

Wireless Sensor Networks

Signal Processing and Communications Perspectives

Edited by

Ananthram Swami
Army Research Laboratory, USA

Qing Zhao
University of California at Davis, USA

Yao-Win Hong
National Tsing Hua University, Taiwan

Lang Tong
Cornell University, USA



John Wiley & Sons.

Wireless Sensor Networks

Wireless Sensor Networks

Signal Processing and Communications Perspectives

Edited by

Ananthram Swami
Army Research Laboratory, USA

Qing Zhao
University of California at Davis, USA

Yao-Win Hong
National Tsing Hua University, Taiwan

Lang Tong
Cornell University, USA



John Wiley & Sons.

Copyright © 2007

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester,
West Sussex PO19 8SQ, England

Telephone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk

Visit our Home Page on www.wileyeurope.com or www.wiley.com

All Rights Reserved. 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 under the terms of the Copyright, Designs and Patents Act 1988 or under the terms of a licence issued by the Copyright Licensing Agency Ltd, 90 Tottenham Court Road, London W1T 4LP, UK, without the permission in writing of the Publisher. Requests to the Publisher should be addressed to the Permissions Department, John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England, or emailed to permreq@wiley.co.uk, or faxed to (+44) 1243 770620.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The Publisher is not associated with any product or vendor mentioned in this book. All trademarks referred to in the text of this publication are the property of their respective owners.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the Publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Other Wiley Editorial Offices

John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030, USA

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 42 McDougall Street, Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada Ltd, 6045 Freemont Blvd, Mississauga, Ontario, L5R 4J3, Canada

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Anniversary Logo Design: Richard J. Pacifico

Library of Congress Cataloging-in-Publication Data

Wireless sensor networks : signal processing and communications perspectives / edited by

A. Swami . . . [et al.].

p. cm.

Includes bibliographical references.

ISBN 978-0-470-03557-3 (cloth)

1. Sensor networks. 2. Wireless LANs. 3. Signal processing – Digital techniques. I. Swami, Ananthram.

TK7872.D48W585 2007

681'.2 – dc22

2007021100

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN: 978-0-470-03557-3 (HB)

Typeset in 10/12 Times by Laserwords Private Limited, Chennai, India

Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire

This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

Contents

List of Contributors	xiii
1 Introduction	1
Part I Fundamental Properties and Limits	7
2 Information-theoretic Bounds on Sensor Network Performance	9
<i>Michael Gastpar</i>	
2.1 Introduction	9
2.2 Sensor Network Models	10
2.2.1 The Linear Gaussian Sensor Network	12
2.3 Digital Architectures	14
2.3.1 Distributed Source Coding	14
2.3.2 Distributed Channel Coding	24
2.3.3 End-to-end Performance of Digital Architectures	31
2.4 The Price of Digital Architectures	33
2.5 Bounds on General Architectures	36
2.6 Concluding Remarks	38
Bibliography	39
3 In-Network Information Processing in Wireless Sensor Networks	43
<i>Arvind Giridhar and P. R. Kumar</i>	
3.1 Introduction	43
3.2 Communication Complexity Model	46
3.3 Computing Functions over Wireless Networks: Spatial Reuse and Block Computation	49
3.3.1 Geographical Models of Wireless Communication Networks	49
3.3.2 Block Computation and Computational Throughput	51
3.3.3 Symmetric Functions and Types	51
3.3.4 The Collocated Network	52
3.3.5 Subclasses of Symmetric Functions: Type-sensitive and Type-threshold	53
3.3.6 Results on Maximum Throughput in Collocated Networks	55

3.3.7	Multi-Hop Networks: The Random Planar Network	57
3.3.8	Other Acyclic Networks	59
3.4	Wireless Networks with Noisy Communications: Reliable Computation in a Collocated Broadcast Network	60
3.4.1	The Sum of the Parity of the Measurements	61
3.4.2	Threshold Functions	62
3.5	Towards an Information Theoretic Formulation	62
3.6	Conclusion	65
	Bibliography	66
4	The Sensing Capacity of Sensor Networks	69
	<i>Rohit Negi, Yaron Rachlin, and Pradeep Khosla</i>	
4.1	Introduction	69
4.1.1	Large-Scale Detection Applications	70
4.1.2	Sensor Network as an Encoder	71
4.1.3	Information Theory Context	73
4.2	Sensing Capacity of Sensor Networks	74
4.2.1	Sensor Network Model with Arbitrary Connections	74
4.2.2	Random Coding and Method of Types	76
4.2.3	Sensing Capacity Theorem	78
4.2.4	Illustration of Sensing Capacity Bound	83
4.3	Extensions to Other Sensor Network Models	84
4.3.1	Models with Localized Sensing	86
4.3.2	Target Models	87
4.4	Conclusion	88
	Bibliography	89
5	Law of Sensor Network Lifetime and Its Applications	93
	<i>Yunxia Chen and Qing Zhao</i>	
5.1	Introduction	93
5.2	Law of Network Lifetime and General Design Principle	94
5.2.1	Network Characteristics and Lifetime Definition	94
5.2.2	Law of Lifetime	95
5.2.3	A General Design Principle For Lifetime Maximization	96
5.3	Fundamental Performance Limit: A Stochastic Shortest Path Framework	96
5.3.1	Problem Statement	97
5.3.2	SSP Formulation	98
5.3.3	Fundamental Performance Limit on Network Lifetime	100
5.3.4	Computing the Limiting Performance with Polynomial Complexity in Network Size	101
5.4	Distributed Asymptotically Optimal Transmission Scheduling	103
5.4.1	Dynamic Protocol for Lifetime Maximization	104
5.4.2	Dynamic Nature of DPLM	105
5.4.3	Asymptotic Optimality of DPLM	106
5.4.4	Distributed Implementation	107
5.4.5	Simulation Studies	108

