HANDBOOK OF SENSOR NETWORKS
ALGORITHMS AND ARCHITECTURES

Edited by
Ivan Stojmenović
University of Ottawa
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Edited by
Ivan Stojmenović
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To my daughter Milica, son Milos, and wife Natasa, my personal sensor network.
To Val and Emily from Wiley, for their timely and professional cooperation.
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Recent technological advances have enabled the development of low-cost, low-power, and multifunctional sensor devices. These nodes are autonomous devices with integrated sensing, processing, and communication capabilities. A sensor is an electronic device that is capable of detecting environmental conditions such as temperature, sound, chemicals, or the presence of certain objects. Sensors are generally equipped with data processing and communication capabilities. The sensing circuitry measures parameters from the environment surrounding the sensor and transforms them into electric signals. Processing such signals reveals some properties of objects located and/or events happening in the vicinity of the sensor. The sensor sends such sensed data, usually via a radio transmitter, to a command center, either directly or through a data-collection station (a base station or a sink). To conserve the power, reports to the sink are normally sent via other sensors in a multihop fashion. Retransmitting sensors and the base station can perform fusion of the sensed data in order to filter out erroneous data and anomalies, and to draw conclusions from the reported data over a period of time. For example, in a reconnaissance-oriented network, sensor data indicates detection of a target, while fusion of multiple sensor reports can be used for tracking and identifying the detected target.

This handbook is intended for researchers and graduate students in computer science and electrical engineering, and researchers and developers in the telecommunication industry. It provides an opportunity for researchers to explore the currently “hot” field of sensor networks. It is a problem-oriented book, with each chapter discussing computing and communication problems and solutions that arise in rapidly emerging wireless sensor networks. The main purpose of the book is to review various algorithms and protocols that were developed in the area, with the emphasis on the most recent ones.

The handbook is based on a number of stand-alone chapters that together cover the subject matter in a fully comprehensive manner. Edited books are normally collections of chapters freely selected by invited authors. This handbook follows a different approach. First, the sensor network arena was divided into meaningful units, reflecting the state of the art, importance, amount of literature, and, above all, comprehensiveness. Then the most suitable author for each chapter was selected, considering their expertise and presentation skills. The editor also considered the geographical distribution of authors, and representations from industry and top research institutions. Among the authors are researchers from Motorola, Intel, and Fujitsu laboratories, MIT, IIT, Cornell University, University of Illinois, all in the United States, plus researchers from Switzerland, Germany, France, Australia, and Canada.
Sensor networks are currently recognized as one of the priority research areas (for example, a multidisciplinary program on sensors and sensor networks was launched in 2003 at the U.S. National Science Foundation), and research activities recently started booming. A number of ongoing projects are being funded in Europe, Asia, and North America. Before Y2K, research on sensor networks was sporadic, and were treated as a special case of emerging ad hoc networks. Sensor networks were then quickly recognized as an independent topic, their name was added to some event titles, and now events specializing in sensor networks have emerged in the last two years. At least two new journals devoted exclusively to sensor networks appeared in 2005.

As a result of the exponential growth in the number of researchers, publications, conferences, and journals on sensor networks, a number of graduate courses fully or partially concentrating on sensor networks have emerged recently. These courses are mostly based on reading a selected set of recent articles, with the focus on certain topics that reflect the interest of the instructor within the sensor networks domain. It is expected that this book will provide a much needed textbook for such graduate courses. Since the area is gaining popularity, a textbook is needed as a reference source for use by students and researchers. The chapters cover subjects in a comprehensive manner, describing the state of the art and surveying important existing 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.

This handbook is intended to cover a wide range of recognized problems in sensor 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. The handbook content addresses the dynamic nature of ad hoc and sensor networks. Due to frequent node addition and deletion from networks (changes between active and inactive periods, done to conserve energy, are one of the contributors to this dynamic) and possible node movement, the algorithms that potentially can be used in real equipment must be localized and must have minimal communication overhead. The overhead should take both the construction and its maintenance for the structure used in solutions and ongoing protocols into consideration. We believe that only this approach will eventually lead to the design of protocols for real applications. We now explain our design principles and priorities, used to cover the subject matter in this handbook.

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, in contrast with most existing protocols, which require global information. In a localized algorithm, each node makes protocol decisions solely based on the 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 huge communication overhead, which is not affordable for bandwidth and power-limited nodes. In addition to being localized, protocols are also required to be \textit{simple, easy to understand and implement}, and to have \textit{good average-case performance}. Efficient solutions often require position information. It has been widely recognized that sensor networks can function properly only if reasonably accurate position information is provided to the nodes.

\section*{BRIEF OUTLINE CONTENT}

This handbook consists of 15 chapters. It begins with an introductory chapter that describes various scenarios where sensor networks may be applied, and various application-layer tools for enabling such applications. Applications include habitat monitoring, biomedical sensor engineering, monitoring environments, water and waste management, and military applications. The second chapter is on physical layer and signal processing in sensor networks.

