



HANDBOOK OF SENSOR NETWORKS

ALGORITHMS AND ARCHITECTURES

& CONTENTS

Preface	ix
Contributors	xv
1. Introduction to Wireless Sensor Networking Fernando Martincic and Loren Schwiebert	1
2. Distributed Signal Processing Algorithms for the Physical Layer of Large-Scale Sensor Networks An-swol Hu and Sergio D. Servetto	41
3. Energy Scavenging and Nontraditional Power Sources for Wireless Sensor Networks Shad Roundy and Luc Frechette	75
4. A Virtual Infrastructure for Wireless Sensor Networks Stephan Olariu, Qingwen Xu, Ashraf Wadaa, and Ivan Stojmenović	107
5. Broadcast Authentication and Key Management for Secure Sensor Networks Peng Ning and Donggang Liu	141
6. Embedded Operating Systems for Wireless Microsensor Nodes Brian Shucker, Jeff Rose, Anmol Sheth, James Carlson, Shah Bhatti, Hui Dai, Jing Deng, and Richard Han	173
7. Time Synchronization and Calibration in Wireless Sensor Networks Kay Römer, Philipp Blum, and Lennart Meier	199
8. The Wireless Sensor Network MAC Edgar H. Callaway, Jr.	239
9. Localization in Sensor Networks Jonathan Bachrach and Christopher Taylor	277
10. Topology Construction and Maintenance in Wireless Sensor Networks Jennifer C. Hou, Ning Li, and Ivan Stojmenović	311

11. Energy-Efficient Backbone Construction, Broadcasting, and Area Coverage in Sensor Networks David Simplot-Ryl, Ivan Stojmenović', and Jie Wu	343
12. Geographic and Energy-Aware Routing in Sensor Networks Hannes Frey and Ivan Stojmenović'	381
13. Data-Centric Protocols for Wireless Sensor Networks Ivan Stojmenović' and Stephan Olariu	417
14. Path Exposure, Target Location, Classification, and Tracking in Sensor Networks Kousha Moaveni-Nejad and Xiang-Yang Li	457
15. Data Gathering and Fusion in Sensor Networks Wei-Peng Chen and Jennifer C. Hou	493
Index	527

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—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 simple, easy to understand and implement, and to have 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.

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.

ACKNOWLEDGMENTS

The editor is grateful to all the authors for their contribution to the quality of this handbook. The assistance of reviewers for all chapters is also greatly appreciated.

The University of Ottawa (with the help of the National Science and Engineering Research Council (NSERC) provided an ideal working environment for the preparation of this handbook. This environment included computer facilities for efficient Internet search, communication by electronic mail, and writing my own contributions.

The editor is thankful to Dr. Albert Zomaya, editor of the Parallel and Distributed Computing book series at Wiley, for his support and encouragement in publishing this handbook at Wiley. Special thanks go to Richard Han and Krishna Sivalingam; this book benefited greatly from their comments and suggestions. Val Moliere (Editor, Wiley-Interscience), Emily Simmons, (Editorial Assistant), and Kirsten Rohstedt (Editorial Program Coordinator) deserve special mention for their timely and professional cooperation, and for their decisive support of this project.

Introduction to Wireless Sensor Networking

FERNANDO MARTINCIC and LOREN SCHWIEBERT
Wayne State University, Detroit, Michigan

This chapter introduces the topic of wireless sensor networks from the applications perspective. A wireless sensor network consists of a possibly large number of wireless devices able to take environmental measurements such as temperature, light, sound, and humidity. These sensor readings are transmitted over a wireless channel to a running application that makes decisions based on these sensor readings.

Authors describe some examples of proposed wireless sensor applications, and consider the following two questions to motivate an application-based viewpoint.

What aspects of wireless sensors make the implementation of applications more challenging, or at least different? One widely recognized issue is the limited power available to each wireless sensor node, but there are other challenges such as limited storage or processing. What services are required for a wireless sensor network application to achieve its intended purpose? A number of widely applicable services, such as time synchronization and location determination are briefly discussed in this chapter. Other services are needed to support database requirements, such as message routing, topology management, and data aggregation and storage. As most of these topics are covered in separate chapters, this chapter serves to provide a broad framework to enable the reader to see how these different topics tie together into a cohesive set of capabilities for building wireless sensor network applications.

