FUNDAMENTALS OF WIRELESS SENSOR NETWORKS

THEORY AND PRACTICE

Waltenegus Dargie
Technical University of Dresden, Germany

Christian Poellabauer
University of Notre Dame, USA

WILEY
A John Wiley and Sons, Ltd., Publication

FUNDAMENTALS OF WIRELESS SENSOR NETWORKS

Wiley Series on Wireless Communications and Mobile Computing

Series Editors: Dr Xuemin (Sherman) Shen, *University of Waterloo, Canada*
Dr Yi Pan, *Georgia State University, USA*

The "Wiley Series on Wireless Communications and Mobile Computing" is a series of comprehensive, practical and timely books on wireless communication and network systems. The series focuses on topics ranging from wireless communication and coding theory to wireless applications and pervasive computing. The books provide engineers and other technical professionals, researchers, educators, and advanced students in these fields with invaluable insight into the latest developments and cutting-edge research.

Other titles in the series:

Misic and Misic: *Wireless Personal Area Networks: Performance, Interconnection, and Security with IEEE 802.15.4*, January 2008, 978-0-470-51847-2

Takagi and Walke: *Spectrum Requirement Planning in Wireless Communications: Model and Methodology for IMT-Advanced*, April 2008, 978-0-470-98647-9

Pérez-Fontán and Espiñeira: *Modeling the Wireless Propagation Channel: A simulation approach with MATLAB®*, August 2008, 978-0-470-72785-0

Ippolito: *Satellite Communications Systems Engineering: Atmospheric Effects, Satellite Link Design and System Performance*, August 2008, 978-0-470-72527-6

Lin and Sou: *Charging for Mobile All-IP Telecommunications*, September 2008, 978-0-470-77565-3

Myung and Goodman: *Single Carrier FDMA: A New Air Interface for Long Term Evolution*, October 2008, 978-0-470-72449-1

Wang, Kondi, Luthra and Ci: *4G Wireless Video Communications*, April 2009, 978-0-470-77307-9

Cai, Shen and Mark: *Multimedia Services in Wireless Internet: Modeling and Analysis*, June 2009, 978-0-470-77065-8

Stojmenovic: *Wireless Sensor and Actuator Networks: Algorithms and Protocols for Scalable Coordination and Data Communication*, February 2010, 978-0-470-17082-3

Liu and Weiss, *Wideband Beamforming: Concepts and Techniques*, March 2010, 978-0-470-71392-1

Riccharia and Westbrook, *Satellite Systems for Personal Applications: Concepts and Technology*, July 2010, 978-0-470-71428-7

Hart, Tao and Zhou: *Mobile Multi-hop WiMAX: From Protocol to Performance*, October 2010, 978-0-470-99399-6

Qian, Muller and Chen: *Security in Wireless Networks and Systems*, January 2011, 978-0-470-512128

FUNDAMENTALS OF WIRELESS SENSOR NETWORKS

THEORY AND PRACTICE

Waltenegus Dargie
Technical University of Dresden, Germany
Christian Poellabauer
University of Notre Dame, USA

WILEY
A John Wiley and Sons, Ltd., Publication

This edition first published 2010

Registered office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

Library of Congress Cataloging-in-Publication Data:

Dargie, Waltenegus.
Fundamentals of wireless sensor networks : theory and practice / Waltenegus Dargie, Christian Poellabauer.
p. cm.
Includes index.
ISBN 978-0-470-99765-9 (cloth)
1. Wireless sensor networks. I. Poellabauer, Christian. II. Title.
TK7872.D48D37 2010
681'.2 – dc22

2010003984

A catalogue record for this book is available from the British Library.

