers from the thread of concept development. To address this concern, we mark the important mathematical results with solid-line frames. The readers may focus on the text and framed equations in the first pass. Detailed derivations contained in other equations can be revisited once the conceptual landscape is understood.

This book is based on the author's experience of teaching "Advanced Digital Communication Systems" at the master's level. In general, the material in each chapter is suitable for one 3-hour lecture. The exceptions are Chapters 5 and 9, which are suitable for two lectures each. Overall, this book is suitable for a master's level course of one semester, while some homework problems can be used as class projects.

1.3 SCOPE

1.3.1 The Physical Layer Transceiver

The prevailing Open Systems Interconnection (OSI) model divides a system into seven layers [1]. This book focuses on layer 1, known as the *physical layer*, or the PHY layer.

The PHY layer functions as a "bit pipe" of the system. A PHY transmitter takes bits from the upper layers and sends them through the physical medium (copper wire, fiber optics, electromagnetic waves, etc.) to the receiver. A PHY receiver recovers the bits and passes them to the upper layers. A *transceiver* is a combination of a transmitter and a receiver. The PHY layer is about point-to-point or point-to-multipoint (in the

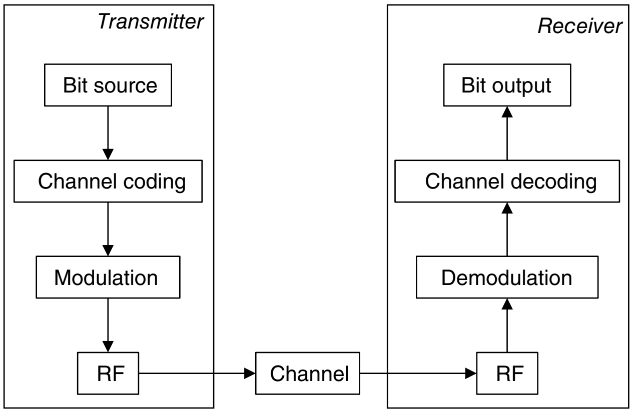

Figure 1.1 Physical layer architecture.

case of broadcast) connections, as opposed to a multi-hop network, which is the concern of the upper layers. The PHY layer transports bits from a transmitter to a receiver with a controlled error probability. The upper layers may perform other functionalities (such as retransmission) to achieve virtually error-free communication.

Figure 1.1 shows the general physical layer architecture of a transmitter/receiver pair. The “Bit Source” block at the transmitter side and the “Bit Output” block at the receiver side are interfaces to the upper layers. At the transmitter side, channel coding is applied to the data bits (Chapter 5) to enhance protection against random errors. Modulation is then performed to convert the bits into signals (i.e., time-varying voltages) (Chapter 3). The signal is then conditioned in various steps and transmitted through the physical medium, known as the channel (Chapters 3 and 4). At the receiver side, the signal is conditioned and demodulated to recover the encoded bits (Chapters 4, 8, and 9). Channel decoding is then performed to recover the data bits (Chapter 5), which is then passed to the upper layer. Chapters 10 and 11 cover more advanced modulation and demodulation techniques.

1.3.2 Prerequisites

This book is for master’s level study. It assumes the readers have some training in electrical engineering and beginning digital communications [2]. For example, the readers should have basic knowledge about filters, shift registers, antennas, etc.

As to mathematics, the readers should have knowledge on statistics (Gaussian distribution and the Bayes’ theorem), calculus, basic differential equations, linear algebra (especially eigenanalysis and singular value decomposition), and Fourier transform. Some mathematics topics are included in the appendices of the relevant chapters. Notably, Chapter 3 includes the formulation of the Fourier transform, which is also used in other chapters. These appendices intend to clarify conventions and notations, rather than teaching the knowledge from scratch. On the other hand, the required mathematics concepts and properties are very limited in this book. Readers can fill potential knowledge gaps by consulting other textbooks or online tutorials.