5.5	A Brief Overview of Network Lifetime Analysis	113
5.6	Conclusion	114
	Bibliography	114
Part II Signal Processing for Sensor Networks		117
6	Detection in Sensor Networks	119
	<i>Venugopal V. Veeravalli and Jean-François Chamberland</i>	
6.1	Centralized Detection	120
6.2	The Classical Decentralized Detection Framework	121
6.2.1	Asymptotic Regime	124
6.3	Decentralized Detection in Wireless Sensor Networks	124
6.3.1	Sensor Nodes	125
6.3.2	Network Architectures	126
6.3.3	Data Processing	127
6.4	Wireless Sensor Networks	127
6.4.1	Detection under Capacity Constraint	129
6.4.2	Wireless Channel Considerations	131
6.4.3	Correlated Observations	134
6.4.4	Attenuation and Fading	136
6.5	New Paradigms	139
6.5.1	Constructive Interference	139
6.5.2	Message Passing	140
6.5.3	Cross-Layer Considerations	141
6.5.4	Energy Savings via Censoring and Sleeping	141
6.6	Extensions and Generalizations	142
6.7	Conclusion	143
	Bibliography	144
7	Distributed Estimation under Bandwidth and Energy Constraints	149
	<i>Alejandro Ribeiro, Ioannis D. Schizas, Jin-Jun Xiao, Georgios B. Giannakis and Zhi-Quan Luo</i>	
7.1	Distributed Quantization-Estimation	150
7.2	Maximum Likelihood Estimation	150
7.2.1	Known Noise pdf with Unknown Variance	152
7.3	Unknown Noise pdf	156
7.3.1	Lower Bound on the MSE	160
7.4	Estimation of Vector Parameters	160
7.4.1	Colored Gaussian Noise	162
7.5	Maximum a Posteriori Probability Estimation	165
7.5.1	Mean-Squared Error	166
7.6	Dimensionality Reduction for Distributed Estimation	167
7.6.1	Decoupled Distributed Estimation-Compression	168
7.6.2	Coupled Distributed Estimation-Compression	171
7.7	Distortion-Rate Analysis	172
7.7.1	Distortion-Rate for Centralized Estimation	174

7.7.2	Distortion-Rate for Distributed Estimation	178
7.7.3	D-R Upper Bound via Convex Optimization	180
7.8	Conclusion	181
7.9	Further Reading	182
	Bibliography	183
8	Distributed Learning in Wireless Sensor Networks	185
	<i>Joel B. Predd, Sanjeev R. Kulkarni, and H. Vincent Poor</i>	
8.1	Introduction	185
8.2	Classical Learning	188
8.2.1	The Supervised Learning Model	188
8.2.2	Kernel Methods and the Principle of Empirical Risk Minimization	189
8.2.3	Other Learning Algorithms	191
8.3	Distributed Learning in Wireless Sensor Networks	192
8.3.1	A General Model for Distributed Learning	193
8.3.2	Related Work	196
8.4	Distributed Learning in WSNs with a Fusion Center	197
8.4.1	A Clustered Approach	198
8.4.2	Statistical Limits of Distributed Learning	198
8.5	Distributed Learning in Ad-hoc WSNs with In-network Processing	201
8.5.1	Message-passing Algorithms for Least-Squares Regression	202
8.5.2	Other Work	208
8.6	Conclusion	208
	Bibliography	209
9	Graphical Models and Fusion in Sensor Networks	215
	<i>Müjdat Çetin, Lei Chen, John W. Fisher III, Alexander T. Ihler, O. Patrick Kreidl, Randolph L. Moses, Martin J. Wainwright, Jason L. Williams, and Alan S. Willsky</i>	
9.1	Introduction	215
9.2	Graphical Models	216
9.2.1	Definitions and Properties	217
9.2.2	Sum-Product Algorithms	218
9.2.3	Max-Product Algorithms	219
9.2.4	Loopy Belief Propagation	220
9.2.5	Nonparametric Belief Propagation	220
9.3	From Sensor Network Fusion to Graphical Models	222
9.3.1	Self-Localization in Sensor Networks	222
9.3.2	Multi-Object Data Association in Sensor Networks	224
9.4	Message Censoring, Approximation, and Impact on Fusion	226
9.4.1	Message Censoring	227
9.4.2	Trading Off Accuracy for Bits in Particle-Based Messaging	228
9.5	The Effects of Message Approximation	230
9.6	Optimizing the Use of Constrained Resources in Network Fusion	233
9.6.1	Resource Management for Object Tracking in Sensor Networks	234
9.6.2	Distributed Inference with Severe Communication Constraints	239

9.7 Conclusion	243
Bibliography	246
Part III Communications, Networking and Cross-Layered Designs	251
10 Randomized Cooperative Transmission in Large-Scale Sensor Networks	253
<i>Birsen Sirkeci-Mergen and Anna Scaglione</i>	
10.1 Introduction	253
10.2 Transmit Cooperation in Sensor Networks	254
10.2.1 Physical Layer Model for Cooperative Radios	254
10.2.2 Cooperative Schemes with Centralized Code Assignment	256
10.3 Randomized Distributed Cooperative Schemes	257
10.3.1 Randomized Code Construction and System Model	257
10.4 Performance of Randomized Cooperative Codes	260
10.4.1 Characterization of the Diversity Order	260
10.4.2 Simulations and Numerical Evaluations	263
10.5 Analysis of Cooperative Large-scale Networks Utilizing Randomized Cooperative Codes	265
10.5.1 Numerical Evaluations and Further Discussions	268
10.6 Conclusion	272
10.7 Appendix	272
Bibliography	274
11 Application Dependent Shortest Path Routing in Ad-Hoc Sensor Networks	277
<i>Saswat Misra, Lang Tong, and Anthony Ephremides</i>	
11.1 Introduction	277
11.1.1 Major Classifications	279
11.2 Fundamental SPR	279
11.2.1 Broadcast Routing	280
11.2.2 Static Shortest Path Routing	281
11.2.3 Adaptive Shortest Path Routing	289
11.2.4 Other Approaches	289
11.3 SPR for Mobile Wireless Networks	290
11.3.1 Broadcast Methods	290
11.3.2 Shortest Path Routing	291
11.3.3 Other Approaches	293
11.4 SPR for Ad-Hoc Sensor Networks	294
11.4.1 A Short Survey of Current Protocols	294
11.4.2 An Argument for Application Dependent Design	296
11.4.3 Application Dependent SPR: An Illustrative Example	296
11.5 Conclusion	305
11.6 A Short Review of Basic Graph Theory	305
11.6.1 Undirected Graphs	305
11.6.2 Directed Graphs	306
Bibliography	307

