

# Chapter 1

## Introduction

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*"My original goal was to bring readers to the frontiers of knowledge in every subject that was treated. But it is extremely difficult to keep up with a field that is economically profitable, and the rapid rise of computer science has made such a dream impossible. The subject has become a vast tapestry with tens of thousands of subtle results contributed by tens of thousands of talented people all over the world. Therefore my new goal has been to concentrate on "classic" techniques that are likely to remain important for many more decades and to describe them as well as I can."*

Donald E. Knuth  
*The Art of Computer Programming:  
Fundamental Algorithms (1997)*

## 1 The Art of Wireless Sensor Networks

Nowadays, the design and development of wireless sensor networks for various real-world applications, such as environmental monitoring, health monitoring, industrial process automation, battlefields surveillance, and seism monitoring, has become possible owing to the rapid advances in both of wireless communications and sensor technology. This type of network is cost-effective and appealing to a wide range of mission-critical situations. These two reasons helped them gain significant popularity compared to other types of networks. A wireless sensor network is a collection of low-powered, physically tiny devices, called *sensor nodes*, which are

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capable of sensing the physical environment, collecting and processing sensed data, and communicating with each other in order to accomplish certain common tasks. Furthermore, wireless sensor networks possess a central gathering point, called the *sink* (or *base station*), where all the collected data can be stored. The major challenge in the design and development of wireless sensor networks is mainly due to the severe constraints that are imposed on the sensing, storage, processing, and communication features of the sensor nodes. More precisely, the sensor nodes suffer from severely constrained power supplies, which shorten their lifetime and make them unreliable. It is worth noting that the sensor nodes may become faulty due to improper hardware functioning and/or low battery power (or energy). The latter is very crucial to be considered in the design and implementation of this type of network for their correct operation and longevity.

Since their inception in the late 1990s, wireless sensor networks have witnessed significant growth and tremendous development in both academia and industry. A large number of researchers, including computer scientists and engineers, have been interested in solving challenging problems that span all the layers of the protocol stack of sensor networking systems. Several venues, such as journals, conferences, and workshops, have been launched to cover innovative research and practice in this promising and rapidly advancing field. Because of these trends, I thought it would be beneficial to provide our sensor networks community with a comprehensive reference on as much of the findings as possible on a variety of topics in wireless sensor networks. As this area of research is in continuous progress, it does not seem to be a reasonable solution to keep delaying the publication of such reference any more.

This book series, titled “*The Art of Wireless Sensor Networks*,” has two volumes that have been designed in a way to address challenging problems in traditional as well as new emerging areas of research in sensor networking. Moreover, all the book chapters in both volumes have been written as surveys of the state-of-the-art and state-of-the-practice of their corresponding topics. Our main goal is to help the readers understand the basic concepts of wireless sensor networks, and also be aware and knowledgeable of most of the underlying research topics although some of them are still in their infancy and not much work has been done to solve those new research problems. These two volumes are titled:

- *The Art of Wireless Sensor Networks: Fundamentals*
- *The Art of Wireless Sensor Networks: Advanced Topics and Applications*

This book relates to the first volume and focuses on the fundamentals concepts in the design, analysis, and implementation of wireless sensor networks. It covers the various layers of the lifecycle of this type of networks from the physical layer up to the application layer. Based on my fruitful discussion with all the contributing authors whom I invited, and, particularly, Drs. Wendi Heinzelman, Kay Römer, and Mohamed Younis, our rationale is that the first volume covers contemporary design issues, tools, and protocols for radio-based two-dimensional terrestrial sensor networks. Following Donald E. Knuth’s above-quoted elegant strategy to focus on stable yet important “classic” techniques (*The Art of Computer*

*Programming: Fundamental Algorithms*, 1997), all the book chapters in this volume include up-to-date research work spanning various classic facets of the physical properties and functional behavior of wireless sensor networks, including physical layer, medium access control, data routing, topology management, mobility management, localization, task management, data management, data gathering, security, middleware, sensor technology, standards, and operating systems. This book will be an excellent source of information for both senior undergraduate and graduate students majoring in computer science, computer engineering, electrical engineering, or any related discipline. In addition, computer scientists, researchers, and practitioners in both academia and industry will find this book useful and interesting.

