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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Synchronization in Digital Communication Systems

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

*Foreword by John Proakis*  
**Preface**  

### 1 An Overview of Digital Communication Systems

1.1 Introduction 1  
1.2 A High-Level View of Digital Communications Systems 2  
1.3 Major Components of Typical Digital Communication Systems 4  
1.3.1 Transmitters and Their Operations 4  
1.3.2 Channel 11  
1.3.3 Receivers and Their Operations 14  
1.4 Overview of Synchronization Functions in Digital Communication Systems 20  
1.4.1 Initial Acquisition 21  
1.4.2 Timing Synchronization 22  
1.4.3 Carrier Synchronization 23  
1.5 Basics of DSSS/DS-CDMA Communications 24  
1.5.1 DS-CDMA Transmitter Operations 25  
1.5.2 DS-CDMA Receiver Operations 27  
1.5.3 RAKE Receiver: The DS-CDMA Demodulator 29  
1.6 Introduction to OFDM Communication 35  
1.6.1 OFDM Transmitter Operations 36  
1.6.2 OFDM Receiver Operations 40  
1.6.3 Demodulation of OFDM Signal Over Single- and Multipath Channels 41  
1.6.4 TDM and FDM Pilot/Reference Signals in OFDM Communication 45  
1.7 Summary and Notations of Parameters 48  

*References*  

### 2 Selected Topics in Detection and Estimation Theory

2.1 Likelihood Function and Maximum Likelihood Estimator 52  
2.1.1 Likelihood Functions of Random Variables 53  
2.1.2 Detection Based on Likelihood Functions 53  
2.1.3 Maximum Likelihood Estimator 54  

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2.2 Likelihood Function of Continuous-Time Signal and Applications 56
  2.2.1 Basics of Likelihood Functions and ML Estimation Based on Continuous-Time Signal Observations 56
  2.2.2 ML Parameter Estimation of Baseband Received Signal 57
  2.2.3 Receiver Filtering for ML and Approximate ML Estimation 58
2.3 Maximum a Posteriori Probability Detectors/Estimators 59
2.4 Cramer–Rao Bound 59
  2.4.1 The Cramer–Rao Bound of a Scalar Unbiased Estimate 59
2.5 Binary Hypothesis Test and the Neyman–Pearson Lemma 61
  2.5.1 The Binary Hypothesis Test 61
  2.5.2 False Alarm, Miss, and Detection Probabilities 61
  2.5.3 The Neyman–Pearson Lemma 61
  2.5.4 Basic Cases of Detecting a Known Signal in Additive Gaussian Noise 62
2.6 Summary and Remarks 65
References 66

3 Initial Acquisition and Frame Synchronization 67
3.1 Introduction 67
3.2 Basic Detection Process in Initial Acquisition 68
  3.2.1 An Overview of the General Detection Process in Initial Acquisition 69
  3.2.2 Detection Procedure and Hypothesis Testing in Initial Acquisition 72
  3.2.3 False Alarm, Miss, and Detection Probabilities 76
3.3 Detection Performance with Pre- and Post-Detection Integration 80
  3.3.1 Predetection Coherent Integration: Optimality and Limitations 81
  3.3.2 Post-Detection Noncoherent Integration 83
  3.3.3 Performance Analysis of Detector with Post-Detection Integration 84
3.4 Theoretical and Practical Aspects of Design and Implementation of Initial Acquisition 87
  3.4.1 Ideal and Practical Transmitter Symbol Sequences Suitable for Initial Acquisition 88
  3.4.2 Noise Variance Estimation 91
  3.4.3 The Impact of \( P_F \) and \( P_{\text{miss}} \) on Acquisition Performance and the Multi-Dwell Search 95
  3.4.4 Impact of Initial Frequency Offset and the Remedies 97
  3.4.5 Initialization of Carrier and Timing Synchronization Parameters 100
  3.4.6 A High-Level View of System Acquisition 100
3.5 Initial Acquisition in DS-CDMA Systems 101
  3.5.1 IS-95/cdma2000-1x 101
  3.5.2 WCDMA (UMTS) 107
3.6 Initial Acquisition in OFDM Systems 112
   3.6.1 LTE Initial Acquisition 112
   3.6.2 802.11a/g Wi-Fi System: Frame and System Acquisitions 120
3.7 Summary and Remarks 127