12 Data-Centric and Cooperative MAC Protocols for Sensor Networks	311
<i>Yao-Win Hong and Pramod K. Varshney</i>	
12.1 Introduction	311
12.2 Traditional Medium Access Control Protocols: Random Access and Deterministic Scheduling	313
12.2.1 Carrier Sense Multiple Access (CSMA)	313
12.2.2 Time-Division Multiple Access (TDMA)	314
12.3 Energy-Efficient MAC Protocols for Sensor Networks	315
12.4 Data-Centric MAC Protocols for Sensor Networks	318
12.4.1 Data Aggregation	318
12.4.2 Distributed Source Coding	319
12.4.3 Spatial Sampling of a Correlated Sensor Field	321
12.5 Cooperative MAC Protocol for Independent Sources	323
12.6 Cooperative MAC Protocol for Correlated Sensors	327
12.6.1 Data Retrieval from Correlated Sensors	328
12.6.2 Generalized Data-Centric Cooperative MAC	336
12.6.3 MAC for Distributed Detection and Estimation	340
12.7 Conclusion	343
Bibliography	344
13 Game Theoretic Activation and Transmission Scheduling in Unattended Ground Sensor Networks: A Correlated Equilibrium Approach	349
<i>Vikram Krishnamurthy, Michael Maskery, and Minh Hanh Ngo</i>	
13.1 Introduction	349
13.1.1 UGSN Sensor Activation and Transmission Scheduling Methodology	350
13.1.2 Fundamental Tools and Literature	351
13.2 Unattended Ground Sensor Network: Capabilities and Objectives	353
13.2.1 Practicalities: Sensor Network Model and Architecture	354
13.2.2 Energy-Efficient Sensor Activation and Transmission Control	355
13.3 Sensor Activation as the Correlated Equilibrium	358
13.3.1 From Nash to Correlated Equilibrium – An Overview	358
13.3.2 Adaptive Sensor Activation through Regret Tracking	360
13.3.3 Convergence Analysis of Regret-based Algorithms	363
13.4 Energy-Efficient Transmission Scheduling	365
13.4.1 Outline of Markov Decision Processes and Supermodularity	366
13.4.2 Optimal Channel-Aware Transmission Scheduling as a Markov Decision Process	367
13.4.3 Optimality of Threshold Transmission Policies	370
13.5 Numerical Results	374
13.5.1 UGSN Sensor Activation Algorithm	374
13.5.2 Energy Throughput Tradeoff via Optimal Transmission Scheduling	378
13.6 Conclusion	381

CONTENTS

13.7 Appendix	382
13.7.1 List of Symbols	382
13.7.2 Proof of Lemma 13.4.3	383
13.7.3 Proof of Theorem 13.4.4	383
Bibliography	385
Index	389

List of Contributors

Müjdat Çetin

Sabanci University
Faculty of Engineering and Natural
Sciences
Orhanli – Tuzla
34956 Istanbul
mctin@sabanciuniv.edu

Jean-François Chamberland

Texas A&M University
Department of Electrical and Computer
Engineering
College Station, TX 77843-3128
USA
chmbrlnd@tamu.edu

Lei Chen

Massachusetts Institute of Technology
77 Massachusetts Avenue, 32-D568
Cambridge, MA 02139
USA
lchen@mit.edu

Yunxia Chen

Department of Electrical and Computer
Engineering
University of California, Davis
Davis, CA 95616
USA
yxchen@ece.ucdavis.edu

Anthony Ephremides

Dept. of Electrical Engineering
University of Maryland
College Park, MD 20742
USA
etony@ece.umd.edu

John W. Fisher III

Massachusetts Institute of Technology
77 Massachusetts Avenue, 32-D468
Cambridge, MA 02139
USA
fisher@csail.mit.edu

Michael Gastpar

University of California, Berkeley
Department of Electrical Engineering and
Computer Sciences
265 Cory Hall
Berkeley, CA 94110-1770
USA
gastpar@eecs.berkeley.edu

Georgios B. Giannakis

Dept. of Electrical and Computer
Engineering
University of Minnesota
200 Union Street SE
Minneapolis, MN 55455,
USA
georgios@umn.edu

Arvind Giridhar

Interest Rate Products Strategies, FICC
Goldman Sachs & Co
85 Broad Street, New York, NY 10004
USA
arvind.giridhar@gmail.com

Yao-Win Hong

101 Section 2 Kuang-Fu Rd.
National Tsing Hua University
EECS Building 620B

Hsinchu, 30013
Taiwan
ywhong@ee.nthu.edu.tw

Alexander T. Ihler

Toyota Technological Institute
University Press Building
1427 East 60th Street, Second Floor
Chicago, Illinois 60637
USA
ihler@tti-c.org

Pradeep Khosla

Department of Electrical and Computer
Engineering
Carnegie Mellon University
5000 Forbes Ave
Carnegie Mellon University
Pittsburgh
PA 15213
USA
pkk@ece.cmu.edu

O. Patrick Kreidl

Massachusetts Institute of Technology
77 Massachusetts Avenue, 32-D572
Cambridge, MA 02139
USA
opk@mit.edu

