Habib M. Ammari

Challenges and Opportunities of Connected $k$-Covered Wireless Sensor Networks
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Prof. Janusz Kacprzyk
Systems Research Institute
Polish Academy of Sciences
ul. Newelska 6
01-447 Warsaw
Poland
E-mail: kacprzyk@ibspan.waw.pl

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Challenges and Opportunities of Connected $k$-Covered Wireless Sensor Networks

From Sensor Deployment to Data Gathering
This book is dedicated

To my first teachers: My mother, Mbarka, and my father, Mokhtar

To my very best friends: My wife, Fadhila, and my children,

Leena, Muath, Mohamed-Eyed, Lama, and Maitham
Preface

“The decomposition of the difficulties to be resolved, or the objects to be known, should be pushed up to the simplest elements … Such elements are seized directly and completely by the intuition.”

René Descartes, Discours de la méthode (1637)

Wireless sensor networks have received significant attention because of their important role and many conveniences in our lives. Indeed, the recent and fast advances in inexpensive sensor technology and wireless communications have made the design and development of large-scale wireless sensor networks cost-effective and appealing to a wide range of mission-critical situations, including civilian, natural, industrial, and military applications, such as health and environmental monitoring, seism monitoring, industrial process automation, and battlefields surveillance, respectively. A wireless sensor network consists of a large number of tiny, low-powered devices, called sensors, which are randomly or deterministically deployed in a field of interest while collaborating and coordinating for the successful accomplishment of their mission. These sensors suffer from very scarce resources and capabilities, such as bandwidth, storage, CPU, battery power (or energy), sensing, and communication, to name a few, with energy being the most critical one. The major challenge in the design process of this type of network is mainly due to the limited capabilities of the sensors, and particularly, their energy, which makes them unreliable.

This book aims to develop a reader’s thorough understanding of the opportunities and challenges of \( k \)-covered wireless sensor networks, where each point in a deployment field is covered (or sensed) by at least \( k \) sensors. Following René Descartes’ most elegant methodology of dividing each difficulty into as many parts as might be possible and necessary to best solve it (Discours de la Method, 1637), this book presents a variety of theoretical studies based on percolation theory and computational geometry as well as protocols that lead to the design of a unified framework, where connected \( k \)-coverage, sensor scheduling, and data routing and dissemination are jointly considered. I have written this book given the tremendous interest of numerous researchers in \( k \)-covered wireless sensor networks, which has been expressed by their very active and productive research for the last 6 years and until now. Indeed, several protocols have been proposed to solve problems related to the design and implementation of energy-efficient \( k \)-covered wireless sensor networks that span a variety of topics, such as sensor deployment, network connectivity, sensing coverage, sensor scheduling (or duty-cycling), and data routing and dissemination.

This text is mainly based on my research work that has been focused so far on the study of \( k \)-covered wireless sensor networks, which has been the main contribution
Preface

of my Ph.D. Dissertation. This is one of the major topics covered in both of the introductory and advanced courses on wireless sensor networks that I have taught at Hofstra University. This book will be useful to senior undergraduate and graduate students in computer science, computer engineering, and any related discipline. It will also be of interest to computer scientists, researchers, and practitioners in both academia and industry with interest in $k$-covered wireless sensor networks from their deployment until data gathering.

Book Organization

The book is divided into four parts which are described as follows.

In Part 1, we introduce wireless sensor networks as a new emerging technology and the background necessary. Chapter 1 gives a brief introduction to wireless sensor networks and presents the major challenging problems in their design. Also, it describes a sample of their potential applications as well as a key set of design requirements of the protocols proposed in this book. Moreover, it states the problems being investigated in this book along with a brief description of their solutions. Chapter 2 introduces the background that is necessary for the description of all the protocols discussed in this book.

In Part 2, we address the problem of almost sure integrated coverage and connectivity in wireless sensor networks from the perspective of percolation theory. Specifically, we are interested in finding the critical sensor density above which the network is almost surely connected and the deployment field is almost surely covered. Chapter 3 proposes our solution to this problem in two-dimensional deployment fields using a probabilistic approach. Chapter 4 discusses our solution to the same problem in three-dimensional deployment fields using an approach that is not a generalization of the one proposed for a two-dimensional space.

