
HANDBOOK ON ARRAY PROCESSING AND SENSOR NETWORKS

Simon Haykin
K. J. Ray Liu



Celebrating 125 Years
of Engineering the Future



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Preface

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

Simon Haykin

Department of Electrical Engineering, McMaster University, Hamilton, Ontario, Canada

The purpose of this introductory chapter is to provide an overview of the material covered in the subsequent 28 chapters of the *Handbook on Array Processing and Sensor Networks*. These 28 chapters are organized in four parts, as described next. Parts I and II constitute the first pillar of this *Handbook*: array signal processing; Parts III and IV constitute the second pillar, sensor networks.

PART I: FUNDAMENTAL ISSUES IN ARRAY SIGNAL PROCESSING

This first part of this *Handbook*, embodying Chapters 1 through 5, addresses the following issues that are considered to be basic to the subject matter of the *Handbook*:

1. The theory of stochastic processes is of fundamental importance in the modeling of practically all the physical systems encountered in practice. Chapter 1, Wavefields by Alfred Hanssen, generalizes the theory of stochastic processes to *stochastic wavefields*. At first, such a generalization may seem to be straightforward; in reality, however, it is not. The starting point of the chapter is harmonizable stochastic processes, the roots of which are traced to the pioneering works of Loève in the 1940s.
2. Chapter 2, Spatial Spectrum Estimation, authored by Petar Djuric follows on quite nicely from Chapter 1 by viewing array signal processing as a spatial spectrum-estimation problem. The many facets of spectrum estimation, nonparametric as well as parametric, are discussed in the chapter.
3. The next chapter, MIMO Radio Propagation, is authored by Tricia J. Willink. After presenting a tutorial treatment of the MIMO channel capacity for wireless communications, building on Shannon's information theory, Willink describes various propagation models that have been developed for the statistical characterization of MIMO channels. Most importantly, the treatment includes analytical model parameterization, supported with practical measurements.
4. The chapter on Robustness Issues in Sensor Array Processing, written by Alex B. Gershman, addresses yet another fundamental issue in array signal processing, namely, *robustness*. In particular, Gershman presents an overview of the state-of-the-art algorithms for adaptive beamforming in a narrowband environment.

5. Chapter 5, entitled *Wireless Communications and Sensing in Multipath Environments Using Multiantenna Transceivers*, co-authored by Akbar M. Sayeed and Thiagarajan Sivanadayan, addresses the fundamental issue of how multipath channels, basic to wireless communications, can be modeled in a generic sense. The aim here is to account for the three dimensions of sensing: time, frequency, and space. Point-to-point MIMO wireless communications and active wireless sensing with wideband transmitter–receiver (transceiver) configurations are discussed in the chapter.

PART II: NOVEL TECHNIQUES FOR AND APPLICATIONS OF ARRAY SIGNAL PROCESSING

The second part of this *Handbook* embodies seven chapters devoted to practical applications of array processing in a multitude of fields, as described next:

