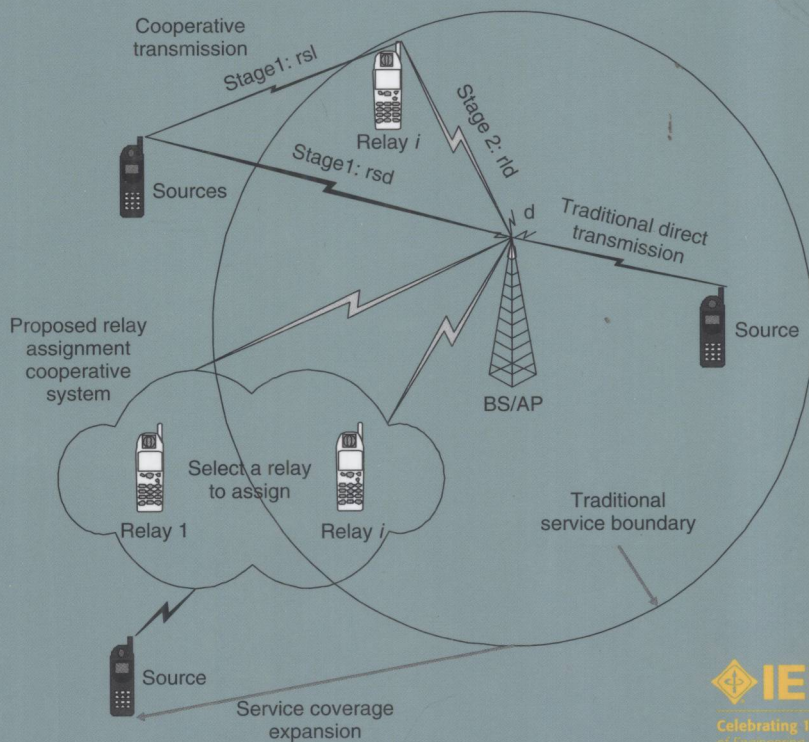


HANDBOOK ON ARRAY PROCESSING AND SENSOR NETWORKS

SIMON HAYKIN • K. J. RAY LIU



TN92

H236

HANDBOOK ON ARRAY PROCESSING AND SENSOR NETWORKS

Simon Haykin
K. J. Ray Liu



Celebrating 125 Years
of Engineering the Future



WILEY

A JOHN WILEY & SONS, INC.



E2010000765

Copyright © 2009 by John Wiley & Sons, Inc. All rights reserved

Published by John Wiley & Sons, Inc., Hoboken, New Jersey

Published simultaneously in Canada

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permissions>.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages; including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data:

Haykin, Simon

Handbook on array processing and sensor networks / Simon Haykin, K. J. Ray Liu.

p. cm.

Includes bibliographical references and index.

ISBN 978-0-470-37176-3 (cloth)

1. Sensor networks. 2. Antenna arrays. 3. Array processors. I. Liu, K. J. Ray, 1961- II. Title.

TK7872.D48H39 2009

621.382'4-dc22

2008055880

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

HANDBOOK ON ARRAY PROCESSING AND SENSOR NETWORKS

More than a decade ago, a book edited by Simon Haykin on array processing was a huge success with significant impact. Ever since, the field of array processing has grown to the extent that one can see its applications everywhere. Indeed, traditional array techniques form the foundation of the more general sensor processing and networking that continue to advance the state-of-the-art research and find ubiquitous applications. Sensor networks and array processing form the two pillars of the proposed handbook.

Sensors and array processing, in their own individual ways, have been active areas of research for several decades: Wireless communications, radar, radio astronomy, and biomedical engineering, just to name a few important ones. This new *Handbook on Array Processing and Sensor Networks* addresses these topics in an organized manner under a single umbrella.

The major goal of this *Handbook* is to collect tutorial discussions on recent advancements and state-of-the-art results by providing a comprehensive overview of array processing and sensor networks. It covers fundamental principles as well as applications. This *handbook* features some of the most prominent researchers from all over the world, addressing the important topics that we consider to be essential for making the *handbook* highly valuable to the readers; this point is well borne out by the list of contents.