1.1 INTRODUCTION

A wireless sensor network consists of a possibly large number of wireless devices able to take environmental measurements. Typical examples include temperature,

light, sound, and humidity. These sensor readings are transmitted over a wireless channel to a running application that makes decisions based on these sensor readings. Many applications have been proposed for wireless sensor networks, and many of these applications have specific quality of service (QoS) requirements that offer additional challenges to the application designer. In this chapter, we introduce the topic of wireless sensor networks from the perspective of the application.

Along with some examples of proposed wireless sensor applications, we consider two questions to motivate an application-based viewpoint:

1. What aspects of wireless sensors make the implementation of applications more challenging, or at least different?

One widely recognized issue is the limited power available to each wireless sensor node, but other challenges such as limited storage or processing capabilities play a significant role in constraining the application development.

2. What services are required for a wireless sensor network application to achieve its intended purpose?

A number of widely applicable services, such as time synchronization and location determination are briefly discussed. Other services are needed to support database requirements, such as message routing, topology management, and data aggregation and storage.

Because some of these topics are covered in separate chapters, this discussion serves to provide a broad framework to enable the reader to see how these different topics tie together into a cohesive set of capabilities for building wireless sensor network applications.

1.2 DESIGN CHALLENGES

Several design challenges present themselves to designers of wireless sensor network applications. The limited resources available to individual sensor nodes implies designers must develop highly distributed, fault-tolerant, and energy-efficient applications in a small memory-footprint. Consider the latest-generation MICAz [1,2] sensor node shown in Figure 1.1.

MICAz motes are equipped with an Atmel128L [4] processor capable of a maximum throughput of 8 millions of instructions per second (MIPS) when operating at 8 MHz. It also features an IEEE 802.15.4/Zigbee compliant RF transceiver, operating in the 2.4–2.4835-GHz globally compatible industrial scientific medical (ISM) band, a direct spread-spectrum radio resistant to RF interference, and a 250-kbps data transfer rate. The MICAz runs on TinyOS [5] (v1.1.7 or later) and is compatible with existing sensor boards that are easily mounted onto the mote. A partial list of specifications given by the manufacturers of the MICAz mote is presented in Figure 1.2.



Figure 1.1 MICAz sensor mote hardware. (Image courtesy of Crossbow Technology [3].)

For wireless sensor network applications to have reasonable longevity, an aggressive energy-management policy is mandatory. This is currently the greatest design challenge in any wireless sensor network application. Considering that in the MICAz mote the energy cost associated with transmitting a byte over the transceiver is substantially greater than performing local computation, developers must leverage local processing capabilities to minimize battery-draining radio communication.

Several key differences between more traditional ad hoc networks and wireless sensor networks exist [6]:

- Individual nodes in a wireless sensor network have limited computational power and storage capacity. They operate on nonrenewable power sources and employ a short-range transceiver to send and receive messages.
- The number of nodes in a wireless sensor network can be several orders of magnitude higher than in an ad hoc network. Thus, algorithm scalability is an important design criterion for sensor network applications.
- Sensor nodes are generally densely deployed in the area of interest. This dense deployment can be leveraged by the application, since nodes in close proximity can collaborate locally prior to relaying information back to the base station.
- Sensor networks are prone to frequent topology changes. This is due to several reasons, such as hardware failure, depleted batteries, intermittent radio interference, environmental factors, or the addition of sensor nodes. As a result, applications require a degree of inherent fault tolerance and the ability to reconfigure themselves as the network topology evolves over time.

Processor	Atmel ATmega128L @ 8 MHz
Program Flash Memory	128 kilobytes
Measurement Serial Flash	512 kilobytes
Configuration electrically erasable programmable read-only memory (EEPROM)	4 kilobytes
Serial Communications	UART
Analog to Digital Converter	10 bit ADC
Other Interfaces	Digital I/O, I2C, SPI
Processor Current Draw	8 mA in active mode < 1 μ A in sleep mode
Frequency band	2400MHz to 2483.5MHz
Transmit (TX) data rate	250kbps
RF power	-24dBm to 0dBm
Receive Sensitivity	-90dBm (min), -94dBm (typ)
Adjacent channel rejection	47 dB, +5-MHz channel spacing 38 dB, -5-MHz channel spacing
Outdoor Range	75m to 100m
Indoor Range	20m to 30m
Radio Current Draw	19.7mA in receive mode 11mA (TX -10dBm) 14mA, (TX -5dBm) 17.4mA (TX 0dBm) 20 μ A in idle mode (voltage regulator on) 1 μ A in sleep mode (voltage regulator off)
Battery	2 AA batteries
User Interface	red, green, and yellow LED
Size	2.25 \times 1.25 \times 0.25in. (w/o battery pack)
Weight	0.7 oz (w/o batteries)
Expansion Connector	51 pin

Figure 1.2 MICAz mote specification [1].

