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

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List of Contributors

Müjdat Çetin
Sabanci University
Faculty of Engineering and Natural Sciences
Orhanli – Tuzla
34956 Istanbul
mcetin@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 Dreese 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
Deptartment 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

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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.

Wireless Sensor Networks: Signal Processing and Communications Perspectives A. Swami, Q. Zhao, Y.-W. Hong and L. Tong

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 innumberable 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