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WIRELESS SENSOR NETWORKS

Signal Processing and Communications Perspectives

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Wireless Sensor Networks

Signal Processing and Communications Perspectives

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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.