I would like to mention that I borrowed the title of this two-volume book series, “*The Art of Wireless Sensor Networks*,” from Dr. Donald E. Knuth, computer scientist and Professor Emeritus at Stanford University, who is the author of the seminal multi-volume set of books, titled “*The Art of Computer Programming*.” In fact, most of the problems being addressed in the area of wireless sensor networks are challenging and mathematical in nature. And, solving those problems requires an ‘art’ to find elegant yet efficient solutions in terms of time, space, and, especially, energy, which is a crucial resource in the design and implementation of algorithms and protocols for wireless sensor networking systems. I hope the readers will see the ‘art’ in this book and enjoy reading it as much as I enjoyed editing it.

## 2 Book Organization

This book has ten parts, each of which includes 2–3 chapters. Next, we briefly summarize the purpose of each part with a short description of its chapters.

In Part 1, titled “*Introduction and Applications*,” Chap. 2 provides an overview of the most relevant applications of wireless sensor network, which have been deployed during the last one and a half decades. Furthermore, it gives a novel taxonomy of those applications with a goal to identify relevant programming constructs and run-time services. Chapter 3 investigates the problem of unattended deployment in a harsh environment and presents a discussion on the pros and cons of a specific wireless sensor network design.

In Part 2, titled “*Wireless Communications and Medium Access Control*,” Chap. 4 investigates physical layer communications of wireless sensor networks. First, it presents an optimal power allocation scheme using the water-filling algorithm with Karush-Kuhn-Tucker conditions. Then, it describes two sensor selection schemes to enhance the parameter estimation in energy-constrained wireless sensor networks. Chapter 5 reviews various network coding techniques along with their assumptions and applications. It considers both general wireless networks and wireless sensor networks. Chapter 6 discusses several sensor sleeping techniques, which apply to either different layers of the protocol stack or multiple layers simultaneously. Also, it describes potential applications in each sleeping technique.

In Part 3, titled “*Routing*,” Chap. 7 presents a classification of energy-aware routing algorithms and shows various issues with respect to data-aggregation, routing overhead, the energy hole phenomenon, and collisions/interferences. Chapter 8 discusses several utility-based routing protocols for wireless sensor networks and classifies them based on their utility properties, such as delay, cost, and packet delivery ratio. Moreover, it discusses the composition-based utility for wireless networks and its extensions in low duty-cycle wireless sensor networks.

In Part 4, titled “*Topology and Mobility Management*,” Chap. 9 describes existing network topology management techniques for node failure tolerance. Also, it provides an analysis of the impact of node failure on network connectivity in wireless sensor networks, and proposes a classification of existing recovery schemes. Chapter 10 focuses on the problem of mobility in wireless sensor networks and its implications on sensing coverage, communication connectivity, and energy consumption. Precisely, it deals with target tracking in mobile wireless sensor networks using the Bayesian estimation theory. Also, it presents a purposeful and distributed mobility management scheme as a potential probabilistic solution to the problem of mobility management.

In Part 5, titled “*Localization and Task Management*,” Chap. 11 surveys a variety of range-free localization techniques in wireless sensor networks, and provides a qualitative comparison of them. Also, it discusses current research directions in range-free localization. Chapter 12 considers two energy-aware task management protocols, which assign sensors to tasks based on their remaining energy while achieving balanced load among all the sensors. Also, it gives a comparison of these two protocols with an optimal task assignment protocol as well as energy-oblivious protocols with respect to the network lifetime.