This *Handbook* consists of an introductory chapter, followed by 28 chapters that are written by leading authorities in sensor networks and array signal processing. Putting all this material together under a single umbrella, we have a *Handbook* that is one of a kind.

This *Handbook* should appeal to researchers as well as graduate students and newcomers to the field of sensors and array processing, and thereby learn not only about the many facets of these two subjects but also exploit the possibility of cross fertilization between them. Moreover, this *Handbook* may also appeal to professors in teaching graduate courses on sensor networks and/or array signal processing.

Simon Haykin
McMaster University

K. J. Ray Liu
University of Maryland, College Park

Contributors

A. Anandkumar, Adaptive Communications & Signal Processing, Electrical & Computer Engineering, Cornell University, Ithaca, NY, USA

Shoko Araki, NTT Communication Science Laboratories, NTT Corporation, Kyoto, Japan

Joshua N. Ash, The Ohio State University, Columbus, OH, USA

Y. Bar-Shalom, Electrical & Computer Engineering Department, University of Connecticut, Storrs, CT, USA

Douglas C.-J. Bock, Project Manager and Assistant Director for Operations, CARMA, Big Pine, CA, USA

Markus Buck, Harman/Becker Automotive Systems, Ulm, Germany

Robert Calderbank, Department of Electrical Engineering, Princeton University, Princeton, NJ, USA

Federico S. Cattivelli, Electrical Engineering Department, University of California, Los Angeles, CA, USA

Bruce Cornell, Surgical Diagnostics Ltd., St. Leonards, Australia

Shuguang Cui, Department of Electrical & Computer Engineering, Texas A&M University, College Station, TX, USA

Petar M. Djurić, Stony Brook University, Stony Brook, NY, USA

Simon Doclo, University of Oldenburg, Signal Processing Group, Oldenburg, Germany

A. Ephremides, Department of Electrical & Computer Engineering, University of Maryland, College Park, MD, USA

Behrouz Farhang-Boroujeny, Department of Electrical & Computer Engineering, University of Utah, Salt Lake City, UT, USA

Christina Fragouli, School of Computer & Communication Sciences, EPFL, Switzerland

Sharon Gannot, Bar-Ilan University, School of Engineering, Ramat-Gan, Israel

Alex B. Gershman, Communications Research Laboratory, McMaster University, Hamilton, Ontario, Canada

Eberhard Hänsler, Technische Universität Darmstadt, Darmstadt, Germany

- Alfred Hanssen**, Department of Physics, University of Tromsø, Tromsø, Norway
- Simon Haykin**, Department of Electrical Engineering, McMaster University, Hamilton, Ontario, Canada
- Soumya Kar**, Department of Electrical & Computer Engineering, Carnegie Mellon University, Pittsburgh, PA, USA
- Usman A. Khan**, Department of Electrical & Computer Engineering, Carnegie Mellon University, Pittsburgh, PA, USA
- T. Kirubarajan**, Electrical & Computer Engineering Department, Communications Research Laboratory, McMaster University, Hamilton, Ontario, Canada
- Mohamed Krini**, Harman/Becker Automotive Systems, Ulm, Germany
- Vikram Krishnamurthy**, Department of Electrical & Computer Engineering, The University of British Columbia, Vancouver, B.C. Canada
- P. R. Kumar**, Department of Electrical & Computer Engineering, & Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Urbana, IL, USA
- Azadeh Kushki**, Department of Electrical & Computer Engineering, University of Toronto, Toronto, Ontario, Canada
- Mauricio Lara**, Ingeniería Eléctrica, Cinvestav, México
- K. J. Ray Liu**, Department of Electrical & Computer Engineering, University of Maryland, College Park, MD, USA
- Angelos D. Liveris**, Department of Electrical & Computer Engineering, Texas A&M University, College Station, TX, USA
- Zhi-Quan Luo**, Department of Electrical & Computer Engineering, University of Minnesota, Minneapolis, MN, USA
- Shoji Makino**, NTT Communication Science Laboratories, NTT Corporation, Kyoto, Japan
- Desmond C. McLernon**, University of Leeds, United Kingdom
- Marc Moonen**, Katholieke Universiteit Leuven, Dept. of Electrical Engineering, Leuven, Belgium
- Bill Moran**, University of Melbourne, Australia
- Randolph L. Moses**, The Ohio State University, Columbus, OH, USA
- José M. F. Moura**, Department of Electrical & Computer Engineering, Carnegie Mellon University, Pittsburgh PA, USA
- Arye Nehorai**, Department of Electrical & Systems Engineering, Washington University, St. Louis, MO, USA
- Peng Ning**, North Carolina State University, Raleigh, NC, USA
- Aldo G. Orozco-Lugo**, Cinvestav-IPN, México
- Mathias Ortner**, INRIA, Sophia Antipolis, France