6. Chapter 6 on *Implicit Training and Array Processing for Digital Communications Systems* is co-authored by Aldo G. Orozco, Mauricio Lara, and Desmond C. McLernon. The concept of “implicit training” refers to a strategy in digital communications, where a special sequence is embodied in the transmitted signal to aid the receiver to perform specific parameter-estimation tasks in such a way that no additional bandwidth is required. After discussing this issue in detail, the chapter describes its application in array-processing systems, using continuous and packet forms of transmission.
7. Next, chapter 7 on *Unitary Design of Radar Waveform Diversity Sets*, co-authored by Michael D. Zoltowski, Tariq R. Qureshi, Robert Calderbank, and Bill Moran, discusses the radar counterpart of MIMO wireless communications, namely, MIMO radar. The challenge in MIMO radar is that of separating the transmitted waveforms at the receiver. This problem is complicated by the relative delay and Doppler shift of the transmitted waveforms, which may destroy the desired property of orthogonality. To mitigate these practical difficulties, examples of diversity waveforms for 2-by-2 and 4-by-4 MIMO radar configurations are studied.
8. Chapter 8 on *Acoustic Array Processing for Speech Enhancement* is co-authored by Markus Buck, Eberhard Hänsler, Mohamed Krini, Gerhard Schmidt, and Tobias Wolff. To deal with the issue of speech enhancement in a speech communication system, the discussion focuses on frequency-domain procedures, which are preferred over time-domain procedures for practical reasons. The techniques considered in the chapter include multichannel echo cancellation, beamforming structures, combined echo cancellation and beamforming, and sensor calibration. The final topic in the chapter is devoted to postprocessing techniques, exemplified by the suppression of residual interferences and background noise, dereverberation, spatial postfiltering, and other issues of practical importance.
9. Chapter 9 on *Acoustic Beamforming for Hearing Aid Applications* is co-authored by Simon Doclo, Sharon Gannot, Marc Moonen, and Ann Spriet. With this chapter devoted to speech processing, it follows quite nicely on the previous chapter on speech enhancement. As the title of the chapter would indicate, the discussion focuses on the design of multimicrophone algorithms in order to improve speech intelligibility in background noise for hearing-aid applications. The techniques

- studied in the chapter include minimum variance distortionless response (MVDR) beamformer, frequency-domain generalized side-lobe canceller (GSLC), and multichannel Wiener filter for monaural processing. Then, with binaural processing as the issue of interest, the multichannel Wiener filter and its variants are discussed in the latter part of the chapter. Experimental results for both monaural and binaural processing are presented.
10. Chapter 10, entitled Underdetermined Blind Source Separation Using Acoustic Arrays and co-authored by Shoji Makino, Shoko Araki, Stefan Winter and Hiroshi Sawada, completes the study of acoustic arrays for speech-related applications. More specifically, this chapter addresses a difficult blind source separation problem that is underdetermined, that is, the number of sensors is smaller than the number of sources (i.e., microphones) responsible for generating the observables. Design of the acoustic array of microphones exploits *sparseness*, which is an inherent characteristic of speech signals. Two methods are discussed in the chapter. The first method is rooted in the time–frequency domain. The second method uses a maximum a posteriori (MAP) probability approach, which combines blind system identification and blind source recovery. Experimental results are presented in support of both methods.
 11. Chapter 11, entitled Array Processing in Astronomy, is authored by Douglas C.-J Bock. The chapter focuses primarily on the theory, design, and signal processing of a special kind of arrays called “correlation arrays,” which consist of arrays of antennas (typically, parabolic reflectors) that are analyzed by cross-correlating the outputs of each pair of antennas as in interferometry. An important feature of correlation arrays is that they permit imaging of the entire field of view of an individual antenna at a resolution determined by the overall extent of the array. Other techniques, namely, aperture-plane phased arrays, focal-plane phased arrays, and array processing at optical and infrared wavelengths are also mentioned in the chapter.
 12. The next chapter, entitled Digital 3D/4D Ultrasound Imaging Technology and authored by Stergios Stergiopoulos, completes Part II of the *Handbook*. Starting with practical limitations of two-dimensional (2D) medical ultrasonic imaging technology in terms of poor resolution, the stage is set for the study of the next 3D/4D ultrasonic image technology for medical diagnostic applications. The study includes synthetic aperture processing for digitizing large-size planar arrays, multifocus transmit beamformer for linear and planar phased arrays, and multifocus receive beamformer for linear and planar phased arrays. The chapter also includes the description of an experimental planar array ultrasound imaging system, including some performance results of the system.

PART III: FUNDAMENTAL ISSUES IN DISTRIBUTED SENSOR NETWORKS

In Part III of this *Handbook*, we move onto the study of sensor networks, constituting its second pillar. This third part consists of nine chapters that cover the following issues:

13. Chapter 13 on Self-Localization of Sensor Networks, authored by Joshua N. Ash and Randolph L. Moses, studies the issue of inference from spatially distributed sensors so as to acquire knowledge of where the individual sensors are located,

hence the use of “selflocalization” in the title. With this objective in mind, the chapter describes Cramér–Rao bounds for self-localization parameters, localization algorithms, and measurement errors.