Vikram Krishnamurthy

Department of Electrical and Computer
Engineering
University of British Columbia
Vancouver, V6T 1Z4
Canada
vikramk@ece.ubc.ca

Sanjeev R. Kulkarni

Department of Electrical Engineering
Princeton University
Princeton, NJ 08540
USA
kulkarni@princeton.edu

P.R. Kumar

University of Illinois

CSL
1308 West Main Street
Urbana, IL 61801
USA
prkumar@uiuc.edu

Zhi-Quan Luo

Dept. of Electrical and Computer
Engineering
University of Minnesota
200 Union Street SE
Minneapolis, MN 55455,
USA
luozq@umn.edu

Michael Maskery

Department of Electrical and Computer
Engineering
University of British Columbia
Vancouver, V6T 1Z4
Canada
mikem@ece.ubc.ca

Saswat Misra

Army Research Laboratory
AMSRD-ARL-CI-CN
2800 Powder Mill Rd.
Adelphi, MD 20783
USA
sm353@cornell.edu

Randolph L. Moses

708 Drees Laboratory
Department of Electrical and Computer
Engineering
The Ohio State University
2015 Neil Avenue
Columbus, OH 43210
USA
moses.2@osu.edu

Rohit Negi

Department of Electrical and Computer
Engineering
Carnegie Mellon University
5000 Forbes Ave

Carnegie Mellon University
Pittsburgh, PA 15213
USA
negi@ece.cmu.edu

Minh Hanh Ngo
Department of Electrical and Computer
Engineering
University of British Columbia
Vancouver V6T 1Z4
Canada
minhn@ece.ubc.ca

H. Vincent Poor
Department of Electrical
Engineering
Princeton University
Princeton, NJ 08540
USA
poor@princeton.edu

Joel B. Predd
RAND Corporation
4570 Fifth Avenue
Pittsburgh, PA 15213
USA
jpredd@rand.org

Yaron Rachlin
Accenture Technology Labs
161 North Clark Street
Chicago, IL 60601
USA
yaron.rachlin@alumni.cmu.edu

Alejandro Ribeiro
Department of Electrical and Computer
Engineering
University of Minnesota
200 Union Street SE
Minneapolis, MN 55455
USA
aribeiro@ece.umn.edu

Anna Scaglione
Cornell University

School of Electrical and Computer
Engineering
325 Rhodes Hall
Ithaca, NY 14853
USA
anna@ece.cornell.edu

Ioannis D. Schizas
Dept. of Electrical and Computer
Engineering
University of Minnesota
200 Union Street SE
Minneapolis, MN 55455
USA
schiz001@umn.edu

Birsen Sirkeci-Mergen
UC Berkeley
EECS Department
273 Cory Hall
University of California
Berkeley, CA 94720
USA
bs233@eecs.berkeley.edu

Ananthram Swami
PO Box 4640
Silver Spring
MD 20914-4640
USA
a.swami@ieee.org

Lang Tong
School of Electrical and Computer
Engineering
Center for Applied Mathematics
384 Frank H.T. Rhodes Hall
Cornell University
Ithaca, NY 14853
USA
ltong@ece.cornell.edu

Pramod K. Varshney
Department of Electrical Engineering and
Computer Science
335 Link Hall

Syracuse University
Syracuse
New York 13244
USA
varshney@syr.edu

Venugopal V. Veeravalli

ECE Department and Coordinated
Science Lab
University of Illinois at Urbana-Champaign
1308 West Main Street
Urbana IL 61801
USA
vvv@uiuc.edu

Martin J. Wainwright

University of California at Berkeley
Department of Electrical Engineering and
Computer Sciences
263 Cory Hall
Berkeley, CA 94720
USA
wainwrig@eecs.berkeley.edu

Jason L. Williams

Massachusetts Institute of Technology
77 Massachusetts Avenue, 32-D572

Cambridge, MA 02139
USA
jlwil@mit.edu

Alan S. Willsky

Massachusetts Institute of Technology
77 Massachusetts Avenue, 32-D582
Cambridge, MA 02139
USA
willsky@mit.edu

Jin-Jun Xiao

Dept. of Electrical and Systems
Engineering
Washington University
One Brookings Drive
St. Louis, MO 63130
USA
xiao@ese.wustl.edu

Qing Zhao

Department of Electrical and Computer
Engineering
University of California Davis
Davis, CA 95616
USA
qzhao@ece.ucdavis.edu

1

Introduction

Modern wireless sensor networks are made up of a large number of inexpensive devices that are networked via low power wireless communications. It is the networking capability that fundamentally differentiates a sensor network from a mere collection of sensors, by enabling cooperation, coordination, and collaboration among sensor assets. Harvesting advances in the past decade in microelectronics, sensing, analog and digital signal processing, wireless communications, and networking, wireless sensor network technology is expected to have a significant impact on our lives in the twenty-first century. Proposed applications of sensor networks include environmental monitoring, natural disaster prediction and relief, homeland security, healthcare, manufacturing, transportation, and home appliances and entertainment. Sensor networks are expected to be a crucial part in future military missions, for example, as embodied in the concepts of network centric warfare and network-enabled capability.

Wireless sensor networks differ fundamentally from general data networks such as the internet, and as such they require the adoption of a different design paradigm. Often sensor networks are application specific; they are designed and deployed for special purposes. Thus the network design must take into account the specific intended applications. More fundamentally, in the context of wireless sensor networks, the broadcast nature of the medium must be taken into account. For battery-operated sensors, energy conservation is one of the most important design parameters, since replacing batteries may be difficult or impossible in many applications. Thus sensor network designs must be optimized to extend the network lifetime. The energy and bandwidth constraints and the potential large-scale deployment pose challenges to efficient resource allocation and sensor management. A general class of approaches – cross-layer designs – has emerged to address these challenges. In addition, a rethinking of the protocol stack itself is necessary so as to overcome some of the complexities and unwanted consequences associated with cross-layer designs.