In Part 6, titled “*Data Management*,” Chap. 13 introduces a data management perspective on large-scale sensor environments applications whose goal is to meet non-functional requirements, such as timeliness, re-liability and accuracy, as well as functional needs of data collection. Chapter 14 presents geometric ideas to organize sensor data based on location information. It considers distributed methods for managing queries regarding isolated events, mobile objects, and general signal fields.

In Part 7, titled “*Data Gathering*,” Chap. 15 considers two case studies of wireless sensor network monitoring systems, namely Life Under Your Feet and RACNet, in order to show the different components that constitute data collection networks. While the first system focuses on extreme duty-cycling and low data rate communications, the second one emphasizes high throughput and efficient channel utilization. Chapter 16 reviews existing techniques for data aggregation and presents their classification. In addition, it discusses a variety of tree-based and cell-based data collection algorithms. Also, it shows the dependency between those data aggregation and data collection techniques and potential applications.

In Part 8, titled “*Security*,” Chap. 17 presents challenges for ensuring security in wireless sensor networks. It describes existing solutions, such as cryptography schemes, key management schemes, as well as some mechanisms for attack detection and prevention mechanisms. Also, it considers the problem of security in routing, localization, and data aggregation. Chapter 18 presents the technologies that are used

for the protection of system privacy, data privacy and context privacy in wireless sensor networks, along with the threats in each of these three kinds of privacy. Moreover, it compares existing privacy-preserving techniques and discusses the strengths and weaknesses of each one of them.

In Part 9, titled “*Middleware*,” Chap. 19 provides an overview of existing design approaches for middleware in wireless sensor networks. Also, it describes the most common middleware services and programming abstractions. Chapter 20 presents an approach to develop systems for wireless sensor networks, called Service Oriented Middleware, where the network is logically viewed as a service provider for consumer applications. This type of system provides abstractions of the network through a set of generic and/or application-specific services, such as data aggregation, adaptation, security, self-organization, resource management.

In Part 10, titled “*Sensor Technology, Standards, and Operating Systems*,” Chap. 21 presents existing operating systems in wireless sensor networks and discusses their strengths and weaknesses. Chapter 22 describes various network simulators, such as NS-2, OMNET++, J-Sim, OPNET and TOSSIM, and network programming languages, such as NesC and Mate. Chapter 23 gives a review of wireless sensor network technologies, such as Zig-Bee, WirelessHART, 6LoWPAN, and ISA.100.11a, along with their network structure, protocol layers, and application areas.

### 3 Acknowledgments

This book of this complete two-volume series, titled “*The Art of Wireless Sensor Networks*,” is a tribute to the fine work of the foremost leading authorities and scholars in their fields of research in the area of sensor networking. Frankly, it is not fair that I am the only one whose name appears on the book cover. And, it is a great pleasure and an honor for me to cordially recognize all of those who contributed a lot to this book and generously supported me throughout this project in order to make this two-volume series a reality. Without them, it would not be possible at all to finish this book and make it available to all the researchers and practitioners, who are interested in the fundamentals of wireless sensor networks.

First and foremost, I am sincerely and permanently grateful to Allah—the Most Gracious, the Most Merciful—for everything He has been providing me with. Particularly, I would very much love to thank Him for giving me the golden opportunity to work with such group of outstanding scientists and researchers to put together this book, and for helping me publish it within two years. I am very pleased to dedicate this modest book to Him and very much hope that He would kindly accept it and put His Blessing in it. His Saying “**And of knowledge, you (mankind) have been given only a little**” has an endless, pleasant echo in my heart and always reminds me that our knowledge is much less than a drop in the ocean.

