Synchronization Techniques for Digital Receivers

Applications of Communications Theory

Series Editor: R. W. Lucky, *Bellcore*

Editorial Board:

Anthony S. Acampora, *University of Southern California*

Tingye Li, *AT&T Bell Laboratories*

William H. Tranter, *Virginia Polytechnic Institute and State University*

Recent volumes in this Series:

BASIC CONCEPTS IN INFORMATION THEORY AND CODING:
The Adventures of Secret Agent 00111
Solomon W. Golomb, Robert E. Peile, and Robert A. Scholtz

COMMUNICATION SYSTEM DESIGN USING DSP ALGORITHMS:
With Laboratory Experiments for the TMS320C30
Steven A. Tretter

COMPUTER COMMUNICATIONS AND NETWORKS
John R. Freer

COMPUTER NETWORK ARCHITECTURES AND PROTOCOLS
Second Edition • Edited by Carl A. Sunshine

DATA COMMUNICATIONS PRINCIPLES
Richard D. Gitlin, Jeremiah F. Hayes, and Stephen B. Weinstein

FUNDAMENTALS OF DIGITAL SWITCHING
Second Edition • Edited by John C. McDonald

AN INTRODUCTION TO BROADBAND NETWORKS:
LANs, MANs, ATM, B-ISBN, and Optical Networks for Integrated Multimedia Telecommunications
Anthony S. Acampora

AN INTRODUCTION TO PHOTONIC SWITCHING FABRICS
H. Scott Hinton

OPTICAL CHANNELS: Fibers, Clouds, Water, and the Atmosphere
Sherman Karp, Robert M. Gagliardi, Steven E. Moran, and Larry B. Stotts

SIMULATION OF COMMUNICATIONS SYSTEMS
Michel C. Jeruchim, Philip Balaban, and K. Sam Shanmugan

SYNCHRONIZATION TECHNIQUES FOR DIGITAL RECEIVERS
Umberto Mengali and Aldo N. D'Andrea

A Continuation Order Plan is available for this series. A continuation order will bring delivery of each new volume immediately upon publication. Volumes are billed only upon actual shipment. For further information please contact the publisher.

Synchronization Techniques for Digital Receivers

Umberto Mengali and
Aldo N. D'Andrea
University of Pisa
Pisa, Italy

SPRINGER SCIENCE+BUSINESS MEDIA, LLC

Library of Congress Cataloging-in-Publication Data

Mengali, Umberto.
Synchronization techniques for digital receivers / Umberto Mengali and Aldo N. D'Andrea.
p. cm. -- (Applications of communications theory)
Includes bibliographical references (p.) and index.
1. Digital communications--Equipment and supplies. 2. Timing circuits--Design and construction. 3. Synchronization.
I. D'Andrea, Aldo N. II. Series.
TK5103.7.M45 1997
621.382--dc21 97-41674
CIP

ISBN 978-1-4899-1809-3 ISBN 978-1-4899-1807-9 (eBook)
DOI 10.1007/978-1-4899-1807-9

© Springer Science+Business Media New York 1997
Originally published by Plenum Press, New York in 1997
Softcover reprint of the hardcover 1st edition 1997

http://www.plenum.com

10 9 8 7 6 5 4 3

All rights reserved

No part of this book may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, microfilming, recording, or otherwise, without written permission from the Publisher

Preface

Synchronization is a critical function in digital communications; its failures may have catastrophic effects on the transmission system performance. Furthermore, synchronization circuits comprehend such a large part of the receiver hardware that their implementation has a substantial impact on the overall costs. For these reasons design engineers are particularly concerned with the development of new and more efficient synchronization structures. Unfortunately, the advent of digital VLSI technology has radically affected modem design rules, to a point that most analog techniques employed so far have become totally obsolete.

Although digital synchronization methods are well established by now in the literature, they only appear in the form of technical papers, often concentrating on specific performance or implementation issues. As a consequence they are hardly useful to give a unified view of an otherwise seemingly heterogeneous field. It is widely recognized that a fundamental understanding of digital synchronization can only be reached by providing the designer with a solid theoretical framework, or else he will not know where to adjust his methods when he attempts to apply them to new situations. The task of the present book is just to develop such a framework.

This is achieved by considering synchronization as a parameter estimation problem and approaching it with the techniques of estimation theory. In doing so two main goals are attained. One is to offer a coherent and systematic methodology to follow when looking for new synchronization structures. The other is to provide the designer with precise indications on the inherent performance limits of these structures.