ISBN 978-0-470-99765-9 (H/B)

Typeset in 10/12 Times by Laserwords Private Limited, Chennai, India.
Printed and Bound in Singapore by Markono

To my wife, Kathy,
and my children, Joshua and Pheben

Waltenegus Dargie

To my wife, Rumana,
and my children, Adam and Maya

Christian Poellabauer

Contents

About the Series Editors

Xuemin (Sherman) Shen (M'97-SM'02) received the B.Sc degree in electrical engineering from Dalian Maritime University, China in 1982, and the M.Sc. and Ph.D. degrees (both in electrical engineering) from Rutgers University, New Jersey, USA, in 1987 and 1990 respectively. He is a Professor and University Research Chair, and the Associate Chair for Graduate Studies, Department of Electrical and Computer Engineering, University of Waterloo, Canada. His research focuses on mobility and resource management in interconnected wireless/wired networks, UWB wireless communications systems, wireless security, and ad hoc and sensor networks. He is a co-author of three books, and has published more than 300 papers and book chapters in wireless communications and networks, control and filtering. Dr. Shen serves as a Founding Area Editor for IEEE Transactions on Wireless Communications; Editor-in-Chief for Peer-to-Peer Networking and Application; Associate Editor for IEEE Transactions on Vehicular Technology; KICS/IEEE Journal of Communications and Networks, *Computer Networks*; ACM/Wireless Networks; and Wireless Communications and Mobile Computing (Wiley), etc. He has also served as Guest Editor for IEEE JSAC, IEEE Wireless Communications, and IEEE Communications Magazine. Dr. Shen received the Excellent Graduate Supervision Award in 2006, and the Outstanding Performance Award in 2004 from the University of Waterloo, the Premier's Research Excellence Award (PREA) in 2003 from the Province of Ontario, Canada, and the Distinguished Performance Award in 2002 from the Faculty of Engineering, University of Waterloo. Dr. Shen is a registered Professional Engineer of Ontario, Canada.

Dr. Yi Pan is the Chair and a Professor in the Department of Computer Science at Georgia State University, USA. Dr. Pan received his B.Eng. and M.Eng. degrees in computer engineering from Tsinghua University, China, in 1982 and 1984, respectively, and his Ph.D. degree in computer science from the University of Pittsburgh, USA, in 1991. Dr. Pan's research interests include parallel and distributed computing, optical networks, wireless networks, and bioinformatics. Dr. Pan has published more than 100 journal papers with over 30 papers published in various IEEE journals. In addition, he has published over 130 papers in refereed conferences (including IPDPS, ICPP, ICDCS, INFOCOM, and GLOBECOM). He has also co-edited over 30 books. Dr. Pan has served as an editor-in-chief or an editorial board member for 15 journals including five IEEE Transactions and has organized many international conferences and workshops. Dr. Pan has delivered over 10 keynote speeches at many international conferences. Dr. Pan is an IEEE Distinguished Speaker (2000–2002), a Yamacraw Distinguished Speaker (2002), and a Shell Oil Colloquium Speaker (2002). He is listed in Men of Achievement, Who's Who in America, Who's Who in American Education, Who's Who in Computational Science and Engineering, and Who's Who of Asian Americans.

Preface

Rapid advances in the areas of sensor design, information technologies, and wireless networks have paved the way for the proliferation of wireless sensor networks. These networks have the potential to interface the physical world with the virtual (computing) world on an unprecedented scale and provide practical usefulness in developing a large number of applications, including the protection of civil infrastructures, habitat monitoring, precision agriculture, toxic gas detection, supply chain management, and health care. However, the design of wireless sensor networks introduces formidable challenges, since the required body of knowledge encompasses a whole range of topics in the field of electrical and computer engineering, as well as computer science.

Wireless sensor networks are currently being offered as a subject at advanced undergraduate and graduate levels at many universities around the world. Moreover, they are the focus of countless graduate theses and student projects. Therefore, this book is primarily written as a textbook aimed at students of engineering and computer science. It provides an introduction into the fundamental concepts and building blocks of wireless sensor network design. An attempt has been made to maintain a balance between theory and practice, as well as established practices and the latest developments. At the end of each chapter, a number of practical questions and exercises are given to help the students to assess their understanding of the main concepts and arguments presented in the chapter. Furthermore, the chapters and parts of the book are sufficiently modular to provide flexibility in course design.

The book will also be useful to the professional interested in this field. It is suitable for self-study and can serve as an essential reference. For such a reader, the material can be viewed as a tutorial in the basic concepts and surveys of recent research results and technological developments.

Structure of the Book

This book provides an introduction to the fundamental concepts and principles of wireless sensor networks (WSNs) and a survey of protocols, algorithms, and technologies at different layers of a sensor system, including the network protocol stack, middleware, and application level.

