

# WIRELESS SENSOR AND ACTUATOR NETWORKS

ALGORITHMS AND PROTOCOLS FOR SCALABLE COORDINATION  
AND DATA COMMUNICATION

AMIYA NAYAK • IVAN STOJMENOVIC



# Wireless Sensor and Actuator Networks

## Algorithms and Protocols for Scalable Coordination and Data Communication

Edited by

Amiya Nayak and Ivan Stojmenovic



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# **Wireless Sensor and Actuator Networks**

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# Preface

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**T**raditional and existing sensor and actuator networks use wired communications, whereas, wireless sensors provide radically new communication and networking paradigms, and myriad new applications. They have small size, low battery capacity, non-renewable power supply, small processing power, limited buffer capacity (thus routing tables, if used at all, must be small), a low-power radio, and lack unique identifiers. Sensors may measure distance, direction, speed, humidity, wind speed, soil makeup, temperature, chemicals, light, vibrations, motion, seismic data, acoustic data, strain, torque, load, pressure, and so on. These nodes are autonomous devices with integrated sensing, processing, and communication capabilities. Nodes in a sensor network are generally densely deployed. Thousands of sensors may be placed, mostly at random, either very close or inside a phenomenon to be studied. Once deployed, the sensors are expected to self-configure into an operational wireless network, and must work unattended. The limited energy budget at the individual sensor level implies that in order to ensure longevity, the transmission range of individual sensors needs to be restricted. In turn, this implies that wireless sensor networks must be multi-hop ones.

Current research and implementation efforts are mostly oriented toward a traditional scenario with stationary sensors and a single static sink that collects information from sensors where the sink is directly connected to the user (or task manager). However, the latest research has unearthed the practically unsolvable problem of uneven energy distribution and energy holes in this scenario. Therefore, generalized scenarios have been considered, such as sensor networks with multiple stationary sinks, single mobile sink, or multiple mobile sinks. Mobile sensors have also been discussed. And, we envision adding actuators to the network. The difference between sinks and actuators is that actuators are able to act on the environment; mobile actuators may additionally act on the sensors. Actuators may also perform the roles of sinks, or both sinks and actuators may coexist in a given network. We will now elaborate on aspects of actuation.

Sensor-actuator networks are heterogeneous networks that comprise networked sensor and actuator nodes which communicate among each other using wireless links to perform distributed sensing and actuation tasks. *Actuators* (called

also *actors*) are resource-rich, potentially mobile, and are involved in taking decisions and performing appropriate actions on themselves (e.g. controlled movement), on sensors (such as activating sensors, moving or replacing a sensor), and/or in the environment (e.g. turn on their own a water sprinkler to stop the fire). Sensor-actuator networks are expected to operate autonomously in unattended environments. They may be directly connected (using, for instance, web infrastructure) and responsive to a user (task manager) who controls the network via sinks. One or more actuator(s) may also play the role of sink(s). In fact, sinks can be treated as special kinds of actuators, although a better interpretation might be to associate them with base stations that communicate directly with the user.

Since the actuating task is a more complicated and energy-consuming activity than the sensing task, actuators are resource-rich nodes equipped with better processing capabilities, higher transmission powers, and longer battery life. Moreover, depending on the application, there may be a need to rapidly respond to sensor input. Therefore, the issue of real-time communication is very important since actions are performed on the environment after the sensing occurs. In addition, while the number of sensor nodes deployed to achieve a specific application objective may be in the order of hundreds or thousands, such a dense deployment is not necessary for actuator nodes due to the different coverage requirements and physical interaction methods of acting a task. Hence, the number of actuators is much less than that of sensors.

The goal of this book is to present a fault-tolerant, reliable, low latency, and energy-aware framework for wireless sensor and actuator networks, so that the ultimate goal of their applications (protecting critical infrastructures, enabling timely emergency responses, and environment monitoring) can be fulfilled. Future sensor-actuator networks will be more heterogeneous and radically distributed, potentially with millions of nodes. They may respond to multiple tasks, to multiple and potentially mobile sinks and/or actuators, and multiple sensor networks may be integrated into a single network. There are algorithmic challenges in the rapidly emerging field of future heterogeneous super-networks where sensor networks will be integrated into wired and/or wireless infrastructure. Challenges of such wide-area sensor systems include scalability, robustness, manageability, and actuation. Having this futuristic vision in mind, this book will provide a protocol framework at the network layer, namely data communication and coordination issues. While being general, the framework should generate optimal solutions when applied/mapped in any specific emerging application; that is, the very same protocols may be applied in scenarios ranging from a simple scenario with one fixed actuator to the envisioned super-networks. To achieve such ambitious goals, several primary criteria for protocol design must be followed: energy consumption, localized design, reliability, parameterless behavior, and simplicity.