This edited book focuses on theoretical aspects of wireless sensor networks, aiming to provide signal processing and communication perspectives on the design of large-scale sensor networks. Emphasis is on the fundamental properties of large-scale sensor networks, distributed signal processing and communication algorithms, and novel cross-layer design paradigms for sensor networking.

The design of a sensor network requires the fusion of ideas from several disciplines. Of particular importance are the theories and techniques of distributed signal processing, recent advances in collaborative communications, and methodologies of cross-layer design.

This book elucidates key issues and challenges, and the state-of-the-art theories and techniques for the design of large-scale wireless sensor networks. For the signal processing and communications research community, the book provides ideas and illustrations of the application of classical theories and methods in an emerging field of applications. For researchers and practitioners in wireless sensor networks, this book complements existing texts with the infusion of analytical tools that will play important roles in the design of future application-specific wireless sensor networks. For students at senior and the graduate levels, this book identifies research directions and provides tutorials and bibliographies to facilitate further investigations.

The book is divided into three parts: I Fundamental Properties and Limits; II Signal Processing for Sensor Networks; and III Communications, Networking and Cross-Layer Designs.

Part I Fundamental Properties and Limits

Despite the remarkable theoretical advances in link-level communications, scientific understanding of and design methodologies for large-scale complex networks, such as wireless sensor networks, are still primitive. The variety of potential applications and sensor devices, the dynamics and unreliability of the wireless communication medium, and the stringent resource constraints all present major obstacles to a fundamental understanding of the structure, behavior, and dynamics of large-scale possibly heterogeneous sensor networks.

Part I presents representative samples of recent developments in the discovery of fundamental properties and performance limits of large-scale sensor networks. The aim is to show that despite the vast differences in applications and communication environments, there exist universal laws and performance bounds, especially in the asymptotic regime, that may lead to systematic approaches to the design of such large-scale complex networks.

Chapter 2 by Gastpar focuses on communication aspects: the rate and fidelity of transporting sensor measurements to a fusion center for data processing. Based on a digital communication architecture that separates source coding from channel coding, limits on the achievable rate-distortion regions under power constraints are presented. Compelling examples are given to illustrate the possible performance loss incurred by such a separated design.

Chapter 3 by Giridhar and Kumar addresses in-network information processing. Instead of transmitting measurements to a fusion center for processing, sensor nodes are responsible for computing a certain function of all measurements, for example, the mean or the maximum, through inter-node communications. The quantities of interest are the maximum rate at which such in-network computation can be performed and how it scales with network size. Interestingly, the scaling behavior depends not only on the communication topology of the network, but also on the properties of the function being calculated.

Chapter 4 by Negi, Rachlin, and Khosla is concerned with the fundamental relationship between the number of sensor measurements and the ability of the network to identify the state of the environment being monitored. The focus of the chapter is on detection problems where the number of possible hypotheses is large. For this problem of

large-scale detection, a lower limit on the sensing capacity of sensor networks is derived that characterizes the minimum rate at which the number of sensor measurements should scale with the number of hypotheses in order to achieve the desired detection accuracy. An intriguing analogy between the sensing capacity of sensor networks and channel coding theory for communication channels points to the possibility of porting the large body of results available on communication channels to the design of large-scale sensor networks.

The last chapter of Part I by Chen and Zhao focuses on the lifetime of sensor networks to address the energy constraint. Given that the sensor network lifetime depends on network architectures, specific applications, and various parameters across the entire protocol stack, an accurate characterization of network lifetime as a function of key design parameters is notably difficult to obtain. It is shown in this chapter that there is, in fact, a simple law that governs the network lifetime for all applications (event-driven, clock-driven, or query-driven), under any network configuration (centralized, ad hoc, or hierarchical). This law of network lifetime reveals the key role of two physical layer parameters – residual energy and channel state – and a general principle for the design of upper layer network protocols.

This set of four chapters points to promising directions toward a scientific understanding of core principles and fundamental properties of large complex sensor networks. Many problems, however, remain. When is the separated design of source coding and channel coding sufficient to achieve the best scaling behavior? How can delay and energy constraints be adequately modeled within the information theoretic framework? What are the fundamental tradeoffs between communication and computation under energy and complexity constraints? These are only a few of the many challenges we face in advancing the basic science of large-scale wireless sensor networks.

Part II Signal Processing for Sensor Networks

Part II of this book focuses on signal processing problems in sensor networks. Fundamental to sensor signal processing are distributed information processing at the individual sensor nodes and the fusion of sensor measurements for global signal processing.

Distributed detection is a classical subject that attracted considerable interest in the late 1980s and early 1990s when the power of DSP and wired communications enabled the networking of distributed radar systems for target detection and tracking. Radars generate enormous amount of data, and transmitting all the measurements to a central processing location is neither feasible nor necessary. The natural research focus then was how to quantize measurements at the local sensor nodes and how to derive optimal inference algorithm at the fusion center.

While many technical issues in classical distributed detection remain in modern wireless sensor networks, several new challenges have arisen. The fading and broadcast aspects of the wireless transmission medium, the presence of interference, and constraints on energy and power demand a new design paradigm. Chapter 6 by Veeravalli and Chamberland is an introduction to distributed detection for modern wireless sensor networks. This chapter provides an informative survey of classical results and sheds new light on the interplay among quantization, sensor fusion under resource constraints, and optimal detection performance. The approach based on asymptotic statistical techniques is especially appropriate for large sensor networks.

Distributed estimation deals with statistical inference problems when the underlying phenomenon cannot be modeled by a few disjoint hypotheses; there are in general innumerable possible distributions from which sensor measurements are generated. It is thus not possible to design a sensor quantization scheme that is uniformly optimal. Chapter 7 on distributed estimation by Ribeiro, Schizas, Xiao, Giannakis and Luo provides a broad coverage of estimation problems in wireless sensor networks when sensor measurements must be quantized or compressed. Both point estimation and Bayesian setups are considered, and performance bounds provided.