14. Chapter 14 on Multitarget Tracking and Classification in Collaborative Sensor Networks via Sequential Monte Carlo methods, written by Tom Vercauteren and Xiaozong Wang, discusses the problem of jointly tracking and classifying targets that evolve within an environment of scattered sensor nodes. The enablers of such a capability involve microelectromechanical systems (MEMS) and microprocessors, coupled with ad hoc networking protocols, all of which make it possible for low-cost sensors to collaborate and attain prescribed tasks at relatively low-power levels. With target dynamics as the topic of interest, use is made of sequential Monte Carlo (SMC) methods and related importance sampling and resampling procedures.
15. The next chapter on Energy-Efficient Decentralized Estimation, co-authored by Jin-Jun Xiao, Shuguang Cui, and Zhi-Quan Luo, addresses a major challenge in wireless sensor networks, namely, how to design these networks subject to a hard-energy constraint. This practical problem is a difficult one because operation of the sensors is dependent on small-size batteries, the replacement costs of which can be expensive if not impossible. The threefold theme of the chapter is energy-efficient distributed estimation in wireless sensor networks that embody:
 - Local data compression
 - Wireless communications
 - Data fusion
16. With multisensor data fusion as an issue of interest in the preceding chapter, its discussion is continued in the chapter on Sensor Data Fusion with Application to Multitarget Tracking, which is written by R. Tharmarasa, K. Punithakumar, T. Kirubarajan, and Y. Bar-Shalom. Naturally, tracking plays a vital role in sensor data fusion, hence the need for algorithms required to perform state estimation, given data received from one or more sensors. Moreover, data association is an essential component in sensor fusion, particularly when there is uncertainty in the original source of data used in the fusion process. Yet another practical issue of concern is that the data may not arrive at the fusion center in the right sequence due to the unavoidable presence of network delays. Confronted with all these practical issues, a reliable solution to the data fusion problem is discussed in the chapter.
17. Chapter 17, entitled Distributed Algorithms in Sensor Networks, by Usman A. Khan, Soumya Kar, and José M.F. Moura, describes an architecture for resource-constrained networks that have a *weblike topology*. This topology embodies decentralized and distributed inference algorithms, where each sensor in the network updates its own local detector using state information gathered by neighboring sensors. The updating is performed iteratively in such a way that the state of the particular sensor in question converges to the state of the optimal centralized or parallel detector. The iterative nature of the distributed algorithm is attributed to the fact that information flow is limited because of sparse connectivity of the network. The chapter focuses on distributed algorithms that are *linear*, for which a systematic study is provided.
18. In chapter 18, the study of sensor networks moves onto another important topic: Cooperative Sensor Communications written by Ahmed Sadek, Weifeng Su, and

Ray Liu. With cooperative communications among the sensors as the goal, the chapter focuses on how to attain this goal with two issues in mind:

- The limited energy available to the component nodes
- The possibility of the nodes attempting to cooperate while the operations of sensing and communication are being carried out

With wireless communication as the method of choice, the cooperative-sensor communication problem becomes complicated by channel fading due to the multipath phenomenon, for which the use of diversity is the standard solution. More specifically, the chapter generalizes multiple-input multiple-output (MIMO) communication and related protocols to tackle cooperative communications among wireless sensor nodes. (The use of MIMO was discussed previously in Chapter 3.)