This book is problem-oriented, with each chapter discussing computing and communication problems and solutions that arise in rapidly emerging wireless sensor and actuator networks. The main direction of the book is to review various algorithms and protocols that have been developed in the area with emphasis on the most recent ones. The book is intended to cover a wide range of recognized

problems in sensor-actuator networks, striking a balance between theoretical and practical coverage. The theoretical contributions are limited to the scenarios and solutions that are believed to have practical relevance. This book is unique in addressing sensor and actuator/actor networking in a comprehensive manner, covering all the aspects, and providing up-to-date information. It is an appropriate and timely forum, where industry, operators, and academics from several different areas can learn more about current trends and become aware of the possible architectures of sensor and actuator networks, their advantages, and their limits in future commercial, social, and educational applications.

This book is intended for researchers and graduate students in computer science and electrical engineering, and researchers and developers in the telecommunication industry. It is directed at those who are looking for a reference resource in sensor and actuator networking and those who want to get a global view of this area.

The book is based on a number of stand-alone chapters that together cover the subject matter in a fully comprehensive manner. As a result of the exponential growth in the number of studies, publications, conferences, and journals on sensor networks, a number of graduate courses fully or partially concentrating on sensor networks have emerged recently. It is expected that this book will act as a supplemental textbook for such graduate courses. It can be also used as a stand-alone textbook for a course specifically on wireless sensor and actuator networks. The chapters cover subjects describing state-of-the-art approaches and surveying the existing important solutions. They provide readable but informative content, with appropriate illustrations, figures, and examples. A number of chapters also provide some problems and exercises for use in graduate courses.

The book content addresses the dynamic nature of wireless sensor and actuator networks. Due to frequent node addition and deletion from networks (changes between active and sleeping periods, done to conserve energy, are one of the contributors to this dynamic), and possible node movement, the algorithms that can be potentially used in real equipments must be *localized* and must have minimal communication overhead. The overhead should consider both the construction and its maintenance for the structure used in solutions and ongoing protocols. We believe that this is the only approach that will eventually lead to the design of protocols for real applications. We will explain now our design principles and the priorities given to the coverage of topics in this book.

A *scalable* solution is one that performs well in a large network. Sensor networks may have hundreds or thousands of nodes. Priority is given to protocols that perform well for small networks, and perform significantly better for large networks (more precisely, are still working as opposed to crashing when other methods are applied). In order to achieve scalability, new design paradigms must be applied. The main paradigm shift is to apply localized schemes as opposed to most existing protocols that require global information. In a *localized* algorithm, each node makes protocol decisions solely based on knowledge about its local neighbors. In addition, the goal is to provide protocols that will minimize



the number of messages between nodes, because bandwidth and power are limited. Protocols should use a small constant number of messages, often even none beyond preprocessing ‘hello’ messages. Localized message-limited protocols provide scalable solutions. Typical local information to be considered is one-hop or two-hop neighborhood information (information about direct neighbors and possibly the neighbors of neighbors). Nonlocalized distributed algorithms, on the other hand, typically require global network knowledge, including information about the existence of every edge in the graph. The maintenance of global network information, in the presence of mobility or changes between sleep and active periods, imposes a huge communication overhead, which is not affordable for bandwidth- and power-limited nodes. In addition to being localized, protocols are also required to be *simple, easy to understand and implement*, and to have *good average case performance*. Efficient solutions often require position information. It was widely recognized that sensor networks can function properly only if reasonably accurate position information is provided to the nodes.

## BRIEF OUTLINE OF THIS BOOK

This book consists of 10 chapters. It begins with an introductory chapter that describes various scenarios where sensor and actuator networks may be applied, problems at physical, medium access, network, and transport layers, and various application layer tools for enabling applications. It argues for the use of localized algorithms, and discusses the generation of sensor and actuator networks for simulation purposes.