In Part 3, we focus on the problem of connected $k$-coverage in densely deployed wireless sensor networks. Precisely, we are interested in achieving connected $k$-coverage with a minimum number of sensors. Chapter 5 describes our solution to this problem under the assumption of static and homogeneous sensors while considering a deterministic sensing model. Chapter 6 extends our above solutions to account for heterogeneous $k$-covered wireless sensor networks. Also, it introduces our solution to the same problem in the context of mission-oriented wireless sensor networks while considering sensor mobility. Chapter 7 addresses the problem of connected $k$-coverage using a more realistic, stochastic sensing model. Moreover, it investigates the problem of connected $k$-coverage in three-dimensional wireless sensor networks using a deterministic sensing model. Chapter 8 gives our measures of unconditional and conditional connectivity and fault tolerance of $k$-covered wireless sensor networks while considering two-dimensional deployment fields.

In Part 4, we are interested in the problem of energy-efficient data forwarding in wireless sensor networks. Chapter 9 describes our solution to this problem for always-on wireless sensor networks using both short-range and long-range data forwarding schemes. Chapter 10 presents our solution to the problem of finding a trade-off between energy and delay when forwarding data to a central gathering point, such as the sink. Chapter 11 proposes our solution to the energy sink-hole
problem, which is inherent to static, always-on wireless sensor networks. Chapter 12 discusses our energy-efficient, unified framework for geographic forwarding in duty-cycled, \(k\)-covered wireless sensor networks while using deterministic sensing and communication models. Furthermore, it considers both two-dimensional and three-dimensional deployment fields.

In Part 5, we conclude and extend our measures of network and fault tolerance in Chap. 8 to account for three-dimensional settings. Chapter 13 focuses on the future trends in connected \(k\)-covered wireless sensor networks. Precisely, it concludes this book with both a summary and a discussion of potential future work and open problems that deserve more attention. Appendix provides measures of unconditional and conditional connectivity and fault tolerance of \(k\)-covered wireless sensor networks deployed in three-dimensional fields.

Acknowledgements

Numerous family members and friends made this book a reality. And, it is time to thank them and acknowledge their excellent support and highly appreciated efforts, which result in writing this book.

First and foremost, I would very much like to express my sincere and permanent gratitude to Allah—the Most Gracious, the Most Merciful for the wonderful opportunity He has given me to put together my research work in this book and for His blessing by helping me finish this project—one of my precious dreams—and make it available to others who are interested in its topics. This modest book is dedicated to Him and I hope He would kindly accept it. And, I always remember His Saying “And of knowledge, you (mankind) have been given only a little”.

Although writing a book is an individual process, it is in reality a shared experience with others who appreciate it and have tremendously helped me in order to make it a successful one. I have been fortunate to have shared this experience with my family closely or distantly. I would like to express my special thanks and deep appreciation to my beloved wife, Fadhila, for her beautiful mind and good humor, exceptional support, constant encouragements, and very constructive advices since the first time I thought about writing this book, and to my wonderful children, Leena, Muath, Mohamed-Eyed, Lama, and Maitham, for their very kind patience and understanding for the long time. I have spent away from them while setting in front of my laptop writing this book. Several times, Leena and Muath told me: “Dady, you are always spending too much time with that electronic rectangle!” – referring to my laptop. Both of my wife and children are providing me with the social and intellectual environment in which I thrive and survive. My hearty gratitude goes to my first teachers, my mother, Mbarka, and my father, Mokhtar, for teaching me the value of knowledge and the importance of family, for providing me with constant support and encouragements, for their wonderful prayers, and more importantly, for believing in me. Also, I would like to thank all my sisters, sisters in law, brothers, brothers in law, nieces, and nephews for their endless support and encouragement.
This book is dedicated to them and to the fond memory of my grand-parents, Fatma and Abdelkarim, and my uncle Mahfoudh, who always wished me to be very successful and well received.