Chapter 8 on distributed learning by Predd, Kulkarni, and Poor introduces learning theory and techniques for sensor networks. The focus here is on nonparametric statistical inference under bandwidth and energy constraints. The authors develop a framework for distributed learning and draw connections with classical concepts. Different network architectures and learning techniques are presented.

Chapter 9 by Çetin, Chen, Fisher, Ihler, Moses, Wainwright, Williams and Willsky introduces graphical models and fusion for sensor networks. Statistical correlations in sensor measurements have a natural graphical model representation in which the graph vertices represent the random variables and corresponding edges their statistical dependency. The study of graphical models has led to fundamental insights in coding and decoding techniques in communications. For statistical inference using wireless sensor networks, one can take the view that inference should be derived from *a posteriori* distributions (belief), and the calculation of such distributions in a distributed fashion is at the core of sensor information processing. This chapter provides an introduction to various message passing techniques and their applications in sensor self-localization, tracking, and data association problems. Energy and bandwidth constraints are once again key design parameters.

The set of four chapters in Part II have explored important aspects of signal processing in sensor networks, including detection, estimation, learning and fusion. However, many challenges remain. What is the role of quantization when nodes must code their bits to cope with fading and noisy channels, or when they must otherwise packetize the data? What is the right architecture for decentralized inference in a sensor network, keeping in mind that the sensing graph is not identical to the communications graph? How should multi-hop delays and temporal (de)correlation be modeled and handled? What is the role of collaboration and consensus in a sensor network? Given that energy and bandwidth constraints are severe, overhead in bits (e.g., in the headers, or number of messages) or Joules (e.g., energy consumed in processing, reception, and transmission) should not be ignored. Finally, while asymptotic analyses provide critical insights and design guidelines, issues related to finite networks need to be explored.

Part III Communications, Networking and Cross-Layered Designs

Conventional networking and communication protocols provide generic designs that are suitable for a large number of applications and utilize performance measures such as throughput, fairness, delay and bit-error-rate (BER) etc. as design criteria. These methods are suitable for applications such as telecommunications or computer data networks, where

users act as equal individuals and transmit messages that have little relation with others. The main concern in these cases is the quality-of-service (QoS) that each user receives.

In contrast to conventional communication and data networks, sensor networks consist of users that are deployed to achieve a common goal, to sense a common event or to measure highly correlated data due to the spatial correlation of most physical phenomenon. The sensors are cooperative in nature and should work together to fulfill their application needs. In fact, two properties of sensor networks can be exploited to improve communication efficiency: the *cooperative nature* of the sensors and *application-dependent* performance measures. In Part III of this book, we gather four chapters that consider these properties in the design of physical-layer transmissions, medium access control policies, routing protocols, sensor actuation and transmission scheduling.

Cooperation can be applied to many areas of communications and networking. At the physical layer, cooperation has been realized by allowing users to relay messages and by adopting signal-combining techniques at the destination to enhance reception. Diversity and multiplexing gains can thereby be achieved by exploiting the independent fading paths attained through cooperative relaying. Local resources such as battery-energy and channel bandwidth can be shared among sensors and optimally allocated from a system-wide perspective. This differs from that in conventional networks where fairness is a critical issue and may reduce the effectiveness of cooperation. In Chapter 10 by Sirkeci-Mergen and Scaglione, a tutorial review of cooperative communication schemes is given along with novel randomized approaches that are used to reduce the system complexity and to enhance the bandwidth efficiency of cooperative methods.

The efficiency of resource utilization can be further improved if the network is designed to optimize application-dependent performance measures. Specifically, data aggregation has been proposed to reduce traffic in multi-hop sensor networks. In contrast to data networks, here data that are unreliable or have low information context can be dropped. The efficiency of data aggregation techniques is highly dependent on the specific routing algorithm. For example, in data gathering applications, sensors may compress the incoming data along with their local data before relaying to the next sensor in the multi-hop route. In this case, the compression efficiency is highly dependent on the correlation between the measurements of the sensors in neighboring hops. A discussion of cross-layer routing protocols is given in Chapter 11 by Misra, Tong and Ephremides. Emphasis is placed on distributed detection applications where the performance depends on the data gathered through the multi-hop transmission routes.

An efficient sensor network MAC protocol also plays an important role in improving the efficiency of resource utilization. Conventional MAC protocols are designed for users that have independent data to transmit and that are competing for the use of the channel. The goal is to avoid interference and collision between different users. In contrast, in a well-designed cooperative sensor network, users that access the same channel simultaneously may improve the detection performance, as opposed to causing interference or collision. A survey of sensor network MAC protocols and design concepts for cooperative MAC protocols is given in Chapter 12 by Hong and Varshney. More interestingly, the cooperative advantages are further exploited by taking into consideration the properties of the underlying application or the statistics of the sensors' measurements. It is shown that MAC efficiency can be improved by allocating the same transmission channel to users that have highly

correlated messages to transmit. Examples are given for two specific sensor applications: a data gathering application and a distributed detection application.

Duty-cycling is a technique used to reduce energy consumption and extend network lifetime. Nodes may enter a sleep state when their presence is not necessary to maintain the functionality of the system, e.g., when no event occurs in the sensor's vicinity or when no message is routed through the sensor. In this case, the activation of sensors should be optimized according to the statistics of the underlying measurements or the goal of the application. Due to the large-scale deployment of sensors, no centralized control can be applied to schedule the activation period of the sensors and, therefore, decentralized methods are required. In Chapter 13 by Krishnamurthy, Maskery and Ngo, decentralized sensor activation and transmission scheduling methods are discussed from a game-theoretic point of view. The sensors are able to learn the reliability of their measurements and decide locally when they should schedule their activation and transmissions.