Adrian Perrig, Carnegie Mellon University, Pittsburgh, PA, USA

Konstantinos N. Plataniotis, Department of Electrical & Computer Engineering, University of Toronto, Toronto, Ontario, Canada

K. Punithakumar, Electrical & Computer Engineering Department, McMaster University, Hamilton Ontario, Canada

Tariq R. Qureshi, Purdue University, West Lafayette, IN, USA

Ahmed Sadek, Qualcomm, San Diego, CA, USA

Hiroshi Sawada, NTT Communication Science Laboratories, NTT Corporation, Kyoto, Japan

Ali H. Sayed, Electrical Engineering Department, University of California, Los Angeles, CA, USA

Akbar M. Sayeed, University of Wisconsin-Madison, Madison, WI, USA

Gerhard Schmidt, Harman/Becker Automotive Systems, Acoustic Signal Processing Research, Ulm, Germany

Thiagarajan Sivanadyan, Wireless Communications Research Laboratory, Department of Electrical & Computer Engineering, University of Wisconsin-Madison, Madison, WI, USA

Ann Spriet, Katholieke Universiteit Leuven, Dept. of Electrical Engineering, Leuven, Belgium

Stergios Stergiopoulos, Diagnosis & Prevention/IRS, DRDC Toronto, Ontario, Canada

Weifeng Su, Department of Electrical Engineering, SUNY, Buffalo, NY, USA

A. Swami, U.S. Army Research Laboratory, Adelphi, MD, USA

R. Tharmarasa, Electrical & Computer Engineering Department, McMaster University, Hamilton, Ontario, Canada

L. Tong, Cornell University, Ithaca, NY, USA

Wade Trappe, WINLAB, Rutgers University, North Brunswick, NJ, USA

Tom Vercauteren, Asclepios Research Project, INRIA Sophia Antipolis, France

Xiaodong Wang, Electrical Engineering Department, Columbia University, New York, NY, USA

Tricia J. Willink, Communications Research Centre, Ottawa, Ontario, Canada

Stefan Winter, NTT Communication Science Laboratories, NTT Corporation, Kyoto, Japan

Tobias Wolff, Harman/Becker Automotive Systems, Ulm, Germany

Jin-Jun Xiao, Department of Electrical & Systems Engineering, Washington University, St. Louis, MO, USA

Liang-Liang Xie, Department of Electrical & Computer Engineering, University of Waterloo, Waterloo, Ontario, Canada

Zixiang Xiong, Department of Electrical & Computer Engineering, Texas A&M University, College Station, TX, USA

Yang Yang, Department of Electrical & Computer Engineering, Texas A&M University, College Station, TX, USA

Michael D. Zoltowski, School of Electrical & Computer Engineering, Purdue University, West Lafayette, IN, USA

CONTENTS

Preface	xiii
<i>Simon Haykin and K. J. Ray Liu</i>	
Contributors	xv
Introduction	1
<i>Simon Haykin</i>	
PART I: FUNDAMENTAL ISSUES IN ARRAY SIGNAL PROCESSING	9
1 Wavefields	11
<i>Alfred Hanssen</i>	
1.1 Introduction	11
1.2 Harmonizable Stochastic Processes	12
1.3 Stochastic Wavefields	15
1.4 Wave Dispersion	19
1.5 Conclusions	26
Acknowledgments	27
References	27
2 Spatial Spectrum Estimation	29
<i>Petar M. Djurić</i>	
2.1 Introduction	29
2.2 Fundamentals	33
2.3 Temporal Spectrum Estimation	34
2.4 Spatial Spectrum Estimation	41
2.5 Final Remarks	56
References	56
3 MIMO Radio Propagation	59
<i>Tricia J. Willink</i>	
3.1 Introduction	59
3.2 Space–Time Propagation Environment	60
3.3 Propagation Models	64
3.4 Measured Channel Characteristics	75
3.5 Stationarity	81