Chapter 2 discusses backbones as subsets of sensors or actuators that suffice for performing basic data communication operations. They are applied for energy-efficient data dissemination tasks. The goal is to minimize the number of re-broadcasts while attempting to deliver messages to all sensors or actuators. Neighbor detection and route discovery algorithms that consider a realistic physical layer are described. An adaptive broadcasting protocol without parameters, suitable for delay-tolerant networks, is further discussed. We also survey existing solutions for the minimal energy broadcasting problem where nodes can adjust their transmission powers.

Sensor networks normally have redundancy for sensing coverage. Some sensors are allowed to sleep while preserving network functionality. Sensors should decide which of them should be active and monitor an area, and which of them may sleep and become active at a later time. Sensor area coverage problem has been considered for both the unit disk graph- and physical layer-based sensing models in Chapter 3. Actuators may similarly run a protocol to decide about their service areas, releasing some of them from their particular duty. Operational range assignment for both sensor and actuators nodes is also discussed.

Chapter 4 surveys existing flooding-based and position-based routing schemes. It also describes a general cost-to-progress ratio-based approach for designing routing protocols under a variety of metrics, such as hop count, power, remaining energy, delay, and others. Chapter 4 also describes routing



with guaranteed delivery for unit disk graphs and ideal MAC layer based on the application of the Gabriel graph, a localized planar and connected structure. Solutions are expanded toward beaconless behavior, where nodes are not aware of their neighborhood. Georouting with virtual coordinates is based on hop distances to some landmarks. This chapter also discusses physical layer aspects of georouting, routing in sensor-actuator networks, and load balancing issues in routing.

Chapter 5 reviews the scenarios where a given message is sent from a single source (sensor) to possibly several destinations (actuators). These scenarios can be subdivided into multicasting, geocasting, multiratecasting, and anycasting. In multicasting, a given message must be routed from one node to a number of destinations whose locations may be arbitrary and spread over the network. Geocasting destinations are all nodes located in a given geographical area. Multiratecasting is a generalization of multicasting, where regular messages are sent from a source to several destinations, possibly at a different rate for each destination. Finally, in an anycasting scenario, a source must send a message to any node, preferably only one, among a given set of destinations. Each of these scenarios corresponds to a typical use case in sensor and actuator networks.

Data gathering aims to collect sensor readings from sensory fields at predefined sinks or actuators (without aggregating at intermediate nodes) for analysis and processing. Research has shown that sensors near a data sink deplete their battery power faster than those far apart, due to their heavy overhead of relaying messages. Nonuniform energy consumption causes degraded network performance and shortens network lifetime. Recently, sink mobility has been exploited to reduce and balance energy expenditure among sensors. The effectiveness has been demonstrated both by theoretical analysis and by experimental study. In Chapter 6, we investigate the theoretical aspects of the uneven energy depletion phenomenon around a sink/actuator, and address the problem of energy-efficient data gathering by mobile sinks/actuators. We present taxonomy and a comprehensive survey of the state of the art on the topic.

The efficiency of many sensor network algorithms depends on characteristics of the underlying connectivity, such as the length and density of links. The number and nature of links that are to be used among all potentially available links can be controlled. Topology control can be achieved by modifying the transmission radii, selecting a given subset of the links, or moving some nodes (if such functionality is available). Chapter 7 reviews some of these problems and related solutions, applicable to the context of sensor and actuator networks. Spanning structures and minimum weight connectivity are applied for power-efficient and delay-bounded data aggregation. Detection of critical nodes and links aims to provide fault tolerance to the applications. Some recent and prospective works considering biconnectivity of mobile sensors/actuators and related deployment of sensors, augmentation, area and point coverage are discussed.

In the location service problem, mobile actuators send location update messages, while stationary sensors send search messages to learn the latest position of actuators. The task is to minimize combined update and search message cost,

while maximizing the success rate of finding a target actuator and subsequently routing to it. In the literature, many location service algorithms have been proposed for mobile *ad hoc* networks, and they can be directly applied to sensor and mobile actuator networks. Chapter 8 reviews research efforts on this topic.

Chapter 9 surveys the existing representative work in both, sensor-actuator and actuator-actuator coordination. Sensor-actuator coordination deals with establishing data paths between sensors and actuators, and can be used for sensor deployment. Actuator-actuator coordination includes robot coordination for sensor placement, dynamic task allocation, selecting the best robot to respond to reported events, robot dispersion, boundary coverage, and fault-tolerant response. In coordinated actuator movement problems, actuators are moved to desired locations to save energy in long-term communication tasks where the traffic is sufficiently regular and large in volume to warrant nodes expending energy for moving. Chapter 9 also reviews recent developments in coordination among flying robots.