In Part III, the importance of cross-layer communication and networking protocols is emphasized. These theoretical studies can provide insights for sensor network design. Nevertheless, caution should be taken when designing cross-layer strategies since it may obviate the advantages of modularization and result in high system complexity. Moreover, when only partial functionalities of two modules are jointly optimized, it is not clear whether the remaining functionalities will be as effective as before. These issues should also be taken into consideration in the future design of sensor systems.

Part I

Fundamental Properties and Limits

- Cooperative transmission, 253–60, 266, 270, 274
 - amplify-and-forward (AF), 256–7
 - cooperative communication, 254, 323–7
 - cooperative networks, 257
 - cooperative radios, 254, 257
 - cooperative relay, 254, 255, 256
 - cooperative protocol, 254, 257, 265
 - cooperative schemes, 255, 256, 257, 259
 - decode-and-forward (DF), 256–7
 - transmit cooperation, 254–7
- Correlation-based Collaborative MAC (CC-MAC), 322–3
- Coupled distributed
 - estimation-compression, 171
- Coupled sensor observations, 171
- Cramer Rao lower bound (CRLB), 150, 155, 160, 165
- CSI, 96, 104–6, 108–9, 112, 369
- CSMA, *see Carrier Sense Multiple Access*
- CTS, *see Clear-To-Send*
- cut-set bounds, 25–26, 28–30, 36–37
- D-MAC, 317
- Data Aggregation, 318
- data association, 224
- Data-Centric MAC, 318
- Data Gathering, 328–40
- data processing inequality, 33
- DCF, *see Distributed Coordination Function*
- decentralized detection, 240
- decision state, 236
- Decision Tree, *see Tree, Decision*
- dependence-balance bound, 27–28
- Detection, 119–20
 - asymptotic regime, 124
 - change point, 143
 - correlated observations, 134
 - decentralized, 119, 121, 124 *see Detection, Distributed*
 - sequential, 143
- Detection, Distributed, 119, 121, 124, 240, 340–3
- Differential inclusion, 351–2
- Digital-amplitude data, 172
- Dijkstra’s algorithm, 283
- Dimensionality reduction, 150, 167, 170, 181, 182
- Distance vector routing, 292
- Distortion-rate (D-R) function, 172–5, 178–9, 182
- Distortion-rate analysis, 172, 174
- Distributed Coordination Function (DCF), 314
- Distributed Detection, *see Detection, Distributed*
- Distributed Estimation, *see Estimation, Distributed*, 149
- Distributed Source Coding, 14–23, 319–21
- Distributed source compression, 64
- Diversity, 256, 260–5, 267, 271
 - deep fade, 260, 261, 271
 - delay diversity, 259, 260
 - fractional diversity, 262, 275
- DPLM, 104–13
- dual optimization, 236
- Dynamic programming, 352, 367, 370, 381
 - Lagrangian dynamic programming, 373, 382
- Dynamic protocol for lifetime maximization, *see DPLM*
- dynamic range, 231
- Eigenvalue decomposition, 169, 174, 176, 179
- Encoder, 174–6, 178–80
- Energy-efficiency index, 104–5, 107–8
- entropy, 235
- Equality testing function, 48
- Equivalent noise increase, 163, 166
- Equivalent noise powers, 163
- Error exponent, 124
- Estimate-first compress afterwards (EC), 170, 182
- Estimation, Distributed, 340–3
- Estimator
 - Unbiased estimator, 151, 159
 - Universal estimator, 158

- Fading channel, 167, 172, 182
 - correlated, 365, 368–9
 - FSMC, 368–9
- Fictitious play, 360
- Fisher Information Matrix (FIM), 163, 166
- Flooding, 280, 290
- Fooing set technique, 48
- Fusion center, 119, 121, 126, 151
- Game theory, 350, 351, 358–9
 - equilibrium, correlated, 350, 351, 359
 - equilibrium, Nash, 359
 - learning, adaptive, 360.
 - noncooperative, 358
- Gaussian CEO problem, 174, 180
- Gauss-Seidel iteration, 241
- Graph theory, 305
 - undirected graphs, 305
 - directed graphs, 306
- graphical model, 217
- Group Testing, 328–9, 339
- GTS, *see Guaranteed Time Slots*
- Guaranteed Time Slots (GTS), 315
- Hammersley-Clifford Theorem, 217
- IEEE 802.11, 314–15, 325–6
- IEEE 802.15.4, 314–15
- Incidence observations, 164
- Inference problems, 119
- information pull, 233
- information push, 233
- In-network processing, 44
- Interior point method, 181
- Karush-Kuhn-Tucker (KKT) conditions, 169
- KD-tree, 221, 229
- KL-divergence, 229
- Koerner-Marton problem, 22, 32, 35
- Kullback-Leibler divergence, 235
- Lagrange multiplier, 170
- Lagrangian, 169
- Langrangian relaxation, 236
- Large deviations, 124
- large-scale detection 70
 - robotic mapping 70
 - chemical sensors 70
- Learning, correlated equilibrium 350, 360
- Liapunov stability, 363–5
- Likelihood ratio, 120, 123
- Limiting performance, 94, 97, 101, 103, 106–7
- Link failures, 286
 - routing loops, 286
 - count-to-infinity, 287
- Link state routing, 292
- link-use-rate, 240
- Log-likelihood, 161, 164, 166
- loopy belief propagation, 220
- MAC, *see Medium Access Control or multi-access channel*
- MACA Wireless (MACAW), 314
- MACA, *see Multiple Access with Collision Avoidance*
- Markov chain, 178, 363, 368
- Markov decision process, 98
- Markov decision process, MDP, 350, 352, 366, 367–74
 - constrained, 373, 382
 - expected total cost, 370
 - value function, 370
 - optimal cost to go, *see value function*
 - state action cost, 370
- Markov property, 217
- Markov random fields, 88, 216
- Markovianity, 217
- maximal correlation, 37
- Maximum a posteriori (MAP), 165
- Maximum Likelihood Detector, 327
- Maximum Likelihood Estimation (MLE), 150, 151, 160, 165
- Quantized observations, 150
- Known noise pdf, 151, 159
- Unknown variance noise, 152, 159
- Invariance property, 151, 153, 159

