Synchronization in Digital Communication Systems

Do you need to know how to develop more efficient digital communication systems? Based on the author's experience of over 30 years in industrial design, this practical guide provides detailed coverage of synchronization subsystems and their relationship with other system components. You will gain a comprehensive understanding of the techniques needed for the design, performance analysis, and implementation of synchronization functions for a range of different modern communication technologies. Specific topics covered include frequency-locked loops in wireless receivers, optimal OFDM timing phase determination and implementation, and interpolation filter design and analysis in digital resamplers. Numerous implementation examples help you develop the necessary practical skills, and slides summarizing key concepts accompany the book online. This is an invaluable guide and essential reference for both practicing engineers and graduate students working in digital communications.

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To my wife, Xiaoyun Ma, and our daughter, Jing

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Foreword

Synchronization is an integral part of any digital communication system that transmits digital information through a communication channel. It is such an important component in the design and implementation of a communication system that numerous books have been written on this subject since the beginning of the digital information era, which now spans over 60 years. As communication system developments have evolved over these past 60 years, especially in the design and implementation of new modulation/demodulation techniques that achieve ever greater transmission rates in wireless communication channels, new synchronization techniques have also been developed to satisfy the more demanding system requirements.

This book provides a novel treatment of synchronization techniques for the design of modern digital communication systems, especially code division multiple access (CDMA) and orthogonal frequency-division multiplexing (OFDM) wireless systems. Included in the book are thorough descriptions on key topics, namely, the design and implementation of methods for initial acquisition of various transmitted signal types, the design and implementation of digital phase-locked loops (PLLs), and the integration of PLLs in synchronization circuits and algorithms for carrier phase recovery and tracking, as well as in circuits and algorithms for obtaining symbol timing and tracking. Also treated in detail is the topic of resampling/rate conversion methods, which are widely used in performing timing phase adjustments in nearly all modern receivers for digital communication systems.

The book is intended for engineers and related technical professionals who wish to acquire in-depth knowledge and understanding of state-of-the-art techniques in the design and implementation of synchronization for modern digital communication systems.

The author of this book has a wealth of hands-on industrial experience in the design and implementation of wireless digital communication systems. His career in the telecommunications industry has spanned over 30 years. The synchronization techniques that are described in this book embody his contributions and those of a number of his colleagues working in this field.

John Proakis

Preface

Synchronization functions are among the most important and critical components of digital communication systems. During my career of over 30 years working in the technical field of digital communications, my fellow engineers and I often spent more time on designing, debugging, and testing the receiver blocks that are related to synchronization than on any other functional blocks. This is especially true in the later stages of system and modem development, such as in the testing the prototypes in the field of real systems.

The reason for the importance and the difficulty of the implementation and debugging the synchronization functions is that they more directly interact with the real-world channel conditions than other receiver functional blocks. For example, in CDMA and OFDM system design and development projects in which I had participated, the most difficult receiver functions, on which engineers spend most of their time, were always related to synchronization.

The main objective of this book is to provide a general treatment of the key synchronization functions in one single resource that is easy to access. Although synchronization is included in almost every textbook on digital communications, this subject is usually treated at a high level and important design details are left out. This is due to page limitation constraints of these books that focus on the many general topics of digital communication systems. Indeed, synchronization functions are well covered in the literature; however, most are published as journal and conference papers that treat their implementation and analysis for specific communication systems. It is difficult to obtain a unified and comprehensive view on this topic from the papers scattered in many different publications. This book supplements the textbooks and scholarly papers by treating synchronization functions, from their theoretical foundations to their analyses, designs, and implementation.

The fundamental theories pertinent to the basics of synchronization are covered in this book because they are important to engineers and researchers in their practice. Similar to other elements of a digital communication system, synchronization has a well-developed theoretical foundation. Even though today's computers are capable of performing efficient simulation studies of various aspects of synchronization, analytical tools can always provide more insight into issues of optimality and other properties of interest. At the same time, the scope of the book is also limited to stating the results and leaving the lengthy proofs to the cited references for the readers.

Any theory is only as accurate as the model on which it is based. Due to the diverse applications of synchronization in different communications systems and their interactions with various environments, it is not possible to establish a single or even a few such models. As all engineers know, approximation is a fact of life. Therefore, this book tries to strike a balance between theoretical and empirical treatments. In addition to establishing a solid theoretical foundation, there are also many practical aspects that need to be considered and some approximations that need to be made. Such practical considerations and approximations are described in various chapters of this book, and we have made sure that these approximations and considerations are consistent with established theories.