The text is broken into three parts. In Part One, **Introduction**, Chapter 1 provides an overview of WSN applications, sensor nodes, and basic system structure. Chapter 2 continues the introduction into the WSN domain by providing an overview of representative sensor network applications. Chapter 3 presents different node architectures and discusses in detail the sensing and processing subsystems as well as communication interfaces. Moreover, it provides several examples of representative prototype implementations. Chapter 4 describes functional and nonfunctional aspects of operating systems and provides a survey of state-of-the-art examples.

Part Two, **Basic Architectural Framework**, provides a detailed discussion of protocols and algorithms used at different network protocol layers in sensor systems. The design choices at these layers significantly impact the operation and resource efficiency of sensor nodes and networks. Chapter 5 begins this discussion with an introduction into physical layer architectures and concepts. Since the wireless medium is shared between many sensor nodes, MAC-layer protocols are required to arbitrate access to the wireless channels. MAC-layer solutions are discussed in Chapter 6. Chapter 7 discusses multi-hop communications in WSNs and the associated challenges. It also surveys existing and proposed routing protocols.

Part Three, **Node and Network Management**, discusses several additional techniques and presents solutions for a variety of challenges. Chapter 8 begins the discussion with an overview of power management techniques for wireless sensor networks. When multiple sensor nodes observe the same event in the physical world, it is important to correctly correlate these observations from the different sensors. This requires the clocks of the sensor nodes to be synchronized with each other. Synchronized clocks are also required by a variety of protocols and algorithms, e.g., many MAC protocols rely on accurate timing to ensure that no two nodes transmit packets at the same time. Therefore, Chapter 9 introduces the concept of time synchronization and provides an overview of several synchronization strategies. For many sensor network applications, it is essential that sensor nodes estimate their own position, either using absolute coordinates (e.g., using GPS) or relative to other nodes or landmarks in the environment. Chapter 10 presents a variety of localization strategies and compares their tradeoffs. Wireless sensor networks pose several security challenges due to the nature of many sensor applications (military, emergency response) and the unique characteristics of sensor networks (e.g., scale and unattended operation). Therefore, security challenges and defenses against attacks on sensor networks are discussed in Chapter 11. Finally, Chapter 12 concludes the book with a description of development environments and programming techniques for sensor networks, including an overview of frequently used sensor network simulators.

Part One

Introduction

1

Motivation for a Network of Wireless Sensor Nodes

Sensors link the physical with the digital world by capturing and revealing real-world phenomena and converting these into a form that can be processed, stored, and acted upon. Integrated into numerous devices, machines, and environments, sensors provide a tremendous societal benefit. They can help to avoid catastrophic infrastructure failures, conserve precious natural resources, increase productivity, enhance security, and enable new applications such as context-aware systems and smart home technologies. The phenomenal advances in technologies such as very large scale integration (VLSI), microelectromechanical systems (MEMS), and wireless communications further contribute to the widespread use of distributed sensor systems. For example, the impressive developments in semiconductor technologies continue to produce microprocessors with increasing processing capacities, while at the same time shrinking in size. The miniaturization of computing and sensing technologies enables the development of tiny, low-power, and inexpensive sensors, actuators, and controllers. Further, embedded computing systems (i.e., systems that typically interact closely with the physical world and are designed to perform only a limited number of dedicated functions) continue to find application in an increasing number of areas. While defense and aerospace systems still dominate the market, there is an increasing focus on systems to monitor and protect civil infrastructure (such as bridges and tunnels), the national power grid, and pipeline infrastructure. Networks of hundreds of sensor nodes are already being used to monitor large geographic areas for modeling and forecasting environmental pollution and flooding, collecting structural health information on bridges using vibration sensors, and controlling usage of water, fertilizers, and pesticides to improve crop health and quantity.