3.6	Summary	86
	References	87
4	Robustness Issues in Sensor Array Processing	91
	<i>Alex B. Gershman</i>	
4.1	Introduction	91
4.2	Direction-of-Arrival Estimation	92
4.3	Adaptive Beamforming	102
4.4	Conclusions	107
	Acknowledgments	108
	References	108
5	Wireless Communication and Sensing in Multipath Environments Using Multiantenna Transceivers	115
	<i>Akbar M. Sayeed and Thiagarajan Sivanadyan</i>	
5.1	Introduction and Overview	115
5.2	Multipath Wireless Channel Modeling in Time, Frequency, and Space	118
5.3	Point-to-Point MIMO Wireless Communication Systems	133
5.4	Active Wireless Sensing with Wideband MIMO Transceivers	156
5.5	Concluding Remarks	165
	References	166
	PART II: NOVEL TECHNIQUES FOR AND APPLICATIONS OF ARRAY SIGNAL PROCESSING	171
6	Implicit Training and Array Processing for Digital Communication Systems	173
	<i>Aldo G. Orozco-Lugo, Mauricio Lara and Desmond C. McLernon</i>	
6.1	Introduction	173
6.2	Classification of Implicit Training Methods	180
6.3	IT-Based Estimation for a Single User	186
6.4	IT-Based Estimation for Multiple Users Exploiting Array Processing: Continuous Transmission	191
6.5	IT-Based Estimation for Multiple Users Exploiting Array Processing: Packet Transmission	199
6.6	Open Research Problems	201
	Acknowledgments	203
	References	203
7	Unitary Design of Radar Waveform Diversity Sets	211
	<i>Michael D. Zoltowski, Tariq R. Qureshi, Robert Calderbank and Bill Moran</i>	
7.1	Introduction	211

7.2	2×2 Space–Time Diversity Waveform Design	213
7.3	4×4 Space–Time Diversity Waveform Design	217
7.4	Waveform Families Based on Kronecker Products	220
7.5	Introduction to Data-Dependent Waveform Design	226
7.6	3×3 and 6×6 Waveform Scheduling	228
7.7	Summary	229
	References	229
8	Acoustic Array Processing for Speech Enhancement	231
	<i>Markus Buck, Eberhard Hänsler, Mohamed Krini, Gerhard Schmidt and Tobias Wolff</i>	
8.1	Introduction	231
8.2	Signal Processing in Subband Domain	233
8.3	Multichannel Echo Cancellation	236
8.4	Speaker Localization	240
8.5	Beamforming	242
8.6	Sensor Calibration	249
8.7	Postprocessing	252
8.8	Conclusions	264
	References	264
9	Acoustic Beamforming for Hearing Aid Applications	269
	<i>Simon Doclo, Sharon Gannot, Marc Moonen and Ann Spriet</i>	
9.1	Introduction	269
9.2	Overview of noise reduction techniques	270
9.3	Monaural beamforming	272
9.4	Binaural beamforming	286
9.5	Conclusion	296
	References	296
10	Underdetermined Blind Source Separation Using Acoustic Arrays	303
	<i>Shoji Makino, Shoko Araki, Stefan Winter and Hiroshi Sawada</i>	
10.1	Introduction	303
10.2	Underdetermined Blind Source Separation of Speeches in Reverberant Environments	305
10.3	Sparseness of Speech Sources	307
10.4	Binary Mask Approach to Underdetermined BSS	312
10.5	MAP-Based Two-Stage Approach to Underdetermined BSS	321
10.6	Experimental Comparison with Binary Mask Approach and MAP-Based Two-Stage Approach	328
10.7	Concluding Remarks	335
	References	337