This book is also intended to fill the gaps of other books in the same technical area published before the late 1990s. Due to the widespread applications of digital communications, especially wireless communications, synchronization technologies also experienced rapid development. Besides the basic theories and general descriptions, most of the examples given in this book are in the context of communication systems in deployment today, including CDMA and OFDM wireless communication systems. Even though these examples are mainly related to third- and fourth-generation wireless systems, the principles and implementations described are also applicable to the future generation of the communication systems that employ the same basic technologies.

Another objective of this book is to share my experiences gained during working in the communications industry for over 30 years with young engineers and researchers. The implementation details of various algorithms and functional blocks are provided in the examples given in the chapters. However, because conditions vary and environments change for different applications, what is described is only intended as references for the readers to approach their problems at hand rather than universal solutions.

The primary readership of this book is engineers, researchers, and graduate students working on digital communication–related projects in industry and academia. This book is intended for their self-study or as a reference book for them. It can also be used as supplemental materials in graduate-level digital communication courses and a textbook in short courses on synchronization. The readers should have an understanding of undergraduate-level digital signal processing, digital communications, and linear system theories. Knowledge of probability and detection and estimation theories is helpful but not necessary.

This book is written with physical layer system engineers/researchers in mind. However, due to the many implementation details described in various examples, it may also be of interest to hardware, software. and firmware engineers working on related projects.

This book is organized as follows:

Chapter 1 provides an overview of how digital communications systems work. The main components of a communication link, including the transmitter, the channel and the receiver, and their typical operations, are presented. Because a significant portion of this book is about synchronization in DS-CDMA and OFDM communications systems, brief reviews of these two communication technologies are given. More specifically, the components and operations of these two communication systems are presented.

A few important topics in detection and estimation theory that are closely related to synchronization are introduced in Chapter 2. These topics, including the likelihood function of continuous signals and the Neyman–Pearson lemma, are essential for establishing the optimality of synchronization functions discussed in later chapters.

In Chapter 3, the general procedure of initial acquisition based on hypothesis testing is first described. The performance and other theoretical and practical aspects of the procedure are then discussed. The implementation details of the procedure in four wireless communication systems are presented to conclude this chapter.

Chapter 4 provides an introduction to the phase-locked loop (PLL) due to its importance in synchronization functions. Given that most current implementations of PLLs are in digital or mixed signal forms, most of the chapter focuses on the digital PLL. The analog PLLs and their implementations are presented separately and serve mainly as a reference.

Chapters 5 and 6 cover the two key synchronization functions: carrier and timing synchronization. The optimal maximum-likelihood carrier and timing phase estimations are first established in the respective chapters. Their classical estimation algorithms in single carrier systems are then presented. Due to the popularity of wireless communications and CDMA and OFDM technologies in recent years, significant portions of these two chapters are devoted to the synchronization in these communication systems.

Finally, Chapter 7 is dedicated to digital resampling/rate-conversion technology, which is employed for performing timing phase adjustment in almost all modern digital receivers. The design, implementation, and performance analysis of resampling/rate-conversion algorithms are presented and their applications to practical receivers are discussed.

This book grew out of my work in the digital communication industry and is based on my experience with conducting many projects that involved the design, analysis, and implementation of synchronization functions. I also gained knowledge from numerous discussions with my colleagues and friends throughout the years. I would like to express my appreciation to them even though I am not able to list all of their names. Below, I would like to acknowledge the people who have had the most influence on me in my career and in the process of writing this book.

First, I would like to thank Dr. John Proakis, my PhD thesis adviser, and my colleague and friend for over 35 years. John introduced me to the field of digital communications and is always there to provide me with guidance and help whenever I need it. I especially appreciate his help during the process of writing this book by reading and editing the entire manuscript as well as providing me with many invaluable comments. I am also strongly indebted to the late Dr. Shahid Qureshi, my first supervisor and mentor when I started my industrial career. He assigned me to and guided me in a number of projects through which I gained most of my knowledge and experience on synchronization. I especially feel grateful for his encouragement for me to start working in the area of wireless communications. Special thanks are due to Dr. David Forney for the help and advice he gave me when I was working at Codex Corporation, and for encouraging and supporting me during the process of writing this book.

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Finally, I would like to thank my wife, Xiaoyun Ma, for her support throughout my career, in particular, in the past two years during the course of writing this book.