Writing a book is a great pleasure yet a challenging project that could not have been accomplished without the support of the people around me who made this experience more joyful. I would like to thank my colleagues and friends at Hofstra University and the Department of Computer Science for the environment they created for me to finish this book. In particular, I am very thankful to Dr. Bernard Firestone, Professor of Political Science and Dean of the Hofstra College of Liberal Arts and Sciences (HCLAS), for supporting my research with a generous new faculty start-up research grant and his great support to WiSeMAN Research Lab; Mr. Richard Apollo, Senior Assistant Dean for HCLAS Planning and Budget, for his wonderful and continuous support to WiSeMAN Research Lab; Dr. John Impagliazzo, Professor Emeritus of Computer Science, Dr. Gretchen Ostheimer, Associate Professor of Computer Science, Dr. Krishnan Pillaiapakkamnatt, Associate Professor of Computer Science, and Ms. Zsa Zsa Tucker, Senior Executive Secretary, for their kind support and encouragement; and Mrs. Sofia Kakoulidis, Associate Provost for Research and Sponsored Programs, for her kind assistance with my research grant proposals. Their support has been very valuable since I joined the Department of Computer Science at Hofstra University on September 1, 2008.

I always remember the wonderful support and encouragements of my Professors and friends in my Department of Computer Science and Engineering at The University of Texas at Arlington—my Alma Mater Studiorum. Indeed, one of the steps towards my goals and success is the exciting and unforgettable years I have spent in the Department of Computer Science and Engineering completing my Ph.D. studies in Computer Science and Engineering. Over those years, I learned a lot from them and acquired solid background and knowledge in computer science, and particularly, the field of wireless sensor networks. Especially, I am very grateful to the following faculty members, Dr. Sajal K. Das (Ph.D. Advisor), Dr. Gautam Das (Ph.D. Committee Member), Dr. Bahram Khalili (Graduate Advisor), Dr. Yonghe Liu (Ph.D. Committee Member), Dr. Fillia Makedon (Chairperson), Dr. Lynn Peterson (Senior Associate Dean of the College of Engineering), Dr. Bob Weems (Ph.D. Committee Member, Associate Chair), and Dr. Gergely Zaruba, and the staff members, Camille Costabile, Pamela Mcbride, and Sherri Warwick for their kindness and for making things easier for me during my doctoral studies. I would like to sincerely thank all of them for helping me achieve my goals and objectives in my career. I am very proud to have graduated with my Ph.D. degree in Computer Science and Engineering from my Department of Computer Science and Engineering at The University of Texas at Arlington, and with two prestigious awards: John Steven Schuchman Award for 2006–2007 Outstanding Research by a PhD Student in February 2008 and Nortel Outstanding CSE Doctoral Dissertation Award in February 2009! I received both awards at the Engineering Week Banquet at my Alma Mater, The University of Texas at Arlington.

I would like to thank numerous experts and researchers for contributing to the growth and development of the field of wireless sensor networks, and particularly
the topics of this book. Especially, I gratefully thank Drs. X. Wang, G. Xing, Y. Zhang, C. Lu, R. Pless, and C. D. Gill, who introduced the concept of $k$-coverage as well as integrated coverage and connectivity in wireless sensor networks in their prestigious SenSys’03 conference and ACM TOSN 2005 journal papers.

I would like to give my sincere thanks to my professional editors, Dr. Janusz Kacprzyk, Editor-in-Chief, and Dr. Thomas Ditzinger, Senior Editor, of the book series, Studies in Computational Intelligence, Springer-Verlag, Heidelberg (Germany) and New York (USA), for their kind invitation, which stimulated me to write this book and devote considerable time to finish it, their enthusiasm, and their generous assistance throughout the entire writing process. It was a great pleasure to work with both of them. The other thing that most attracted me to have Drs. Kacprzyk and Ditzinger as my preferred editors for this book is the red-and-blue cover of their prestigious Studies in Computational Intelligence book series! I would like to acknowledge the publisher, Springer, who made this book possible. Last but not least, my special thanks go to SCI Data Processing Team – SPS for their professionalism and hard work.

January 2009

Habib M. Ammari
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