This book provides a thorough introduction to the fundamental aspects of *wireless sensor networks* (WSNs), covering both theoretical concepts and practical aspects of network technologies and protocols, operating systems, middleware, sensor programming, and security. The book is targeted at researchers, students, and practitioners alike, with the goal of helping them to gain an understanding of the challenges and promises of this exciting field. It has been written primarily as a textbook for graduate or advanced undergraduate courses in wireless sensor networks. Each chapter ends with a number of exercises and questions that will allow students to practice the described concepts and techniques. As the field of wireless sensor networks is based on numerous other domains, it is recommended that

Fundamentals of Wireless Sensor Networks: Theory and Practice Waltenegus Dargie and Christian Poellabauer

students have taken courses such as networking and operating systems (or comparable courses) before they take a course on sensor networks. Also, some topics covered in this book (e.g., security) assume previous knowledge in other areas or require that an instructor provides an introduction into the basics of these areas before teaching these topics.

1.1 Definitions and Background

1.1.1 Sensing and Sensors

Sensing is a technique used to gather information about a physical object or process, including the occurrence of events (i.e., changes in state such as a drop in temperature or pressure). An object performing such a sensing task is called a *sensor*. For example, the human body is equipped with sensors that are able to capture optical information from the environment (eyes), acoustic information such as sounds (ears), and smells (nose). These are examples of *remote sensors*, that is, they do not need to touch the monitored object to gather information. From a technical perspective, a sensor is a device that translates parameters or events in the physical world into signals that can be measured and analyzed. Another commonly used term is *transducer*, which is often used to describe a device that converts energy from one form into another. A sensor, then, is a type of transducer that converts energy in the physical world into electrical energy that can be passed to a computing system or controller. An example of the steps performed in a sensing (or *data acquisition*) task is shown in Figure 1.1. Phenomena in the physical world (often referred to as *process*, *system*, or *plant*) are observed by a sensor device. The resulting electrical signals are often not ready for immediate processing, therefore they pass through a *signal conditioning* stage. Here, a variety of operations can be applied to the sensor signal to prepare it for further use. For example, signals often require amplification (or attenuation) to change the signal magnitude to better match the range of the following analog-to-digital conversion. Further, signal conditioning often applies *filters* to the signal to remove unwanted noise within certain frequency ranges (e.g., highpass filters can be used to remove 50 or 60 Hz noise picked up by surrounding power lines). After conditioning, the analog signal is transformed into a digital signal using an *analog-to-digital converter* (ADC). The signal is now available in a digital form and ready for further processing, storing, or visualization.

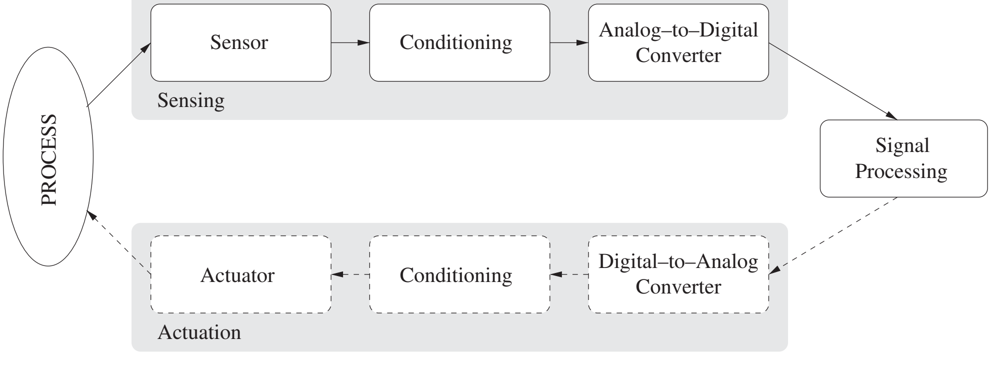

Figure 1.1 Data acquisition and actuation.

Many wireless sensor networks also include *actuators* which allow them to directly control the physical world. For example, an actuator can be a valve controlling the flow of hot water, a motor that opens or closes a door or window, or a pump that controls the amount of fuel injected into an engine. Such a *wireless sensor and actuator network* (WSAN) takes commands from the processing device (controller) and transforms these commands into input signals for the actuator, which then interacts with a physical process, thereby forming a closed control loop (also shown in Figure 1.1).