References 129

4 Basics of Phase-Locked Loop Techniques 131
   4.1 Introduction 131
   4.2 An Overview of Phase-Locked Loop Techniques 132
      4.2.1 History and Evolution of PLLs 132
      4.2.2 System Description and Major Components 133
      4.2.3 Order and Characteristics of PLLs 134
      4.2.4 PLL Applications in Digital Communication Systems and the Trends 135
   4.3 Analog PLLs 136
      4.3.1 Basic Structures and Transfer Functions of APLLs 136
      4.3.2 First-Order APLL 138
      4.3.3 Second-Order APLL 138
      4.3.4 Third- and Higher-Order APLLs 141
      4.3.5 Parameters and Characteristics of APLLs 141
   4.4 Digital PLLs 147
      4.4.1 Structure and Components of DPLLs 148
      4.4.2 First-Order DPLL 148
      4.4.3 Second-Order DPLL 155
      4.4.4 Mapping Between DPLL and APLL 164
   4.5 Design and Implementation of Digital PLLs 167
      4.5.1 Practical DPLL Components and Their Characteristics 167
      4.5.2 An Example of an All-Digital/Software DPLL Implementation 177
      4.5.3 Topics on System Design and Parameter Selection 179
   4.6 Applications of Phase-Locked Loops 185
      4.6.1 Application of PLLs to Synchronization in Digital Communications 185
      4.6.2 An Introduction to Applications of PLL in Frequency Synthesis 186
   4.7 Summary and Remarks 189

References 191

5 Carrier Synchronization 193
   5.1 Introduction 193
   5.2 Overview of Carrier Synchronization in Digital Communication Systems 193
   5.3 Carrier Synchronization of Single-Carrier Systems: Passband Analog Signal Processing 196
      5.3.1 Passband Carrier Phase and Frequency Synchronization: Non-Data-Assisted Analog Processing 196
5.3.2 Squaring Loop 197
5.3.3 Costas loop 199
5.3.4 Mth-Power Loop 200
5.3.5 Carrier Recovery of QAM by a Fourth-Power Loop 202

5.4 Carrier Synchronization of Single-Carrier Systems: Baseband Digital Signal Processing 203
5.4.1 Maximum Likelihood Phase Estimation 204
5.4.2 Data-Assisted Carrier Phase Detection 205
5.4.3 Simplified Phase Detector: The Quadrature Phase Detector 207
5.4.4 Applications of Carrier Phase Detection to Coherent Demodulation 209
5.4.5 Data-Assisted Frequency-Offset Detection 213
5.4.6 Non-Data-Assisted Baseband Carrier Phase and Frequency Detection 215
5.4.7 Digital Frequency-Locked Loop 220

5.5 Carrier Phase and Frequency Synchronization: OFDM Systems 228
5.5.1 Pilot-Assisted Channel Estimation for Carrier Phase Estimation 229
5.5.2 Carrier Frequency Synchronization 236

5.6 Carrier Synchronization for Communications over Wireline/Quasi-Static Channels 248
5.6.1 Characteristics of Wireline Channels 248
5.6.2 Carrier Synchronization Process and Operations 249
5.6.3 Practical Considerations 250

5.7 Carrier Synchronization in Wireless Communications 251
5.7.1 Wireless Channel Characteristics and System Design Considerations 252
5.7.2 VC-TCXO-Based Implementation of Carrier Frequency Synchronization 254
5.7.3 XO-Based All-Digital Implementation of Carrier Frequency Synchronization 256
5.7.4 Implementation of Frequency Binning 259

5.8 Examples of Carrier Synchronization Implementations in Wireless Communication Systems 260
5.8.1 CDMA2000-1x 260
5.8.2 WCDMA 262
5.8.3 802.11 a/g 263
5.8.4 LTE 264

5.9 Summary and Remarks 266
References 268

6 Timing Synchronization 271
6.1 Introduction 271
6.2 Fundamental Aspects of Timing Synchronization 272
6.2.1 Baseband Signal Model and ML Timing Phase Estimation 272
6.2.2 Optimal Timing Phase Synchronization 274
## Contents