- max-marginals, 219
- max-product algorithm, 219
- Mean Squared Error (MSE), 150, 157, 160, 165, 166
- Medium Access Control (MAC), 311–48
 - ALOHA, 315, 320
 - Carrier Sense Multiple Access (CSMA), 313–14, 322
 - Correlation-based Collaborative MAC, 322–3
 - Data-Centric MAC, 318
 - D-MAC, 317
 - Energy Efficient MAC Protocols, 315
 - MACA Wireless, 314
 - Multiple Access with Collision Avoidance (MACA), 313–14
 - S-MAC, 317
 - T-MAC, 317
 - Time Division Multiple Access (TDMA), 314–15.
 - WiseMAC, 316
- Memoryless source, 173
- Message passing, 140
- message schedule, 227
- Minimum weight spanning trees, 280
 - Prim-Dijkstra algorithm, 281
- multi-access channel, 24–31
- Multicarrier modulation, 167
- Multi-hop, 254, 265, 274
- Multiple Access with Collision Avoidance (MACA), 313–14
- Multi-sensor optimization, 168, 171
- Mutual information, 175, 235
- NBP, 221
- Network age, 105, 108, 112
- Network behavior, 254, 265–75
 - broadcast, 254, 265, 266, 272
 - continuum model, 254, 267, 268, 272
 - narrowband network, 267–9
 - wideband network, 267–9
- Network coding, 45
- Network lifetime, 93–101, 106–113
 - law of, 94–6, 99, 104
- network source/channel separation
 - theorems, 36
 - counter-examples, 33–35
- Networks
 - flat ad hoc, 94
 - hierarchical, 94
 - clock-driven, 94
 - event-driven, 94
 - demand-driven, 94
- node-error-rate, 240
- non-parametric belief propagation, 220, 221
- Non-parametric estimation, 156
- Numerical integration, 157, 158
 - trapezoidal rule, 157, 158
 - Simpson's rule, 157
 - Newton-Cotes formulas, 157
- ODE method, 351, 364
- OLFC, 236
- open loop feedback control, 236
- Opportunistic carrier sensing, 104, 107–8
- Orthogonal channels, 168, 174
- Orthogonality principle, 178
- Packet switching, 279
 - virtual circuit based, 279
 - datagram based, 279
- Parity function, 61
- partially observed Markov decision process, 235
- partition function, 217
- PCF, *see Point Coordinated Function*
- person-by-person optimality, 241
- Phase transition, 254, 269, 272
- Point Coordinated Function (PCF), 315
- Policy, 100, 102–3, 106
 - stationary, 100–1
 - optimal, 97, 101, 106
- potential functions, 217
- Proactive routing, 292
- Protocol
 - pure opportunistic, 104–11
 - pure conservative, 104, 108–11
 - max-min, 108–11

- Quantization, 151, 166
- Quantization signal to noise ratio (Q-SNR), 152, 158
- Quantization-Estimation, 150, 152
- Quantized Observations 150
- Random increments, 180
- Random Multi-Hop Wireless Networks, 49
- Random planar network, 57
- Randomized codes, 257–263, 265, 267, 272
 - Gaussian randomization, 259, 263 (Tab.), 264, 265
 - random antenna selection, 259, 260, 262, 263 (Tab.), 265
 - randomization matrix, 258–63, 267, 272
 - rank criterion, 260
 - spherical randomization, 259, 263 (Tab.), 264, 265
 - uniform phase randomization, 259, 263 (Tab.), 264, 265
- Rate constraint, 172, 174, 175, 178, 182
- Rate distortion curve, 64
- rate-distortion function, 16
 - CEO, 21
 - indirect, 18–22
 - Koerner-Marton problem, 22–23
 - remote, *see* indirect
 - distortion scaling law comparison, 22
 - Wyner-Ziv problem, 16
- Reactive routing, 293
- Regret tracking, 360–2, 374
 - algorithm, 362
 - convergence, 351, 360, 363–5, 375–7
- Regular Networks, 50
- REI, 96, 104–6, 108
- Request-to-Send (RTS), 314, 322, 325
- Residual energy information, *see* REI
- Reverse water-filling, 174–6, 179
- Routing
 - classifications of, 279
 - Chernoff based, 298
 - distance vector, 292
 - link state, 292
 - proactive, 292
 - reactive, 293
 - shortest path, 279, 291
- RTS, *see* Request-To-Send
- rumor propagation, 228
- Scheduling
 - centralized, 94
 - distributed, 94, 104
 - sensor, 97, 100–1
 - transmission, 97, 100–4, 106, 108–10
- sensing capacity 74
 - arbitrary connections model, 74
 - definition, 76
 - achievability theorem, 79
 - extensions, 84
 - localized sensing, 86
 - environment models, 87
- sensor localization, 222
- Sensor network with mobile access, 94
 - censoring sensor, 141
- Shortest path routing, 279, 291
 - static, 281
 - adaptive, 289
- signal-to-noise ratio (SNR), 169, 177, 180–1
- Single-letter characterization, 174
- Sleep-Wake Protocols, 316–317
- Slepian-Wolf Theorem, 64
- S-MAC, 317
- source/channel separation theorem, 31, 33
- Space-time codes, 257, 259, 260
 - Alamouti, 257, 258, 260, 264, 274
 - Distributed space-time codes, 257, 274
- Spatial correlations, 63
- Spatial reuse, 45, 49
- Spatial Sampling, 321–3
- SSP, 97–8, 100, 103–4, 114
- Stationary point, 172
- Stochastic approximation, 351, 361–5, 381
 - Convergence, 351