. Wireless sensor networks do not employ a point-to-point communication paradigm because they are usually not aware of the entire size of the network and nodes are not uniquely identifiable. Consequently, it is not possible to individually address a specific node. Paradigms, such as directed diffusion [7,8], employ a data-centric view of generated sensor data. They identify information produced by the sensor network as key-value pairs. Nodes request data by disseminating interests for this named data throughout the network. Data that matches the criterion are relayed back toward the querying node.

Even with the limitations individual sensor nodes possess and the design challenges application developers face, several advantages exist for instrumenting an area with a wireless sensor network [9]:

- . Due to the dense deployment of a greater number of nodes, a higher level of fault tolerance is achievable in wireless sensor networks.
- . Coverage of a large area is possible through the union of coverage of several small sensors.
- . Coverage of a particular area and terrain can be shaped as needed to overcome any potential barriers or holes in the area under observation.
- . It is possible to incrementally extend coverage of the observed area and density by deploying additional sensor nodes within the region of interest.
- . An improvement in sensing quality is achieved by combining multiple, independent sensor readings. Local collaboration between nearby sensor nodes achieves a higher level of confidence in observed phenomena.
- . Since nodes are deployed in close proximity to the sensed event, this overcomes any ambient environmental factors that might otherwise interfere with observation of the desired phenomenon.

1.3 WIRELESS SENSOR NETWORK APPLICATIONS

Several applications have been envisioned for wireless sensor networks [6]. These range in scope from military applications to environment monitoring to biomedical applications. This section discusses proposed and actual applications that have been implemented by various research groups.

1.3.1 Military Applications

Wireless sensor networks can form a critical part of military command, control, communications, computing, intelligence, surveillance, reconnaissance, and target- ing (C4ISRT) systems. Examples of military applications include monitoring of friendly and enemy forces; equipment and ammunition monitoring; targeting; and nuclear, biological, and chemical attack detection.

By equipping or embedding equipment and personnel with sensors, their condition can be monitored more closely. Vehicle-, weapon-, and troop-status information can be gathered and relayed back to a command center to determine the best course of action. Information from military units in separate regions can also be aggregated to give a global snapshot of all military assets.

By deploying wireless sensor networks in critical areas, enemy troop and vehicle movements can be tracked in detail. Sensor nodes can be programmed to send notifications whenever movement through a particular region is detected. Unlike other surveillance techniques, wireless sensor networks can be programmed to be completely passive until a particular phenomenon is detected. Detailed and timely

intelligence about enemy movements can then be relayed, in a proactive manner, to a remote base station.

In fact, some routing protocols have been specifically designed with military applications in mind [10]. Consider the case where a troop of soldiers needs to move through a battlefield. If the area is populated by a wireless sensor network, the soldiers can request the location of enemy tanks, vehicles, and personnel detected by the sensor network (Fig. 1.3). The sensor nodes that detect the presence of a tank can collaborate to determine its position and direction, and disseminate this information throughout the network. The soldiers can use this information to strategically position themselves to minimize any possible casualties.

In chemical and biological warfare, close proximity to ground zero is needed for timely and accurate detection of the agents involved. Sensor networks deployed in friendly regions can be used as early-warning systems to raise an alert whenever the presence of toxic substances is detected. Deployment in an area attacked by chemical or biological weapons can provide detailed analysis, such as concentration levels of the agents involved, without the risk of human exposure.

1.3.2 Environmental Applications

By embedding a wireless sensor network within a natural environment, collection of long-term data on a previously unattainable scale and resolution becomes possible. Applications are able to obtain localized, detailed measurements that are otherwise more difficult to collect. As a result, several environmental applications have been proposed for wireless sensor networks [6,9]. Some of these include habitat monitoring, animal tracking, forest-fire detection, precision farming, and disaster relief applications.