1.1.1.1 Sensor Classifications

Which sensors should be chosen for an application depends on the physical property to be monitored, for example, such properties include temperature, pressure, light, or humidity. Table 1.1 summarizes some common physical properties, including examples of sensing technologies that are used to capture them. Besides physical properties, the classification of sensors can be based on a variety of other methods, for example, whether they require an external power supply. If the sensors require external power, they are referred to as *active* sensors. That is, they must emit some kind of energy (e.g., microwaves, light, sound) to trigger a response or to detect a change in the energy of the transmitted signal. On the other hand, *passive* sensors detect energy in the environment and derive their power from this energy input – for example, passive infrared (PIR) sensors measure infrared light radiating from objects in the proximity.

The classification of sensors can also be based on the methods they apply and the electrical phenomena they utilize to convert physical properties into electrical signals. *Resistive* sensors rely on changes to a conductor's electrical resistivity, ρ, based on physical properties such as temperature. The resistance, R, of a conductor can be determined as:

$$R = \frac{l \times \rho}{A} \tag{1.1}$$

where l is the length of the conductor and A is the area of the cross-section. For example, the well-known Wheatstone bridge (Figure 1.2) is a simple circuit that can be used to convert a physical property into an observable electric effect. In this bridge, R_1, R_2, and R_3 are

Table 1.1 Classification and examples of sensors

Type	Examples
Temperature	Thermistors, thermocouples
Pressure	Pressure gauges, barometers, ionization gauges
Optical	Photodiodes, phototransistors, infrared sensors, CCD sensors
Acoustic	Piezoelectric resonators, microphones
Mechanical	Strain gauges, tactile sensors, capacitive diaphragms, piezoresistive cells
Motion, vibration	Accelerometers, gyroscopes, photo sensors
Flow	Anemometers, mass air flow sensors
Position	GPS, ultrasound-based sensors, infrared-based sensors, inclinometers
Electromagnetic	Hall-effect sensors, magnetometers
Chemical	pH sensors, electrochemical sensors, infrared gas sensors
Humidity	Capacitive and resistive sensors, hygrometers, MEMS-based humidity sensors
Radiation	Ionization detectors, Geiger–Mueller counters

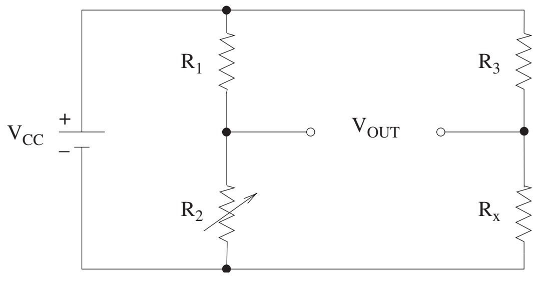

Figure 1.2 Wheatstone bridge circuit.

resistors of known resistance (where the resistance of R_2 is adjustable) and R_x is a resistor of unknown value. If the ratio R_2/R_1 is identical to the ratio R_x/R_3, the measured voltage V_{OUT} will be zero. However, if the resistance of R_x changes (e.g., due to changes in temperature), there will be an imbalance, which will be reflected by a change in voltage V_{OUT}. In general, the relationship between the measured voltage V_{OUT}, the resistors, and the supply voltage (V_{CC}) can be expressed as:

$$V_{\mathrm{OUT}} = V_{\mathrm{CC}} \times \left(\frac{R_x}{R_3 + R_x} - \frac{R_2}{R_1 + R_2} \right) \tag{1.2}$$

A similar principle can be applied to *capacitive* sensors, which can be used to measure motion, proximity, acceleration, pressure, electric fields, chemical compositions, and liquid depth. For example, in the parallel plate model, that is, a capacitor consisting of two parallel conductive plates separated by a dielectric with a certain permittivity ε, the capacitance is determined as:

$$C = \frac{\varepsilon \times A}{d} \tag{1.3}$$

where A is the plate area and d is the distance between the two plates. Similar to the resistive model, changes in any of these parameters will change the capacitance. For example, if pressure is applied to one of the two plates, the separation d can be reduced, thereby increasing the capacitance. Similarly, a change in the permittivity of the dielectric can be caused by an increase in temperature or humidity, thereby resulting in a change in capacitance.