Coverage is the functional basis of any sensor network. The impact on coverage from stochastic node dropping and inevitable node failure, coupled with controlled node mobility, gives rise to the problem of movement-assisted sensor placement in wireless sensor and actuator networks (WSAN). One or more actuators may carry sensors, and drop them at a proper position, while moving around, in the region of interest (ROI) to construct desired coverage. Mobile sensors may change their original placement so as to improve existing coverage. Emerging coverage holes are to be covered by idle sensors. Actuators may place spare sensors according to certain energy optimality criteria. If sensors are mobile, they can relocate themselves to fill holes. Chapter 10 comprehensively reviews existing solutions to the sensor placement problem in WSAN.

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We hope that the readers will find this book informative and worth reading. Comments received by readers will be greatly appreciated.

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## ON WIRELESS SENSORS

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# Chapter 1

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## Applications, Models, Problems, and Solution Strategies

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### Abstract

This introductory chapter describes various applications, scenarios, and models of wireless sensor and actuator networks. Problems at the physical, medium access, network, and transport layers as well as various tools needed to enable their functioning are identified. Various assumptions and metrics used in simulations and protocol descriptions are discussed. The chapter then describes ways of generating sensor and actuator networks based on widely accepted unit disk graph models. Finally, this chapter discusses solution approaches arising in sensor networks and advocates the use of localized protocols, where individual sensors and actuators make their decisions based on local knowledge.

### 1.1 WIRELESS SENSORS

We will elaborate first on wireless sensors; then on wireless sensor networks (WSNs) (with a single sink), their properties, models, and application types. Afterwards, we will add actuators to the model and discuss various combinations of sensors and actuators that can form a heterogeneous network with different levels of complexity.

Recent technological advances have enabled the development of small-sized (a few cubic centimeters), low-cost, low-power, and multifunctional sensor devices. There are different types of sensors. Sensors are normally specialized, but sometimes a few capabilities may be available in a single sensor. They may measure distance, direction, speed, humidity, wind speed, soil makeup, temperature, chemical composition, light, vibration, motion, seismic activity, acoustic properties, strain, torque, load, pressure, and so on.

Traditionally, sensors are attached to the environment and their measurements are sent to a base station (BS) with wired communication. There exists a large body of knowledge on such models and applications of sensors which have been studied by a huge community of researchers. During the last decade, a new vision of sensor nodes as autonomous devices with integrated sensing, processing, and communication capabilities has emerged. Attaching antenna for receiving signals and a transmitter enables wireless communication of sensors. Sensors also have a small processor and a small memory for coding and decoding signals, as well as for running simple communication protocols. They differ in their battery capacity; for example, some of them run on small batteries and last a day, whereas others have larger batteries attached that let them last up to a month with continuous operation. In some applications, a renewable power supply such as a solar panel is used. Further, some sensors are embedded into other devices and draw their required energy from them. Such sensors do not have energy limitations in their functioning. In some scenarios, sensors could be provided with a wireless single-hop access to infrastructure networks such as the Internet.

For some applications, sensors may be of a large size, especially if they are protected by boxes or lifted to a height that improves their communication and protection level. When collected data is not time critical, sensors may function in isolation. For example, seismological data or bird presence detected acoustically can simply be collected in the local sensor memory and downloaded when visited by humans. This book concentrates, however, on scenarios involving networks of wireless sensors.

## 1.2 SINGLE-HOP WIRELESS SENSOR NETWORKS

The majority of the existing applications for “wireless” sensors rely on a single-hop wireless network to reach a BS for further processing of the measured phenomena. That is, sensor measurements are sent directly, using a wireless medium, from sensor to BS. Most of these applications rely on sensors that are *embedded* into a different device. Also, the majority of applications for embedded sensors rely on single-hop wireless communication. For example, small sensors can be embedded into a traffic surveillance system to monitor traffic on congested roads or be used to monitor hot spots in a region or building.

Health care is one of the primary applications for wireless networks composed of embedded sensors. Sensors can be embedded into watches which, when attached to patients, monitor and analyze data such as pulse and blood pressure. In case of potential health risks, individual sensors send alarm messages to