

# Chapter 1

## Introduction

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*“I have tried to write this set of books in such a way that it will fill several needs. In the first place, these books are reference works that summarize the knowledge that has been acquired in several important fields. In the second place, they can be used as textbooks for self-study or for college courses in the computer and information sciences”*

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 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

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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 second volume and focuses on the advanced topics and applications of wireless sensor networks. Based on my fruitful discussion with the contributing authors whom I invited, and, particularly, Drs. Wendi Heinzelman, Kay Römer, and Mohamed Younis, our rationale is that the second volume has all application-specific and non-conventional sensor networks, emerging techniques, and advanced topics that are not as matured as what is covered in the first volume. Thus, the second volume deals with three-dimensional, underground, underwater, body-mounted, and societal networks. Following Donald E. Knuth’s above-quoted elegant strategy to focus on several important fields (*The Art of Computer Programming: Fundamental Algorithms*, 1997), all the book chapters in this volume include up-to-date research work spanning various topics, such as stochastic modeling, barrier and spatiotemporal coverage, tracking, estimation, counting, coverage and localization in three-dimensional sensor networks, topology control and routing in three-dimensional sensor networks, underground and underwater sensor networks, multimedia and body sensor networks, and social sensing. Most of these major topics

can be covered in an advanced course on wireless sensor networks. This book will be an excellent source of information for graduate students majoring in computer science, computer engineering, electrical engineering, or any related discipline. Furthermore, 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 eight 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 Stochastic Modeling*,” Chap. 2 provides a comprehensive cross-layer probabilistic analysis framework in order to investigate the probabilistic evaluation of quality of service performance provided by wireless sensor networks. The latter is evaluated in two levels, namely node level and network level.

In Part 2, titled “*Barrier and Spatiotemporal Coverage*,” Chap. 3 presents a comprehensive survey on barrier coverage of wireless sensor networks. It focuses on the critical conditions and construction of barrier coverage in 2-dimensional wireless sensor networks, barrier coverage under a line-based sensor deployment scheme, as well as the effect of sensor mobility on barrier coverage, and barrier coverage in three-dimensional underwater sensor networks. Chapter 4 explores the fundamental limits of spatiotemporal coverage based on stochastic data fusion models in order to capture the stochastic nature of sensing. It derives the scaling laws between spatiotemporal coverage, network density, and signal-to-noise ratio. Also, it shows that data fusion can significantly improve spatiotemporal coverage by exploiting the collaboration among sensors when several physical properties of the target signal are known.

In Part 3, titled “*Tracking, Estimation, and Counting*,” Chap. 5 describes various methods using sophisticated computations in pursuit of high localization accuracy with low hardware investment and moderate set-up cost. Also, it shows a profile-based approach to infer the positions of mobile wireless devices in complex indoor environments, a two-tier statistical positioning scheme that helps improve efficiency by adding movement detection, and joint cluster-head placement optimization for

localization and movement detection. Chapter 6 discusses methods and protocols for controlling the behavior of nodes in order to allow maximal use of the shared medium for real-time estimation. It shows how transmission control protocols can be applied in a wireless network of mobile sensors to achieve high accuracy given the limitations of the medium. Chapter 7 reviews four existing classes of counting methods, namely binary counting, numeric counting, energy counting, and compressive counting. It describes methods for each class and discusses their advantages and disadvantages. Moreover, it compares those methods to illustrate the impact of different sensor network settings on the target counting accuracy.

In Part 4, titled “*Coverage and Localization in Three-Dimensional Wireless Sensor Networks*,” Chap. 8 surveys existing methods on coverage and connectivity in three-dimensional wireless sensor networks. It provides a study of different placement strategies, fundamental characteristics, modeling schemes, analytical methods, and limiting factors, as well as the practical constraints imposed on coverage and connectivity in three-dimensional wireless sensor networks. Chapter 9 focuses on localization in three-dimensional wireless sensor networks. It describes generic, airborne, terrestrial, and submerged localization schemes along with their strengths and weaknesses.

In Part 5, titled “*Topology Control and Routing in Three-Dimensional Wireless Sensor Networks*,” Chap. 10 presents most recent work on three-dimensional topology control. Chapter 11 reviews several classes of routing techniques in three-dimensional wireless sensor networks.

In Part 6, titled “*Underground and Underwater Sensor Networks*,” Chap. 12 discusses the challenges facing the design of underground sensor networks, the perceived limitations, and recent technological advances in this field. It shows that the design of underground sensor networks must be tailored to the application. As an illustrative example, a proposed study concludes that the design of an underground sensor network for detecting oil pipeline leakage is totally different from that of an underground sensor network for agricultural draught or landslide monitoring. Chapter 13 presents a solution to optimize communications in autonomous underwater vehicles by delaying packet transmissions while waiting for a favorable network topology.

In Part 7, titled “*Multimedia and Body Sensor Networks*,” Chap. 14 examines the challenges in the implementation of wireless multimedia sensor network, and how to develop one with the same performance as a traditional scalar wireless sensor network. Also, it shows how to exploit compressed sensing to reduce the energy consumption due to encoding and transmitting high quality video in a severely resource constrained environment. Chapter 15 considers one application of body sensor networks, which involves processing of wearable accelerometer data for recognizing ambulatory or simple activities and activity gestures. Also, it discusses various aspects that are associated with a real-time activity recognition system.

In Part 8, titled “*Social Sensing*,” Chap. 16 describes new research challenges that need to be addressed in social sensing frameworks, which should allow massive information dissemination. Chapter 17 reviews existing work on behavior-aware routing. Also, it presents a framework showing all the steps involved in the design

of social behavior-aware routing. Chapter 18 gives an overview of cultural applications of wireless sensing systems from four perspectives, namely the Internet of things, smart grid, participatory sensing, and event-based point of view. Moreover, it discusses the challenges and unique requirements of these applications.

### 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 advanced topics and applications 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 2 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 advanced topics and applications of 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. Tarek F. Abdelzaher, Jeffrey A. Burke, Xiuzhen Cheng, Ahmed Helmy, Benyuan Liu, Mingyan Liu, Tommaso Melodia, Sethuraman Panchanathan, Yannis Paschalidis, Dario Pompili, Raja Sengupta, Mehmet Can Vuran, Yu Wang, and Guoliang Xing. I am really honored to have led and 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 advanced topics and applications 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. Mingyan Liu, Professor of Electrical Engineering and Computer Science at the University of Michigan, Ann Arbor, 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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