Inductive sensors are based on the electrical principle of inductance, that is, where an electromagnetic force is induced by a fluctuating current. Inductance is determined by the dimensions of the sensor (cross-sectional area, length of coil), the number of turns of the coil, and the permeability of the core. Changes in any of these parameters (e.g., caused by movements of the core within the coil) change the inductance. Inductive sensors are often used to measure proximity, position, force, pressure, temperature, and acceleration.

Finally, *piezoelectric* sensors use the piezoelectric effect of some materials (e.g., crystals and certain ceramics) to measure pressure, force, strain, and acceleration. When a pressure is applied to such a material, it causes a mechanical deformation and a displacement of charges, proportional to the amount of pressure. The main advantage of piezoelectric devices over other approaches is that the piezoelectric effect is not sensitive to electromagnetic fields or radiation.

1.1.2 Wireless Sensor Networks

While many sensors connect to controllers and processing stations directly (e.g., using local area networks), an increasing number of sensors communicate the collected data wirelessly to a centralized processing station. This is important since many network applications require hundreds or thousands of sensor nodes, often deployed in remote and inaccessible areas. Therefore, a *wireless* sensor has not only a sensing component, but also on-board processing, communication, and storage capabilities. With these enhancements, a sensor node is often not only responsible for data collection, but also for in-network analysis, correlation, and fusion of its own sensor data and data from other sensor nodes. When many sensors cooperatively monitor large physical environments, they form a *wireless sensor network* (WSN). Sensor nodes communicate not only with each other but also with a *base station* (BS) using their wireless radios, allowing them to disseminate their sensor data to remote processing, visualization, analysis, and storage systems. For example, Figure 1.3 shows two *sensor fields* monitoring two different geographic regions and connecting to the Internet using their base stations.

The capabilities of sensor nodes in a WSN can vary widely, that is, simple sensor nodes may monitor a single physical phenomenon, while more complex devices may combine many different sensing techniques (e.g., acoustic, optical, magnetic). They can also differ in their communication capabilities, for example, using ultrasound, infrared, or radio frequency technologies with varying data rates and latencies. While simple sensors may only collect and communicate information about the observed environment, more powerful devices (i.e., devices with large processing, energy, and storage capacities) may also perform extensive processing and aggregation functions. Such devices often assume additional responsibilities in a WSN, for example, they may form communication backbones that can be used by other resource-constrained sensor devices to reach the

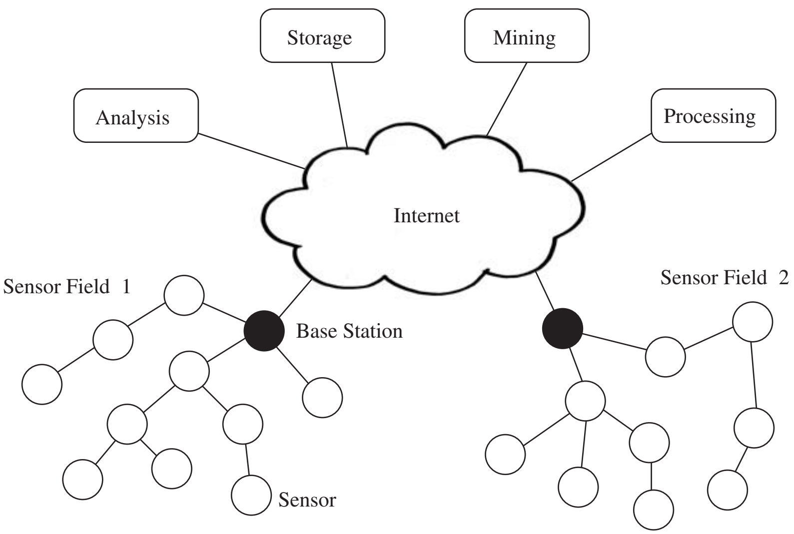

Figure 1.3 Wireless sensor networks.

base station. Finally, some devices may have access to additional supporting technologies, for example, Global Positioning System (GPS) receivers, allowing them to accurately determine their position. However, such systems often consume too much energy to be feasible for low-cost and low-power sensor nodes.