It is worth mentioning that all the contributing authors were invited to contribute to this book, and that no Call for Book Chapters had ever been sent through any mailing list. All of those authors whom I invited were chosen very selectively to cover most of

the fundamental topics in wireless sensor networks. They have been contributing to the growth and development of the field of wireless sensor networks. This book would never have been written without their great contributions, support, and cooperation. Therefore, my cordial recognition is due to my colleagues—the ones whom I invited to contribute with their book chapters to this book—whose names are listed in the alphabetical order: Drs. Nirwan Ansari, Qing Cao, Krishnendu Chakrabarty, Xiuzhen Cheng, Flavia Delicato, Zygmunt Haas, Tian He, Wendi Heinzelman, Qilian Liang, Mingyan Liu, Sharad Mehrotra, Stephan Olariu, Christian Poellabauer, Kay Römer, Rik Sarkar, Andreas Terzis, Nalini Venkatasubramanian, Jie Wu, and Mohamed Younis. I am really honored to have worked with such an amazing crew of scientists. I learned a lot from them throughout this project, and it was an incredible experience for me in finishing this book.

Every book chapter has undergone two rounds of reviews. Moreover, in each round, every book chapter received 3–5 reviews by experts in the scope of the chapter. Our ultimate goal is to provide the readers with a high-quality reference on the fundamentals of wireless sensor networks. Precisely, all book chapters were carefully reviewed in both rounds by all the contributing authors. I would like to express my sincere gratitude to all the contributing authors for their constructive feedback to improve the organization and content of all book chapters. My special thanks go to Dr. Stephan Olariu for his generous offer to review all book chapters of both books of this two-volume series. Also, my original plan was to publish only one book, titled “*The Art of Wireless Sensor Networks*.” But, I ended up with 40 book chapters. Therefore, I suggested to all the above-mentioned invited authors to split the book (i.e., 40 book chapters) into two volumes along with their book chapters and titles. Here, again, my special thanks go to all the invited authors for their very helpful feedback with regard to the content of each volume. Moreover, I am very grateful to Dr. Wendi Heinzelman, Professor of Electrical and Computer Engineering, and Dean of Graduate Studies for Arts, Sciences and Engineering at the University of Rochester, for her great foreword.

I started this project on Sunday, August 28, 2011 at 06:56 AM when I contacted the Publishing Editor, Dr. Thomas Ditzinger, who approved my proposal for an edited book. All book chapters for both volumes were uploaded on the website of Springer and made accessible to the Editorial Assistant, Mr. Holger Schaepe, on March 11, 2013. Hence, this project lasted over 18 months. During all this period of time, I exchanged 4, 840 emails with all contributing authors with regard to their book chapters. I would like to thank all the contributing authors for their invaluable time, flexibility, and wonderful patience in responding to all of my emails in a timely manner. Please forgive me for your time, and I hope that the readers will appreciate all of your great efforts and love all the materials in this book. We all have devoted a considerable time to finish this book and hope it will be paid off in the future.

I would like to acknowledge my family members who have provided me with excellent source of support and constant encouragement over the course of this project. In particular, I am most grateful to my best friend and beloved wife, Fadhila, for her genuine friendship and good sense of humor, and for being extremely supportive and unboundedly patient while I was working on this book. My special

thanks and deep appreciation go to her for putting the *Art* into this book. In addition, I would like to express my hearty gratitude to my lovely and beautiful children, Leena, Muath, Mohamed-Eyed, Lama, and Maitham, for their endless support and encouragement. They have been one of my greatest joys, very patient, and understanding. I hope they will forgive me for spending several hours away from them while I was setting in front of my PC in my office or my laptop at home busy with this book. Several times, they all told me: “Daddy, your books and emails are always dragging you away from us!” My lovely wife and children have been a wonderful inspiration to me, and very patient throughout the life of this project. Without their warm love and care, this project would never even have been started. Also, I owe a lot to both of my first teachers, my mother, Mbarka, and my father, Mokhtar, for their sincere prayers, love, support, and encouragement, and for always teaching me and reminding me of the value of knowledge and the importance of family. Furthermore, I would like to thank my mother-in-law, Hania, and my father-in-law, Hedi, for their thoughtful prayers, concern, and valuable support. Besides, I would like to thank my sisters, sisters-in-law, brother, and brothers-in-law for their support and thoughts.

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