6.2.3 Timing-Frequency Synchronization 275
6.2.4 Implementation Considerations of Timing Synchronization 276

6.3 Timing Synchronization with Unknown Transmitter Data Symbols 278
6.3.1 Squarer-Based Timing Synchronization 278
6.3.2 Early-Late Gate-Based Timing Phase Error Detector 280
6.3.3 Gardner’s Algorithm 282

6.4 Data/Decision-Assisted Timing Synchronization 283
6.4.1 Mueller-Müller Algorithm 284
6.4.2 Data-Assisted Early-Late Gate Timing Phase Detector 285
6.4.3 Timing Synchronization Utilizing Estimated CIR/Equalizer Coefficients 287

6.5 Timing Synchronization in DS-CDMA Systems 293
6.5.1 Initial Timing Determination 293
6.5.2 Timing Phase Tracking 295
6.5.3 Searcher Operations in the Data Mode 300
6.5.4 An Example of DLL Implementation in cdma2000 Receivers 301

6.6 Timing Synchronization in OFDM Systems 304
6.6.1 Fundamentals of OFDM Timing Phase Synchronization 304
6.6.2 Impact of Timing Frequency Offset on OFDM Receiver Performance 309
6.6.3 Timing Initialization 312
6.6.4 Data Mode Timing Tracking 315
6.6.5 A Baseline Design Example 316

6.7 Summary and Remarks 318

References 320

7 Timing Control with Digital Resampling 322

7.1 Introduction and History of Digital Timing Control 322

7.2 Basics of Digital Resampling 324
7.2.1 Nyquist Sampling Theorem and Analog Signal Reconstruction 324
7.2.2 Digital Resampling and Rate Conversion 325
7.2.3 A Summary of Digital Resampling–Related Terminology 327

7.3 Polyphase FIR Filter Bank for Digital Resampling/Rate Conversion 328
7.3.1 Integer Sampling Rate Up-Conversion with Digital Interpolation 328
7.3.2 Rational Up/Down Rate Conversion 332
7.3.3 Rate Conversion by an Arbitrary Factor 332

7.4 Design and Properties of Interpolation Filters with Polyphase FIR Filter Bank Structure 340
7.4.1 Requirements and Properties of Interpolation Filters for Timing Synchronization 341
7.4.2 Examples of Interpolation Filter Design 344

7.5 Other Implementations of Digital Resampling 350
7.5.1 Farrow’s Digital Variable Delay Controller 350
7.5.2 Resampling with Arbitrary Delay Using Lagrange Interpolation 351
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5.3 Comparison of Three Resampler Realizations</td>
<td>355</td>
</tr>
<tr>
<td>7.6 All-Digital Timing Control with Digital Resampling</td>
<td>356</td>
</tr>
<tr>
<td>7.6.1 A Typical All-Digital Timing Synchronization Block</td>
<td>357</td>
</tr>
<tr>
<td>7.6.2 Implementation of the Digital Resampler for the TPC in TLL</td>
<td>358</td>
</tr>
<tr>
<td>7.6.3 Additional Considerations of Practical Digital TLL Implementations</td>
<td>360</td>
</tr>
<tr>
<td>7.7 Examples of Digital Rate Conversion for Timing Control in Communication Systems</td>
<td>361</td>
</tr>
<tr>
<td>7.7.1 Application to Timing Control in Echo/Self-Interference Cancellation Modems</td>
<td>361</td>
</tr>
<tr>
<td>7.7.2 Implementation of Timing Control with Digital Resampling in DS-CDMA Receivers</td>
<td>365</td>
</tr>
<tr>
<td>7.7.3 Digital Rate Conversion for OFDM Timing Synchronization in a Multimode Receiver</td>
<td>368</td>
</tr>
<tr>
<td>7.8 Summary and Remarks</td>
<td>371</td>
</tr>
<tr>
<td>References</td>
<td>372</td>
</tr>
<tr>
<td>Index</td>
<td>375</td>
</tr>
</tbody>
</table>
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.
Preface

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.
Preface

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