1.1.2.1 History of Wireless Sensor Networks

As with many other technologies, the military has been a driving force behind the development of wireless sensor networks. For example, in 1978, the Defense Advanced Research Projects Agency (DARPA) organized the Distributed Sensor Nets Workshop (DAR 1978), focusing on sensor network research challenges such as networking technologies, signal processing techniques, and distributed algorithms. DARPA also operated the Distributed Sensor Networks (DSN) program in the early 1980s, which was then followed by the Sensor Information Technology (SensIT) program.

In collaboration with the Rockwell Science Center, the University of California at Los Angeles proposed the concept of Wireless Integrated Network Sensors or WINS (Pottie 2001). One outcome of the WINS project was the Low Power Wireless Integrated Microsensor (LWIM), produced in 1996 (Bult *et al.* 1996). This smart sensing system was based on a CMOS chip, integrating multiple sensors, interface circuits, digital signal processing circuits, wireless radio, and microcontroller onto a single chip. The Smart Dust project (Kahn *et al.* 1999) at the University of California at Berkeley focused on the design of extremely small sensor nodes called *motes*. The goal of this project was to demonstrate that a complete sensor system can be integrated into tiny devices, possibly the size of a grain of sand or even a dust particle. The PicoRadio project (Rabaey *et al.* 2000) by the Berkeley Wireless Research Center (BWRC) focuses on the development of low-power sensor devices, whose power consumption is so small that they can power themselves from energy sources of the operating environment, such as solar or vibrational energy. The MIT μAMPS (micro-Adaptive Multidomain Power-aware Sensors) project also focuses on low-power hardware and software components for sensor nodes, including the use of microcontrollers capable of dynamic voltage scaling and techniques to restructure data processing algorithms to reduce power requirements at the software level (Calhoun *et al.* 2005).

While these previous efforts are mostly driven by academic institutions, over the last decade a number of commercial efforts have also appeared (many based on some of the academic efforts described above), including companies such as Crossbow (www.xbow.com), Sensoria (www.sensoria.com), Worldsens (http://worldsens.citi.insa-lyon.fr), Dust Networks (http://www.dustnetworks.com), and Ember Corporation (http://www.ember.com). These companies provide the opportunity to purchase sensor devices ready for deployment in a variety of application scenarios along with various management tools for programming, maintenance, and sensor data visualization.

1.1.2.2 Communication in a WSN

The well-known IEEE 802.11 family of standards was introduced in 1997 and is the most common wireless networking technology for mobile systems. It uses different frequency bands, for example, the 2.4-GHz band is used by IEEE 802.11b and IEEE 802.11g, while the IEEE 802.11a protocol uses the 5-GHz frequency band. IEEE 802.11 was frequently used in early wireless sensor networks and can still be found in current networks when bandwidth

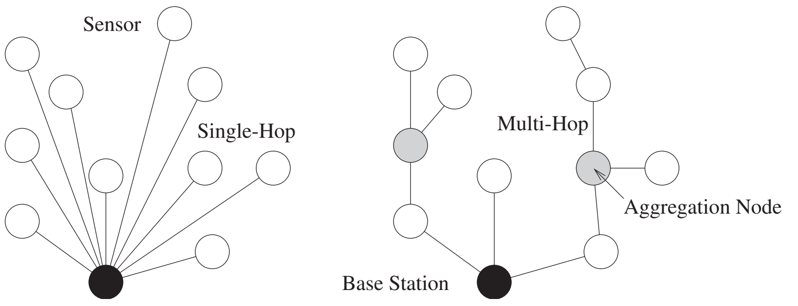

Figure 1.4 Single-hop versus multi-hop communication in sensor networks.

demands are high (e.g., for multimedia sensors). However, the high-energy overheads of IEEE 802.11-based networks makes this standard unsuitable for low-power sensor networks. Typical data rate requirements in sensor networks are comparable to the bandwidths provided by dial-up modems, therefore the data rates provided by IEEE 802.11 are typically much higher than needed. This has led to the development of a variety of protocols that better satisfy the networks' need for low power consumption and low data rates. For example, the IEEE 802.15.4 protocol (Gutierrez *et al.* 2001) has been designed specifically for short-range communications in low-power sensor networks and is supported by most academic and commercial sensor nodes.