Synchronization circuits are occasionally devised on an ad hoc basis and proven eventually by demonstration in hardware or computer simulation. Ad hoc synchronization procedures are welcome and fully acknowledged in this book. They result from application of physical insight and may lead to valuable

solutions. When facing more complex problems, however, like those encountered with continuous-phase modulations, they seem of lesser efficacy and a theoretical oriented approach is indispensable.

Exercises have been inserted throughout the text as a convenient means for providing examples of application of the proposed techniques. They are not merely routine manipulations of equations. Their purpose is rather to supplement the text in various ways: (*i*) to gain familiarity with important concepts; (*ii*) to apply these concepts to practical situations; (*iii*) to fill in missing details.

The book is intended for three categories of readers. Primarily, it should be a valuable tool for design engineers in telecommunications industry. Second, it might be used as supplementary material in digital transmission courses or as a separate course in synchronization or digital modem design. As a text for a graduate-level course the book can be covered in one semester. Finally, it should be useful to researchers. On several occasions in the book we have pointed out open problems of considerable technical relevance.

The book is self-contained and any significant results are derived either in the text or in the appendices. The underlying assumptions and methods employed in the derivations are accurately outlined and the final outcomes are discussed and compared with other situations, in order to stress the physical significance. Nevertheless, as many aspects of synchronization can only be expressed in mathematical terms, the reader must have some mathematical background. In particular, a working knowledge of linear system theory, Fourier transforms, and stochastic processes is needed.

This leaves only the pleasant task of acknowledging the contribution of several people to the creation of this book. Many thanks go to our good friends and colleagues Floyd Gardner, Des Taylor, and Ruggero Reggiannini, who suggested valuable improvements and reviewed several portions of the manuscript. We would also like to express gratitude to our co-workers and students Antonio D'Amico, Alberto Ginesi, Michele Morelli, and Giorgio Vitetta, who performed many simulations, reviewed the manuscript in detail, and offered corrections and changes. There are no words to describe adequately our indebtedness to all of them.

Contents

1. Introduction 1

1.1. What Synchronization Is About 1
1.2. Outline of the Book 4
References 7

2. Principles, Methods and Performance Limits 9

2.1. Introduction 9
2.2. Synchronization Functions 9
2.2.1. Timing Recovery with Baseband Systems. 10
2.2.2. Degradations Due to Timing Errors 12
2.2.3. Passband PAM Systems 15
2.2.4. Synchronization in PAM Coherent Receivers. 18
2.2.5. Degradations Due to Phase Errors 20
2.2.6. Synchronization in PAM Differential Receivers 25
2.2.7. Synchronization in CPM Systems 28
2.2.8. Synchronization in Simplified CPM Receivers 31
2.3. Maximum Likelihood Estimation 37
2.3.1. ML Estimation from Continuous-Time Waveforms . . . 38
2.3.2. Baseband Signaling 44
2.3.3. ML Estimation from Sample Sequences 47
2.3.4. Baseband Signaling 52
2.4. Performance Limits in Synchronization 53
2.4.1. True and Modified Cramer-Rao Bounds 53
2.4.2. An Alternative Approach to the Bounds 57
2.4.3. $MCRB(\nu)$ with PAM Modulation 58
2.4.4. $MCRB(\nu)$ with CPM Modulation 60

2.4.5. $MCRB(\theta)$ with PAM and CPM Modulations 61
2.4.6. $MCRB(\tau)$ with PAM Modulation 64
2.4.7. $MCRB(\tau)$ with CPM Modulation 67
2.5. Key Points of the Chapter 69
Appendix 2.A 70
2.A.1. Power Spectral Density for Baseband Signals 70
2.A.2. Power Spectral Density for Bandpass Signals 71
2.A.3. Extension to Trellis-Coded Modulations 73
Appendix 2.B 73
References 75

3. Carrier Frequency Recovery with Linear Modulations 79

3.1. Introduction 79
3.2. Data-Aided Frequency Estimation 80
3.2.1. Maximum Likelihood Estimation 80
3.2.2. Practical Frequency Estimators 84
3.2.3. First Method (Kay [3]) 86
3.2.4. Second Method (Fitz [4]) 88
3.2.5. Third Method (Luise and Reggiannini [6]) 89
3.2.6. Fourth Method (Approximate ML Estimation) 91
3.2.7. Performance Comparisons 92
3.3. Decision-Directed Recovery with DPSK 97
3.3.1. Decision-Directed Algorithms with Differential PSK . . 97
3.4. Non-Data-Aided but Clock-Aided Recovery 100
3.4.1. Closed-Loop Algorithm 100
3.4.2. Extension to M-ary PSK and QAM 104
3.4.3. Open-Loop Algorithms 105
3.5. Closed-Loop Recovery with No Timing Information 108
3.5.1. Likelihood Function 108
3.5.2. Open-Loop Search 115
3.5.3. Closed-Loop Estimator 115
3.5.4. Frequency Acquisition 120
3.5.5. Frequency Tracking 124
3.5.6. Comparison with MCRB 128
3.5.7. Other Frequency Error Detectors 130
3.6. Open-Loop Recovery with No Timing Information 133
3.6.1. Delay-and-Multiply Method 133
3.6.2. Digital Implementation 139
3.6.3. Effects of Adjacent Channel Interference 140