19. In a distributed sensor network, we typically find that the transmitters in the network are not permitted to communicate with each other due to increased complexity and/or power constraints. To address this issue, we look to *distributed source coding*, the foundation of which was laid out in a 1973 study by Slepian and Wolf. During the past 35 years, many important contributions have been made to this topic. Chapter 19, Distributed Source Coding, written by Zixiang Xiong, Angelos D. Liveris, and Yang Yang, reviews the theory, design, and applications of distributed source coding. In particular, detailed descriptions of the following topics are presented in the chapter:

- Multiterminal source-coding methods of the direct and indirect kinds
- The designs of Slepian–Wolf, Wyner–Ziv codes and their variants
- The applications of distributed source codes in secure biometrics, lossless compression in multiterminal networks, and, most importantly, distributed video coding

20. The next chapter, Network Coding for Sensor Networks, by Christina Fragouli, explores the relatively new idea of *network coding*, which has the potential to revolutionize the way information is treated in a sensor network. As such, network coding may impact various network functionalities such as routing, network storage, and network design. Basically, network coding deals with information flow across a sensor network. However, it may well be that it is in ad hoc wireless sensor networks, where network coding may have an immediate impact.

21. The final chapter of Part III is by Liang-Liang Xie and P. R. Kumar on Information-Theoretic Studies of Wireless Sensor Networks. A basic characteristic of wireless networks is their *broadcast nature*, which necessarily causes *interference* across a network. In the current approach to the formulation of protocols for wireless networks, interference is usually viewed to be undesirable. In reality, however, interference is not “noise;” rather, it should be viewed as a signal that carries information, but it is unintentionally received. This reality motivates the challenge of finding ways to exploit interference rather than succumb to it. Using information-theoretic ideas, Xie and Kumar develop wireless communication schemes that exploit unintentionally received signals in sensor networks.

PART IV: NOVEL TECHNIQUES FOR AND APPLICATIONS OF DISTRIBUTED SENSOR NETWORKS

In the fourth and final part of this *Handbook* dealing with distributed sensor networks, we have assembled seven chapters on novel techniques and applications, which start with adaptivity and finish with security and privacy.

22. Chapter 22 by Ali H. Sayed and Federico S. Cattivelli on ‘Distributed Adaptive Learning Mechanisms’ describes recent developments in distributed processing over networks. The presentation covers adaptive learning algorithms that make it possible for neighboring nodes in a distributed network to communicate with each other at each iteration of the algorithm. Specifically, each node in the network exchanges estimates with its neighboring nodes, with the estimates being fused and quickly incorporated into local adaptation rules. In this way, the network as a whole becomes adaptive, whereby it is enabled to respond to space–time variations in the underlying statistical profile of the data. The chapter describes different learning rules at the nodes along with different cooperation protocols, thereby yielding adaptive networks with varying complexity and potential application.
23. The classical approach in distributed sensor networks addresses two problems: distributed statistical inference and minimum-cost routing of the measurements to the fusion center. A shortcoming of this approach is the failure to exploit the “inherent” saving in routing costs. In Chapter 23, entitled Routing for Statistical Inference in Sensor Networks, its co-authors A. Anandkumar, A. Ephremides, A. Swami, and L. Tong, take a different approach in the following sense: In-network processing of the likelihood function, representing the minimal sufficient statistic, is performed and delivered to the fusion center for inference. To this end, the *Markov random field (MRF) model* of spatial correlation of sensor data is employed. Accordingly, the underlying structure of the likelihood function is known for the MRF model by invoking the well-known *Hammersley–Clifford theorem*. By exploiting this structure, it is shown that the minimum-cost routing for computing and delivering the likelihood function is a *Steiner tree on a transformed graph*. With the approximation ratio preserved, it follows that any Steiner tree approximation can be employed for minimum-cost fusion at the same approximation ratio. An overview of the minimum-cost fusion procedure is presented in the chapter.
24. In this chapter, Behrouz Farhang-Boroujeny introduces the idea of cognitive radio. Lately, interest in cognitive radios has been growing exponentially as a way of solving the current underutilization of the electromagnetic radio spectrum. Simply put, there are *spectrum holes* (i.e., underutilized subbands of the radio spectrum) at certain points in time and geographic locations. These spectrum holes can be made available to *secondary users*, which are to be distinguished from the primary users who are legally entitled to occupy those subbands. A basic problem on which the very essence of cognitive radio rests is that of identifying the location of spectrum holes in the radio spectrum. One way of accomplishing this task is to use spectral estimation, hence the title of Chapter 24: Spectral Estimation in Cognitive Radios. In particular, Farhang-Boroujeny describes the multitaper spectral estimator (MTSE), which has several attributes as a spectral estimator. Instead of following the original approach used by David Thomson in 1982 to derive the MTSE, its formulation in this chapter is centered on the idea of filter