In sensor networks with tiny devices, which are usually designed to run on batteries, the replacement of depleted batteries is not practical. The goal of the third chapter is to explore methods of scavenging ambient power for use by low-power wireless electronic devices in an effort to make the wireless nodes and resulting wireless sensor networks indefinitely self-sustaining.

Chapter 4 describes a vision to build ultra-low-power wireless sensor systems and a self-contained, millimeter-scale sensing and communication platform for a massively distributed sensor network. This vision is based on realistic assumptions about sensors, such as limited ability to provide accurate position information (therefore proposing the concept of cluster position information rather than individual position information), and lack of individual sensor identities (the property commonly recognized but often implicitly assumed in protocols).

The power, computation, and communication limitations of sensor networks make the design and utilization of security and fault-tolerance schemes particularly challenging. Chapter 5 is intended as a starting point for studying sensor network security. It focuses on recent advances in broadcast authentication and key management in sensor networks, which are foundational cryptographic services for sensor network security. It describes random key predistribution techniques proposed for establishing pairwise keys between resource-constrained sensor nodes. Attacks against location discovery and some additional security problems in sensor networks are also discussed.
Chapter 6 reviews research on operating systems and middleware issues in the emerging area of embedded, networked sensors. Chapter 7 addresses the issue of calibration and time synchronization in sensor networks and related problems, such as temporal message ordering. Chapter 8 reviews various medium-access schemes for sensor networks, and the power efficiency aspects of these schemes.

In the position-determination problem, each sensor should be designed to decide about its geographic position based on several reference nodes in the network, in case it has no direct position service such as global positioning system (GPS) attached. The position needs to be determined in cooperation with other sensors, based on hop counts to reference nodes or other information. Chapter 9 reviews triangulation, multilateration, diffusion, and other types of solutions for this problem.

The problem of deciding the best transmission radius of each sensor, and the links that are desirable to have, is a challenging one. For instance, it is known that the probability that a random-unit graph is connected has a sharp transition from 0 to 1, meaning that it is difficult to decide the best uniform transmission radius for network connectivity and congestion avoidance. On the other hand, efficient localized methods exist where each node is designed to decide its own transmission radius and links. Chapter 10 reviews topology construction and maintenance schemes under various sensor architectures.

In a broadcasting (also known as data dissemination) task, a message is sent from one node, which could be a monitoring center, to all the nodes in the network. The activity scheduling problem is one of deciding which sensors should be active and which should go to sleep mode, so that the sensor network’s life is prolonged. The best known solutions to these two problems are based on the concept of localized connected dominating sets. Sensors that are randomly placed in an area should be designed to decide which of them should be active and monitor an area, and which of them may sleep and become active at a later time. The connectivity is important so that the measured data can be reported to the monitoring center. Sensors may also be placed deterministically in an area to optimize coverage and reduce their power consumption. Chapter 11 reviews solutions to these three related problems in sensor networks.

Position information enables development of localized routing methods (greedy routing decisions are made at each node, based solely on knowledge of positions of neighbors and destination, with considerable savings in communication overhead and with guaranteed delivery, provided location update schemes are efficient for a given movement pattern. Power consumption can be taken into account in the routing process. Chapter 12 surveys existing position based and power aware routing schemes. It also reviews physical layer aspects of position based routing.

Chapter 13 covers the emerging topic of data-driven routing, for example, directed diffusion. It also covers the emerging topics of constructing and maintaining reporting trees, dynamic evolution of the monitoring region for moving targets, various training options, and receiving reports from a particular area of interest, that is, geocasting.
In order to monitor a region for traffic traversal, sensors can be deployed to perform collaborative target detection. Such a sensor network achieves a certain level of detection performance with an associated cost of deployment. Chapter 14 reviews solutions for the various path-exposure protocols and sensor deployment for increased reliability of measurements. In the object-location problem, sensors collaborate to detect the position of a mobile object. The goal is to derive the location accurately, with a minimum number of sensors involved in the process. This chapter also discusses sensor networks for target classification and tracking, with respect to location-aware data routing to conserve system resources, such as energy and bandwidth. Distributed classification algorithms exploit signals from multiple nodes in several modalities and rely on prior statistical information about target classes.

Data gathering in sensor networks differs from the general ad hoc network’s data communication protocols. Sensors in general monitor or measure the same event or data and report it to the monitoring center. Their data may be combined while being routed (data fusion), to save energy and increase reliability of reports. Chapter 15 reviews protocols for data gathering and fusion in sensor networks. This chapter also discusses the challenging problem of transport-layer protocols in sensor networks. Due to severe power and computational limitations, providing quality of service, delay, or jitter guarantees, in routing and data dissemination tasks by sensors is a difficult problem. This chapter also reviews efficient sensor database querying, for example, TinyDB. The sensor system should provide scalable, fault-tolerant, flexible data access and intelligent data reduction, as its design involves a confluence of novel research in database query processing, networking, algorithms, and distributed systems.

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