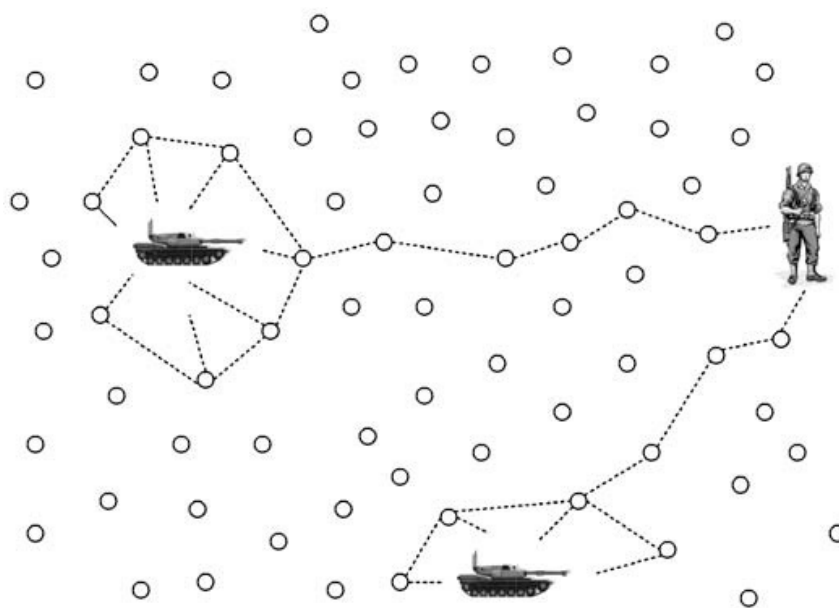


Figure 1.3 Enemy target localization and monitoring.

Habitat monitoring permits researchers to obtain detailed measurements of a particular environment in an unobtrusive manner. For example, applications such as the wireless sensor network deployed on Great Duck Island [11] allow researchers to monitor the nesting burrows of Leach's Storm Petrels without disturbing these sea-birds during the breeding season. Deployment of the sensor network occurs prior to the arrival of these offshore birds. Monitoring of the birds can then proceed without direct human contact. Similarly, the PODS project [12,13] at the University of Hawaii uses wireless sensor networks to observe the growth of endangered species of plants. Data collected by the sensor network is used to determine the environmental factors that support the growth of these endangered plants. These two applications are discussed in detail in Sections 1.3.4 and 1.3.5.

Consider a scenario where a fire starts in a forest. A wireless sensor network deployed in the forest could immediately notify authorities before it begins to spread uncontrollably (see Fig. 1.4). Accurate location information [14] about the fire can be quickly deduced. Consequently, this timely detection gives firefighters an unprecedented advantage, since they can arrive at the scene before the fire spreads uncontrollably.

Precision farming [15] is another application area that can benefit from wireless sensor network technology. Precision farming requires analysis of spatial data to determine crop response to varying properties such as soil type [16]. The ability to embed sensor nodes in a field at strategic locations could give farmers detailed soil analysis to help maximize crop yield or possibly alert them when soil and crop conditions attain a predefined threshold. Since wireless sensor networks are designed to run unattended, active physical monitoring is not required.