11	Array Processing in Astronomy	343
	<i>Douglas C.-J. Bock</i>	
11.1	Introduction	343
11.2	Correlation Arrays	343
11.3	Aperture Plane Phased Arrays	361
11.4	Future Directions	362
11.5	Conclusion	364
	References	365
12	Digital 3D/4D Ultrasound Imaging Array	367
	<i>Stergios Stergiopoulos</i>	
12.1	Background	367
12.2	Next-Generation 3D/4D Ultrasound Imaging Technology	372
12.3	Computing Architecture and Implementation Issues	392
12.4	Experimental Planar Array Ultrasound Imaging System	394
12.5	Conclusion	403
	References	404
	PART III: FUNDAMENTAL ISSUES IN DISTRIBUTED SENSOR NETWORKS	407
13	Self-Localization of Sensor Networks	409
	<i>Joshua N. Ash and Randolph L. Moses</i>	
13.1	Introduction	409
13.2	Measurement Types and Performance Bounds	411
13.3	Localization Algorithms	420
13.4	Relative and Transformation Error Decomposition	427
13.5	Conclusions	434
	References	435
14	Multitarget Tracking and Classification in Collaborative Sensor Networks via Sequential Monte Carlo Methods	439
	<i>Tom Vercauteren and Xiaodong Wang</i>	
14.1	Introduction	439
14.2	System Description and Problem Formulation	440
14.3	Sequential Monte Carlo Methods	446
14.4	Joint Single-Target Tracking and Classification	448
14.5	Multiple-Target Tracking and Classification	452
14.6	Sensor Selection	456
14.7	Simulation Results	459
14.8	Conclusion	464

Appendix: Derivations of (14.38) and (14.40)	465
References	466
15 Energy-Efficient Decentralized Estimation	469
<i>Jin-Jun Xiao, Shuguang Cui and Zhi-Quan Luo</i>	
15.1 Introduction	469
15.2 System Model	471
15.3 Digital Approaches	472
15.4 Analog Approaches	476
15.5 Analog versus Digital	485
15.6 Extension to Vector Model	487
15.7 Concluding Remarks	492
Acknowledgments	494
References	494
16 Sensor Data Fusion with Application to Multitarget Tracking	499
<i>R. Tharmarasa, K. Punithakumar, T. Kirubarajan and Y. Bar-Shalom</i>	
16.1 Introduction	499
16.2 Tracking Filters	500
16.3 Data Association	511
16.4 Out-of-Sequence Measurements	521
16.5 Results with Real Data	524
16.6 Summary	527
References	527
17 Distributed Algorithms in Sensor Networks	533
<i>Usman A. Khan, Soumya Kar and José M. F. Moura</i>	
17.1 Introduction	533
17.2 Preliminaries	535
17.3 Distributed Detection	538
17.4 Consensus Algorithms	539
17.5 Zero-Dimension (Average) Consensus	542
17.6 Consensus in Higher Dimensions	544
17.7 Leader–Follower (Type) Algorithms	545
17.8 Localization in Sensor Networks	548
17.9 Linear System of Equations: Distributed Algorithm	551
17.10 Conclusions	553
References	553
18 Cooperative Sensor Communications	559
<i>Ahmed K. Sadek, Weifeng Su and K. J. Ray Liu</i>	
18.1 Introduction	559