3.7. Key Points of the Chapter 143
Appendix 3.A 144
References 145

4. Carrier Frequency Recovery with CPM Modulations 147

4.1. Introduction 147
4.2. Laurent Expansion 148
4.3. Data-Aided Frequency Estimation 154
4.3.1. Frequency Estimation with MSK 154
4.3.2. Extension to MSK-Type Modulation 156
4.4. ML-Based NDA Frequency Estimation 157
4.4.1. MSK-Type Modulation 157
4.4.2. General CPM Modulation 161
4.4.3. Loop Performance 167
4.5. Delay-and-Multiply Schemes 169
4.5.1. Open-Loop Scheme 169
4.5.2. Closed-Loop Scheme 174
4.6. Clock-Aided Recovery 176
4.6.1. Delay-and-Multiply Method 176
4.6.2. $2P$-Power Method with Full Response Formats 179
4.7. Key Points of the Chapter 182
Appendix 4.A 183
Appendix 4.B 185
Appendix 4.C 187
References 188

5. Carrier Phase Recovery with Linear Modulations 189

5.1. Introduction 189
5.2. Clock-Aided and Data-Aided Phase Recovery 190
5.2.1. ML Estimation with Non-Offset Formats 190
5.2.2. Performance with Non-Offset Formats 192
5.2.3. ML Estimation with Offset Formats 194
5.2.4. Performance with Offset Formats 195
5.2.5. Degradations Due to Frequency Errors 198
5.3. Decision-Directed Phase Recovery with Non-Offset Modulation 201
5.3.1. Feedback Structures 201

5.3.2. First Approach 202
5.3.3. Second Approach 205
5.3.4. Acquisition and Tracking Characteristics 206
5.3.5. S-Curves for General Modulation Formats 211
5.3.6. Tracking Performance 213
5.3.7. Effect of Frequency Errors 217
5.3.8. Second-Order Tracking Loops 220
5.3.9. Phase Noise 224
5.4. Decision-Directed Phase Recovery with Offset Modulation . . . 228
5.4.1. Phase Estimation Loop 228
5.4.2. Tracking Performance with Offset Formats 232
5.4.3. Effects of Phase Noise and Frequency Errors 236
5.5. Multiple Phase-Recovery with Trellis-Coded Modulations 236
5.5.1. Tentative Decisions 236
5.5.2. Multiple Synchronizers 240
5.6. Phase Tracking with Frequency-Flat Fading 245
5.6.1. Channel Estimation Problem 245
5.6.2. Pilot-Tone Assisted Modulation 251
5.6.3. Pilot-Symbol Assisted Modulation 252
5.6.4. Per-Survivor Channel Estimation 259
5.7. Clock-Aided but Non-Data-Aided Phase Recovery with Non-Offset Formats 266
5.7.1. Likelihood Function 266
5.7.2. High SNR 269
5.7.3. Low SNR 271
5.7.4. Feedforward Estimation with PSK 277
5.7.5. Feedforward Estimation with QAM 281
5.7.6. Ambiguity Resolution 282
5.7.7. The Unwrapping Problem 284
5.8. Clock-Aided but Non-Data-Aided Phase Recovery with OQPSK 286
5.8.1. Likelihood Function 286
5.8.2. Feedback Estimation Method 288
5.8.3. ML-Oriented Feedforward Method 291
5.8.4. Viterbi-Like Method 295
5.9. Clockless Phase Recovery with PSK 297
5.9.1. ML-Based Feedforward Estimation 297
5.10. Clockless Phase Recovery with OQPSK 299
5.10.1. Ad Hoc Method 299
5.11. Key Points of the Chapter 301
References 303