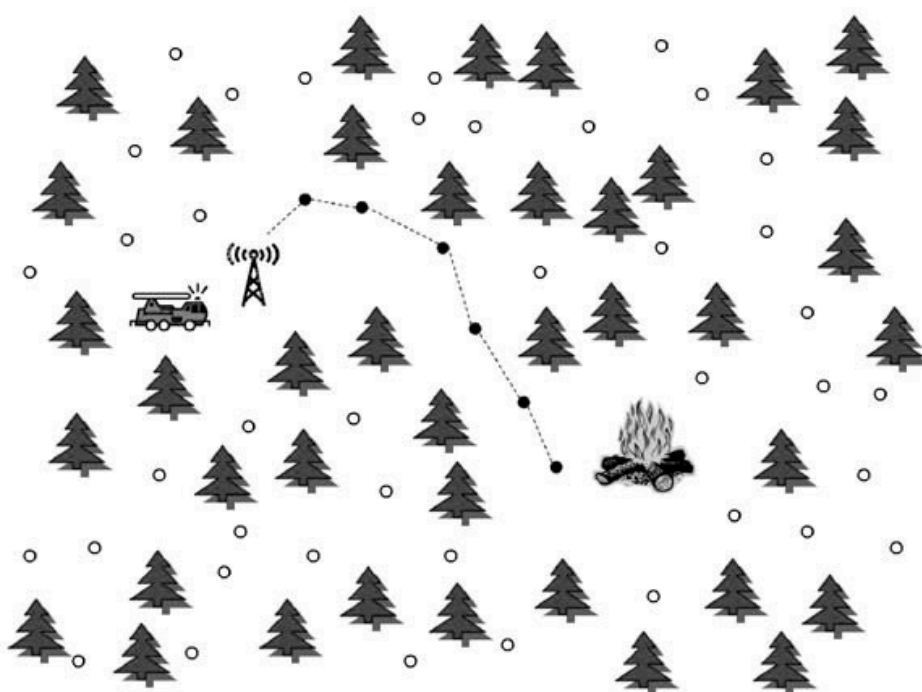


Figure 1.4 Forest-fire monitoring application.

Disaster relief efforts such as the ALERT flood-detection system [17] make use of remote field sensors to relay information to a central computer system in real time. Typically, an ALERT installation comprises several types of sensors, such as rainfall sensors, water-level sensors, and other weather sensors. Data from each set of sensors are gathered and relayed to a central base station.

1.3.3 HealthApplications

Potential health applications abound for wireless sensor networks. Conceivably, hospital patients could be equipped with wireless sensor nodes that monitor the patients' vital signs and track their location. Patients could move about more freely while still being under constant supervision. In case of an accident—say, the patient trips and falls—the sensor could alert hospital workers as to the patient's location and condition. A doctor in close proximity, also equipped with a wireless sensor, could be automatically dispatched to respond to the emergency.

Glucose-level monitoring is a potential application suitable for wireless sensor networks [18]. Individuals with diabetes require constant monitoring of blood sugar levels to lead healthy, productive lives. Embedding a glucose meter within a patient with diabetes could allow the patient to monitor trends in blood-sugar levels and also alert the patient whenever a sharp change in blood-sugar levels is detected. Information could be relayed wirelessly from the monitor to a wristwatch display. It would then be possible to take corrective measures to normalize blood- sugar levels in a timely manner before they get to critical levels. This is of particular importance when the individual is asleep and may not be aware that their blood- sugar levels are abnormal.

The Smart Sensors and Integrated Microsystems (SSIM) project at Wayne State University and the Kresge Eye Institute are working on developing an artificial retina [18]. One of the project goals is to build a chronically implanted artificial retina that allows a visually impaired individual to “see” at an acceptable level. Currently, smart sensor chips equipped with 100 microsensors exist that are used in ex vivo retina testing. The smart sensor comprises an integrated circuit (with transmit and receive capabilities) and an array of sensors. Challenges in this application include establishing a communication link between the retinal implant and an external computer to determine if the image is correctly seen. Regulating the amount of power used by the system to avoid damage to the retina and surrounding tissue is also a primary concern.

1.3.4 HabitatMonitoringonGreatDuckIsland

Leach's Storm Petrel (Fig. 1.5) is a common elusive seabird in the western North Atlantic. Most of their lives are spent off-shore, only to return to land during the breeding season. During this time, they nest in burrows located in soft, peaty soil, and are active predominantly at night. It is believed Great Duck Island, located 15 km off the coast of Maine, has one of the largest petrel breeding colonies in the eastern United States.



Figure 1.5 Leach's Storm Petrel. (U.S. Geological Survey photo by J. A. Splendelow.)

Petrel activity monitoring is a delicate problem, since disturbance or interference on the part of humans can lead to nest abandonment or increased predation on chicks or eggs.

To circumvent this problem, in the spring of 2002, the Intel Research Laboratory at Berkeley initiated a collaboration with the College of the Atlantic in Bar Harbor and the University of California at Berkeley to deploy a series of wireless sensor networks on the island [11,19,20]. By the summer of 2002, 43 sensor nodes were deployed on the island. The primary purpose of the sensor network was to monitor the microclimates in and around nesting burrows used by the petrels. Thus, researchers could take multiple measurements of biological parameters at frequent intervals, with minimal disturbance to the breeding colony. It was necessary to enter the colony only at the beginning of the study to insert sensor nodes into burrows and other areas of interest. Three major issues explored in this experiment included:

1. Determination of the usage pattern of nesting burrows over the cycle when one or both members of the breeding pair may alternate between incubation and feeding.
2. Determination of changes in the environmental conditions of burrows and surface areas throughout the course of the breeding season.
3. Measuring the differences in the microenvironments with and without large numbers of nesting petrels.