- banks, the underlying theory of which is well known in the signal processing literature.
25. Chapter 25, by Azadeh Kushki, and Konstantinos N. Plantaniotis, discusses Nonparametric Techniques for Pedestrian Tracking in Wireless Local Area Networks. The choice of nonparametric techniques for tracking is influenced by the fact that an explicit form for the position-received signal strength (RSS) is typically unknown. The discussion starts with nonparametric kernel-density estimation, which has the advantage of providing a covariance matrix that is used to gauge the reliability of the position estimate. It is this feature that prompted the development of state-space filters, which augment memoryless estimates with knowledge of pedestrian motion dynamics. Global feedback is employed to guide the selection of anchor points and wireless access points used during the estimation procedure. This is done to mitigate difficulties that arise due to practical discrepancies between training and testing conditions, which do arise from the nonstationary character of the indoor wireless environment.
 26. Chapter 26, by Vikram Krishnamurthy and Bruce Cornell, addresses a challenging problem: Reconfigurable Self-Activating Ion-Channel-Based Biosensors: Signal Processing and Networking via the Theory of Global Games. Biological ion channels are water-filled subnano-sized ports that are formed by protein molecules in the membrane of all living cells. These ion channels play a crucial role in living organisms in that their flow into and out of a cell regulates the biochemical activities of the cell. The chapter builds on classical to state-of-the-art tools in signal processing and control theory to model the underlying dynamics of ion channel biosensors in a novel way. Moreover, the powerful concept of *global games* is used to derive biosensor activation algorithms that appear to have a simple threshold Nash equilibrium.
 27. Chapter 26 on biological ion channels is followed nicely by Chapter 27 written by Mathias Ortner and Arye Nehorai, dealing with a biochemical problem, namely, Biochemical Transport Modeling, Estimation, and Detection in Realistic Environments. This chapter introduces a new approach for computing and using a numerical forward physical dispersion model, the purpose of which is to relate the source given by an array of biochemical sensors in realistic environments. The approach described therein provides a modeling framework, which accounts not only for complex geometries but also permits the full use of software-simulated random wind turbulence. The key feature of the model is that the “fluid simulation” part of the model is decoupled from the “transport computation” part. The chapter also includes an illustrative example on monitoring biochemical events. Other related topics covered in the chapter include the following: a sequential detector for dealing with unknown parameters, namely, start time of the spread, original concentration, and location of the initial delivery.
 28. The study of distributed sensor networks would be incomplete without a discussion of two critical issues: security and privacy, which is precisely what we have in the very final chapter of this *Handbook*. More specifically, the chapter entitled Security and Privacy for Sensor Networks written by Wade Trappe, Peng Ning, and Adrian Perrig, explores the following pair of issues:
 - Security and privacy challenges that face designers of sensor networks

- Defense strategies that may be employed to protect a sensor network against external attacks

Naturally, the need for security and privacy is prompted by the fact that sensor networks are deployed in environments that are typically unattended. The attacks confronting sensor networks may range from threats that seek to corrupt the basic processes of measurements (hence, compromising the reliability of the network), to attacks aimed at wireless connectivity, and to attacks where knowledge of routing functionality is used by an adversary for its own advantage, discussions of which are all covered in the chapter.

PART I

FUNDAMENTAL ISSUES IN ARRAY SIGNAL PROCESSING