When the transmission ranges of the radios of all sensor nodes are large enough and the sensors can transmit their data directly to the base station, they can form a star topology as shown on the left in Figure 1.4. In this topology, each sensor node communicates directly with the base station using a single hop. However, sensor networks often cover large geographic areas and radio transmission power should be kept at a minimum in order to conserve energy; consequently, *multi-hop communication* is the more common case for sensor networks (shown on the right in Figure 1.4). In this *mesh topology*, sensor nodes must not only capture and disseminate their own data, but also serve as *relays* for other sensor nodes, that is, they must collaborate to propagate sensor data towards the base station. This *routing* problem, that is, the task of finding a multi-hop path from a sensor node to the base station, is one of the most important challenges and has received immense attention from the research community. When a node serves as a relay for multiple routes, it often has the opportunity to analyze and pre-process sensor data in the network, which can lead to the elimination of redundant information or aggregation of data that may be smaller than the original data.

1.2 Challenges and Constraints

While sensor networks share many similarities with other distributed systems, they are subject to a variety of unique challenges and constraints. These constraints impact the design of a WSN, leading to protocols and algorithms that differ from their counterparts in other distributed systems. This section describes the most important design constraints of a WSN.

1.2.1 Energy

The constraint most often associated with sensor network design is that sensor nodes operate with limited energy budgets. Typically, they are powered through batteries, which must be either replaced or recharged (e.g., using solar power) when depleted. For some nodes, neither option is appropriate, that is, they will simply be discarded once their energy source is depleted. Whether the battery can be recharged or not significantly affects the strategy applied to energy consumption. For nonrechargeable batteries, a sensor node should be able to operate until either its *mission time* has passed or the battery can be replaced. The length of the mission time depends on the type of application, for example, scientists monitoring glacial movements may need sensors that can operate for several years while a sensor in a battlefield scenario may only be needed for a few hours or days.

As a consequence, the first and often most important design challenge for a WSN is energy efficiency. This requirement permeates every aspect of sensor node and network design. For example, the choices made at the physical layer of a sensor node affect the energy consumption of the entire device and the design of higher-level protocols (Shih *et al.* 2001). The energy consumption of CMOS-based processors is primarily due to switching energy and leakage energy (Sinha and Chandrakasan 2000):

$$E_{\mathrm{CPU}} = E_{\mathrm{switch}} + E_{\mathrm{leakage}} = C_{\mathrm{total}} V_{\mathrm{dd}}^2 + V_{\mathrm{dd}} I_{\mathrm{leak}} \Delta t \tag{1.4}$$

where C_{total} is the total capacitance switched by the computation, V_{dd} is the supply voltage, I_{leak} is the leakage current, and Δt is the duration of the computation. While the switching energy still dominates the energy consumption of processors, it is expected that in future processor designs, the leakage energy will be responsible for more than half the energy consumption (De and Borkar 1999). Some techniques to control leakage energy include progressive shutdown of idle components and software-based techniques such as Dynamic Voltage Scaling (DVS).

The medium access control (MAC) layer is responsible for providing sensor nodes with access to the wireless channel. Some MAC strategies for communication networks are *contention-based*, that is, nodes may attempt to access the medium at any time, potentially leading to collisions among multiple nodes, which must be addressed by the MAC layer to ensure that transmissions will eventually succeed. Downsides of these approaches include the energy overheads and delays incurred by the collisions and recovery mechanisms and that sensor nodes may have to listen to the medium at all times to ensure that no transmissions will be missed. Therefore, some MAC protocols for sensor networks are *contention-free*, that is, access to the medium is strictly regulated, eliminating collisions and allowing sensor nodes to shut down their radios when no communications are expected. The network layer is responsible for finding routes from a sensor node to the base station and route characteristics such as length (e.g., in terms of number of hops), required transmission power, and available energy on relay nodes determine the energy overheads of multi-hop communication.

Besides network protocols, the goal of energy efficiency impacts the design of the operating system (e.g., small memory footprint, efficient switching between tasks), middleware, security mechanisms, and even the applications themselves. For example, *in-network processing* is frequently used to eliminate redundant sensor data or to aggregate multiple sensor readings. This leads to a tradeoff between computation (processing the sensor data) and communication (transmitting the original versus the processed data), which can often be exploited to obtain energy savings (Pottie and Kaiser 2000; Sohrabi *et al.* 2000).