By November 2002, 32 sensor nodes had collected over one million sensor readings. For this particular application, the nodes were equipped with a separate weather board that contained sensors to detect temperature, humidity, barometric pressure, and midrange infrared. Motes periodically sampled and relayed their sensor readings to different base stations located throughout the island. These base stations provided researchers access to real-time environmental data gathered by the sensor nodes via the Internet.

In June 2003, a second-generation network comprising 56 nodes was deployed. This network was further augmented in July 2003 with an additional 49 nodes. Finally, in August 2003, over 60 additional burrow nodes and 25 weather-monitoring nodes were deployed on the island.

1.3.4.1 Hardware The system designers employed Mica motes (Fig. 1.6), which are small devices equipped with a microcontroller, low-power radio, memory, and batteries. The motes are designed with a single-channel 916-MHz radio that provides bidirectional communication at 40 kbps, an Atmel Atmega 103 microcontroller operating at 4MHz, and 512kB of nonvolatile storage.

Power to the mote is supplied by a pair of AA batteries and a DC boost converter. To allow sampling of the environment, the Mica mote was equipped with a Mica weather board that contains temperature, photoresistor, barometric pressure, humidity, and passive infrared sensors [11]. To protect the motes from adverse weather conditions, the sensor package was sealed in a 10-micron parylene sealant that protected the electrical contacts from water. The sensors themselves remained exposed so as not to hinder their sensitivity. The coated sensor was then encased in a ventilated acrylic enclosure. The acrylic enclosure was radio and infrared transparent and also elevated the mote off the ground.

Due to the longevity of the proposed application, battery life was budgeted carefully. A conservative estimate of 2200 mAh total capacity was utilized. For illustrative purposes, Table 1.1 lists the costs associated with performing basic Mica mote operations and Table 1.2 lists the costs associated with basic sensor operations [21].

For the habitat monitoring application, an application lifetime of 9 months was desired. Thus, with 2200 mAh of total power available, the sensor motes were

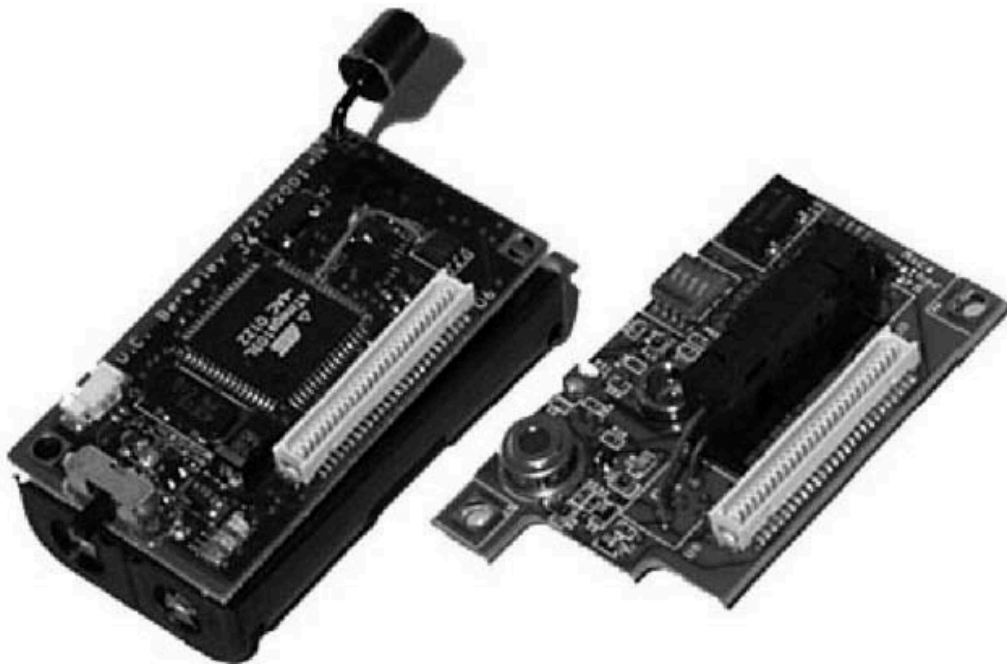


Figure 1.6 Mica sensor node (left) with the Mica Weather Board (right).