6. Carrier Phase Recovery with CPM Modulations 307

6.1. Introduction 307
6.2. Data-Aided Phase Estimation with MSK-Type Modulation . . . 308
6.2.1. MSK-Type Receivers 308
6.2.2. Data-Aided Phase Estimation with MSK-Type Modulation 311
6.2.3. Estimator Performance with MSK 312
6.3. Decision-Directed Estimation with MSK-Type Modulation . . . 314
6.3.1. Decision-Directed Estimation with MSK 314
6.4. Decision-Directed Estimation with General CPM 319
6.4.1. ML Receivers for CPM 319
6.4.2. Decision-Directed Phase Estimation 322
6.5. CPM Signaling over Frequency-Flat Fading Channels 327
6.5.1. ML Receiver 327
6.5.2. Approximate ML Receiver Based on Per-Survivor-Processing Methods 328
6.5.3. Improved Methods for Fast-Fading Channels 333
6.5.4. Linearly Time-Selective Channels 336
6.6. Clock-Aided but Non-Data-Aided Phase Estimation 339
6.6.1. $2P$-Power Method for Full-Response Systems 339
6.6.2. ML-Oriented Phase Estimation 342
6.7. Clockless Phase Estimation 346
6.8. Key Points of the Chapter 351
References 351

7. Timing Recovery in Baseband Transmission 353

7.1. Introduction 353
7.2. Synchronous Sampling 355
7.2.1. Hybrid NCO 355
7.2.2. Timing Adjustment for Synchronous Sampling 357
7.3. Non-Synchronous Sampling 359
7.3.1. Feedback Recovery Scheme 359
7.3.2. Piecewise Polynomial Interpolators 362
7.3.3. Timing Adjustment with Non-Synchronous Sampling . . 366
7.3.4. Timing Adjustment with Feedforward Schemes 368
7.4. Decision-Directed Timing Error Detectors 371
7.4.1. ML-Based Detectors 371
7.4.2. S-Curve 375

7.4.3. Tracking Performance 377
7.4.4. Approximate-Derivative Method 383
7.4.5. Other Timing Error Detectors 385
7.5. Non-Data-Aided Detectors 391
7.5.1. ML-Based Detector 391
7.5.2. The Gardner Detector 393
7.5.3. Tracking Performance 395
7.5.4. Self Noise Elimination with the Gardner Detector 396
7.6. Feedforward Estimation Schemes 398
7.6.1. Non-Data-Aided ML-Based Algorithm 398
7.6.2. Oerder and Meyr Algorithm 402
7.7. Key Points of the Chapter 406
Appendix 7.A 407
References 408

8. Timing Recovery with Linear Modulations 411

8.1. Introduction 411
8.2. Decision-Directed Joint Phase and Timing Recovery with Non-Offset Formats 412
8.2.1. ML-Based Joint Phase and Timing Estimation 413
8.2.2. Remark 415
8.2.3. Ad Hoc Timing Detectors 417
8.2.4. Equivalent Model of the Synchronizer 418
8.2.5. Tracking Performance 425
8.3. Non-Data-Aided Feedback Timing Recovery with Non-Offset Formats 428
8.3.1. ML-Oriented NDA Feedback Timing Recovery 428
8.3.2. The Gardner Detector and Its Performance 431
8.4. Non-Data-Aided Feedforward Estimators with Non-Offset Formats 433
8.5. Timing Recovery with Frequency-Flat Fading Channels 438
8.5.1. DD-CA Timing Recovery 439
8.5.2. NDA Timing Recovery 442
8.5.3. High SNR Approximation to the ML Estimator 444
8.5.4. Modified ML Algorithm 449
8.6. Decision-Directed Joint Phase and Timing Recovery with Offset Formats 452
8.6.1. ML-Based Joint Phase and Timing Estimation 453
8.6.2. Other Timing Detectors 459

8.7. NDA Feedforward Joint Phase and Timing Recovery with Offset Formats 462
8.7.1. Computation of the Likelihood Function 462
8.7.2. ML-Based Estimator 464
8.7.3. Estimator Performance 467
8.8. Key Points of the Chapter 470
Appendix 8.A 470
Appendix 8.B 472
Appendix 8.C 473
References 475

9. Timing Recovery with CPM Modulations 477

9.1. Introduction 477
9.2. Decision-Directed Joint Phase and Timing Recovery 478
9.2.1. ML Formulation 478
9.2.2. Approximate Digital Differentiation 483
9.2.3. Tracking Performance and Spurious Locks 485
9.3. NDA Feedback Timing Recovery 487
9.3.1. Approximate Expression for the Likelihood Function . . 487
9.3.2. Timing Error Detector 491
9.3.3. Performance 493
9.3.4. False Lock Detection 495
9.4. Ad Hoc Feedback Schemes for MSK-Type Modulations 497
9.5. NDA Feedforward Timing Estimation 502
9.6. Ad Hoc Feedforward Schemes for MSK Modulation 505
9.6.1. MCM Scheme 505
9.6.2. LM Scheme 509
9.7. Key Points of the Chapter 513
Appendix 9.A 514
References 516

Index 517