1.3.3 Topics Not Covered

This book focuses on advanced and practical topics in digital communications. Some topics such as analog modulation techniques and noncoherent detections are usually covered in the prerequisite courses [2] and are not repeated in this book. While covering basic concepts and techniques of digital communications, the book focuses on the mainstream commercial applications such as mobile cellular systems and wireless local area network (WLAN). Special applications such as underwater communications, satellite communications, military communications, and optical communications are not covered in this book.

This book is on point-to-point communications, that is, a single transmitter–receiver pair. The issue of access, that is, multiple users sharing a medium in coordinated or uncoordinated ways, is only briefly addressed in Chapters 10–13. Since the scope is limited to the PHY-layer, protocols and networking issues are not discussed.

Some of the uncovered topics are briefly discussed in Chapter 13.

1.4 ROADMAP

The book can be roughly divided into four parts.

The first part covers the basic techniques. It starts with Chapter 2, which introduces the foundation of modern digital communication theories: the Shannon theorem. In addition to guiding the development of channel coding, the Shannon theorem also provides some valuable insights into the practical case of white noise channels. Chapter 3 covers several techniques involved in the modulation process, which converts bits to symbols. These techniques include modulation, pulse shaping, and up-converting. They are based on various interesting mathematical concepts discussed in the chapter. Chapter 4 discusses the reverse process, that is, converting received symbols to bits. The chapter focuses on optimal demodulation theories and analyses of error probability. A detailed study of the additive white Gaussian noise (AWGN) channel and various expressions of the signal-to-noise ratio (SNR) is included. We then move on to channel coding in Chapter 5. Channel coding is a technique to improve noise immunity and to ultimately achieve the channel capacity predicted by the Shannon theorem. This book does not provide details on channel code designs and performance evaluations. It only outlines the basic concepts and decoding methodologies of common code types and qualitatively compares the various codes.

The second part continues with more practical matters. Chapter 6 discusses various properties of propagation channels beyond the AWGN. It lays the ground for further discussion of the various receiver techniques that take the channel characteristics into account. This chapter also discusses link budget computation, which is a critical part of the process of system requirement development. Chapter 7 discusses a practical concern: synchronization between the transmitters and receivers. Two issues are addressed in this chapter: how to estimate timing errors and how to correct them. It also points out that the methods of synchronization depend on the magnitude and dynamics of the original timing errors. The next two chapters describe channel equalization, which is a required processing technique for dispersive channels. Chapter 8 provides a general discussion of adaptive filters, which is the basis for equalizers. The chapter also discusses full-duplex radios with self-interference cancellation as another application of the adaptive filters. Chapter 9 describes linear equalizers and decision feedback equalizers, including their structures, training methods, and expected performances.

Chapters 10 and 11 constitute the third part of the book. These two chapters cover the two advanced modulation techniques developed in the 1990s: orthogonal frequency division multiplexing (OFDM) and multiple-in multiple-out (MIMO). These two techniques build onto the basic techniques discussed in part one, with additional gains in performance and simplicity.

The last part of the book provides an overview of the emerging technologies in digital communications. Chapter 12 introduces the 5G cellular technologies currently being developed. The chapter starts with a general overview of the cellular concept and history, as well as the current status of the 5G cellular standard. It then outlines three emerging technologies used in the 3GPP 5G proposal: massive MIMO, millimeter wave communications, and nonorthogonal multiple access. Chapter 13 further outlines several uncovered topics, most of which are current research areas.

The chapters are designed to be self-contained, so that a reader can quickly access a specific topic of interest, instead of reading the entire book. When contents in other chapters are used, explicit cross-references are provided. Each chapter starts with an introduction stating the scope and roadmap, as well as a summary outlining the main points. Figure 1.1 is used in most chapters to orient the readers relative to the overall physical layer architecture. For the sake of narrative flow, nonessential contents are often collected into footnotes and appendices.

1.5 OTHER NOTES

This section contains some notes that are helpful in using this book.

1.5.1 Mathematical Notation

This book follows the common mathematical conventions, with the following particular choices.