18.2	Cooperative Relay Protocols	561
18.3	SER Analysis and Optimal Power Allocation	568
18.4	Energy Efficiency in Cooperative Sensor Networks	589
18.5	Experimental Results	599
18.6	Conclusions	606
	References	606
19	Distributed Source Coding	609
	<i>Zixiang Xiong, Angelos D. Liveris and Yang Yang</i>	
19.1	Introduction	609
19.2	Theoretical Background	610
19.3	Code Designs	619
19.4	Applications	631
19.5	Conclusions	638
	References	639
20	Network Coding for Sensor Networks	645
	<i>Christina Fragouli</i>	
20.1	Introduction	645
20.2	How Can We Implement Network Coding in a Practical Sensor Network?	649
20.3	Data Collection and Coupon Collector Problem	653
20.4	Distributed Storage and Sensor Network Data Persistence	657
20.5	Decentralized Operation and Untuned Radios	660
20.6	Broadcasting and Multipath Diversity	662
20.7	Network, Channel, and Source Coding	663
20.8	Identity-Aware Sensor Networks	664
20.9	Discussion	666
	Acknowledgments	666
	References	666
21	Information-Theoretic Studies of Wireless Sensor Networks	669
	<i>Liang-Liang Xie and P. R. Kumar</i>	
21.1	Introduction	669
21.2	Information-Theoretic Studies	670
21.3	Relay Schemes	674
21.4	Wireless Network Coding	684
21.5	Concluding Remarks	688
	Acknowledgments	689
	References	689

PART IV: NOVEL TECHNIQUES FOR AND APPLICATIONS OF DISTRIBUTED SENSOR NETWORKS	693
22 Distributed Adaptive Learning Mechanisms	695
<i>Ali H. Sayed and Federico S. Cattivelli</i>	
22.1 Introduction	695
22.2 Motivation	697
22.3 Incremental Adaptive Solutions	698
22.4 Diffusion Adaptive Solutions	707
22.5 Concluding Remarks	720
Acknowledgments	721
References	721
23 Routing for Statistical Inference in Sensor Networks	723
<i>A. Anandkumar, A. Ephremides, A. Swami and L. Tong</i>	
23.1 Introduction	723
23.2 Spatial Data Correlation	724
23.3 Statistical Inference of Markov Random Fields	730
23.4 Optimal Routing for Inference with Local Processing	731
23.5 Conclusion and Future Work	744
23.6 Bibliographic Notes	745
References	745
24 Spectral Estimation in Cognitive Radios	749
<i>Behrouz Farhang-Boroujeny</i>	
24.1 Filter Bank Formulation of Spectral Estimators	750
24.2 Polyphase Realization of Uniform Filter Banks	751
24.3 Periodogram Spectral Estimator	752
24.4 Multitaper Spectral Estimator	757
24.5 Filter Bank Spectral Estimator	766
24.6 Distributed Spectrum Sensing	773
24.7 Discussion	776
Appendix A: Effective Degree of Freedom	777
Appendix B: Explanation to the Results of Table 24.1	779
References	779
25 Nonparametric Techniques for Pedestrian Tracking in Wireless Local Area Networks	783
<i>Azadeh Kushki and Konstantinos N. Plataniotis</i>	
25.1 Introduction	783

25.2	WLAN Positioning Architectures	785
25.3	Signal Models	786
25.4	Zero-Memory Positioning	788
25.5	Dynamic Positioning Systems	790
25.6	Cognition and Feedback	796
25.7	Tracking Example	799
25.8	Conclusions	801
	References	801
26	Reconfigurable Self-Activating Ion-Channel-Based Biosensors	805
	<i>Vikram Krishnamurthy and Bruce Cornell</i>	
26.1	Introduction	805
26.2	Biosensors Built of Ion Channels	807
26.3	Joint Input Excitation Design and Concentration Classification for Biosensor	812
26.4	Decentralized Deployment of Dense Network of Biosensors	816
26.5	Discussion and Extensions	826
	References	827
27	Biochemical Transport Modeling, Estimation, and Detection in Realistic Environments	831
	<i>Mathias Ortner and Arye Nehorai</i>	
27.1	Introduction	831
27.2	Physical and Statistical Models	832
27.3	Transport Modeling Using Monte Carlo Approximation	835
27.4	Localizing the Source(s)	843
27.5	Sequential Detection	846
27.6	Conclusion	849
	References	851
28	Security and Privacy for Sensor Networks	855
	<i>Wade Trappe, Peng Ning and Adrian Perrig</i>	
28.1	Introduction	855
28.2	Security and Privacy Challenges	856
28.3	Ensuring Integrity of Measurement Process	860
28.4	Availability Attacks against the Wireless Link	868
28.5	Ensuring Privacy of Routing Contexts	876
28.6	Conclusion	882
	References	883
	Index	889