- In sections that involve linear algebra, vectors are expressed in boldface lowercase letters, matrices in capital letters, and scalars in normal style lowercase letters. I, in the context of matrix expressions, represents an identity matrix. I_N is an identity matrix of dimension N by N. When there is no confusion, "0" may express a vector or a matrix whose components are all zero.

- Identity matrices may be omitted. For example, if A is a matrix and α is a scalar, then $A + \alpha$ means $A + \alpha I$.
- Letters I to N, both upper case and lowercase, are reserved for integers.
- Exceptions to these practices include traditional electrical engineering notations, such as N_0 for noise power spectrum density, n for noise, j for $\sqrt{-1}$, E_s for total transmit power, t for time, ω for angular frequency, f for frequency, etc.
- $(\cdot)^H$ denotes matrix Hermitian operation. $(\cdot)^T$ denotes transposition operation. $(\cdot)^*$ denotes complex conjugate operation.
- $E(\cdot)$ denotes expectation value.
- $\exp(x)$ is used interchangeably with e^x.
- For summations, we typically use lowercase letters i to n for the summing indices and the corresponding uppercase letters for limits. When the limits are not given explicitly, they are either clear in the context or infinity. If a limit exceeds the range of the summed sequence, the undefined terms are considered as zero. Similar conventions apply to product notations and integrals.
- Notation $\{a_k, k = 1, \ldots, K\}$ denotes the set of a_k, where integer k is in the range of 1 to K. The second part is often omitted when the index range is clear in the context.
- When Fourier transform is involved, the tilde sign is used to indicate the Fourier transform of a function. For example, $\tilde{f}(\omega)$ is the Fourier transform of $f(t)$.
- Following the traditions in electrical engineering, a dimensionless quantity (such as a ratio) can be expressed linearly and in dB, as indicated by the context.

As an engineering textbook, we intentionally overlook some requirements on the rigor of mathematical treatments. For example, we assume all relevant functions are integrable. We also assume all relevant stochastic variables have well-defined probability density functions (pdf).

Mathematical symbols are used consistently within a chapter. Namely, the same symbol always represents the same quantity. However, a symbol may have different meanings in different chapters. Symbols are defined when first used. Such a definition is sometimes repeated later for easy reference.

All equations are numbered for the ease of cross-referencing. Equations representing significant results instead of intermediate steps are marked with shaded boxes.

1.5.2 References

Reference citations in this book are included to provide a historical perspective of the subject, to support statements made in the book without derivation, and to provide leads for further exploration. For the last purpose, newly published papers are preferred, as their introduction sections usually provide an overview of the state-of-the-art with references to the seminal works. When the same content can be found from multiple sources, those available online are preferred.

For current research activities, we often cite review papers published on the *IEEE Communications Surveys & Tutorials*. These papers are not necessarily insightful by themselves. However, they contain an extensive collection of annotated references serving as good starting points for further studies. Special issues of the various IEEE journals are also a good source for overview information. While the collection of papers in a special issue may not reflect the holistic picture of the research field, the combination of their introductions usually provides complete coverage.

Note that some citations (e.g., online articles, technical reports, preprints posted on arxiv.org, and patents) were not peer reviewed. Verification of the derivation and simulation is recommended before adopting the conclusions of these references.

1.5.3 Homework

Practicing engineers typically learn and work at the same time; they do not have much time for homework and practices. On the other hand, they are engaged in work activities related to the knowledge to learn. For this reason, this book contains only a few homework problems for each chapter. The readers are expected to reinforce and evaluate their learning through daily work instead of homework. Therefore, homework problems are more explorative than evaluative.

In addition to the homework, the readers are encouraged to try to reproduce the various simulation results provided in the book. Such exercise ensures that the readers understand the algorithmic details.

1.5.4 Simulation

This book provides quantitative examples through simulations. All simulation plots are generated with MATLAB version R2017a. Some key functions for simulation are mentioned in the text. Parameters used in the simulations are usually stated so that the plots can be reproduced by the readers.

1.5.5 Acronyms

All acronyms are spelled out when first used in a chapter, except for some common terms in electrical engineering such as SNR (signal-to-noise ratio).

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