

Carlos de Moraes Cordeiro • Dharma Prakash Agrawal

Ad Hoc^{and} Sensor Networks

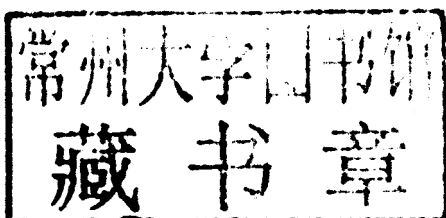
Theory and Applications (2nd Edition)



World Scientific

Ad Hoc^{and} Sensor Networks

Theory and Applications (2nd Edition)



Carlos de Moraes Cordeiro

Intel Corporation, USA

Dharma Prakash Agrawal

University of Cincinnati, USA

 **World Scientific**

NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI

Published by

World Scientific Publishing Co. Pte. Ltd.

5 Toh Tuck Link, Singapore 596224

USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601

UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

British Library Cataloguing-in-Publication Data

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

AD HOC AND SENSOR NETWORKS (2nd Edition)

Theory and Applications

Copyright © 2011 by World Scientific Publishing Co. Pte. Ltd.

All rights reserved. This book, or parts thereof, may not be reproduced in any form or by any means, electronic or mechanical, including photocopying, recording or any information storage and retrieval system now known or to be invented, without written permission from the Publisher.

For photocopying of material in this volume, please pay a copying fee through the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA. In this case permission to photocopy is not required from the publisher.

ISBN-13 978-981-4338-88-2

ISBN-10 981-4338-88-5

ISBN-13 978-981-4338-89-9 (pbk)

ISBN-10 981-4338-89-3 (pbk)

Printed in Singapore by B & Jo Enterprise Pte Ltd

Ad Hoc^{and} Sensor Networks

Theory and Applications (2nd Edition)

To my wife Wilma and our sons Matheus and Alex.

Carlos de Moraes Cordeiro

To my wife Purnima.

Dharma Prakash Agrawal

Preface to the Second Edition

The area of ad hoc and sensor networks is growing at a much faster rate than any one's anticipation. To reflect such rapid advances, we have added three new chapters: Chapter 6 on Wireless Mesh Networks, Chapter 8 on Cognitive Radio and Networks, and Chapter 12 on Sensor Networks for Controlled Environment and Actuators. Besides this, the remaining chapters have been updated to reflect recent advances and changes in the area. Specifically, the Chapters on Wireless LAN, Wireless PAN, Applications of Sensor Networks, Sensor Networks Design Considerations, and Security in Ad Hoc and Sensor Networks have been thoroughly revised. Additional questions have been added in most of the chapters.

The authors are planning to prepare power point slides for all the chapters and will supply them to instructors if the book is adopted for a class. We hope, this new edition will continue to serve the readership in the best possible way.

Carlos de Morais Cordeiro
Dharma Prakash Agrawal

Preface to the First Edition

The intention of this textbook is to serve as the primary reference in the field of ad hoc and sensor networks for individuals with academic, industry, or military background. It targets not only researchers and engineers, but also those who would like to have a deep yet easy coverage of this growing field, and the current state of research in this area. It comes to fill in the gap of existing literature on ad hoc and sensor networks by providing a comprehensive coverage of the subject matter. This textbook has been written with great care to address the need of those who seek not only detailed knowledge of this important field, but also the breadth. After all, this area is poised to be a key component of future communication networks and likely to have an undaunted impact on our daily lives.

If there is one thing that we have learnt in all these years of research and development on ad hoc and sensor networks is that there is a major interdependence among various layers of the network protocol stack. Contrary to wired or even one-hop wireless (e.g., cellular or mobile) networks, the lack of a fixed infrastructure, the inherent mobility, and the underlying routing mechanism by ad hoc and sensor networks introduce a number of technological challenges that are very hard to be addressed within the boundaries of a single protocol layer. Despite of this clear fact, all existing edited textbooks on ad hoc and sensor networks often focus on a specific aspect of the technology in isolation, fail to provide critical insights on cross-layer interdependencies, and hence leave major questions in the minds of the readers.

Our experience in dealing with students, professionals, and researchers working on ad hoc and sensor networks have revealed the

need for a textbook that covers the many interrelated aspects of these networks and which can also clearly pinpoint iterative interactions between different layers. The study of ad hoc and sensor networks is very peculiar and intriguing, and to be able to fully understand this area it is not only enough to understand specific solutions individually, but also their many interdependencies and cross-layer interactions. We are confident that this knowledge will allow readers to firmly grasp this topic, understand its intricacies, and stimulate creativity.

This is in essence the approach we take in this textbook. From the physical up to the application layer, we provide a detailed investigation of ad hoc and sensor networks to date. In addition, wherever applicable, the discussion of these topics is closely followed by their impact on other layers of the network protocol stack. With this explanatory model, we aim to provide the readers with not only the depth in understanding but also the breadth. The ultimate goal is to provide a superior experience that opens up new horizons as one move on from one chapter to another.

The organization of this textbook is based on the authors' long experience in academia and industry, dealing with students and professionals, where we feel that the easiest way to start this journey is through the routing layer. Technologies in this layer are often more easily absorbable so as to create a solid foundation for the follow-up subject areas. Therefore, after an introduction and overview of existing and future wireless communication systems in Chapter 1, we start with detailed technical discussions in Chapter 2 by examining unicast routing protocols and algorithms. To accommodate important new applications and improve the system performance of ad hoc and sensor networks, this is followed by the investigation of mechanisms for broadcasting, multicasting and geocasting in Chapter 3. Once all networking concepts are in place, it is time to move down in the protocol stack. In Chapters 4 and 5 we discuss the enabling technologies that are used at the physical and medium access control (MAC) layers of ad hoc and sensor networks. From IEEE 802.11 to IEEE 802.15, these chapters provide a detailed coverage of existing and forthcoming wireless technologies. Chapter 6

deals with directional antennas, which is a powerful way of increasing the capacity, connectivity, and covertness of ad hoc networks. This is the first textbook that deals with directional antennas from a networking perspective, concentrating on the MAC and routing issues when these types of antennas are in use. Next, we move up the stack to the transport layer and look at the many performance issues of the Transmission Control Protocol (TCP) over ad hoc networks, and discuss ways for improvements. Chapters 8 and 9 are fully dedicated to sensor networks and the unique characteristics and issues they face. As it shall be clear, sensor networks demand special treatment of certain issues which are inherently specific to them as compared to a generic ad hoc network. As both ad hoc and sensor networks are wireless, security becomes a critical component and is extensively discussed in Chapter 10. Finally, Chapter 11 investigates the increasingly important area of *all wireless networks* towards future fourth generation wireless systems and beyond. Among other things, we discuss the integration of heterogeneous wireless networks, such as cellular and wireless local area networks (LANs), with ad hoc and sensor networks, which will form the basis of the universal ubiquitous networking paradigm of the future. To ensure deep understanding of the subject, each chapter is accompanied by numerical questions and topics for simulation projects. Many of the exercises are open-ended and have been taken from open-book examination questions given to graduate students.

The authors are confident that the approach taken in this textbook together with its vast and extensive coverage of topics, will enable the readers to not only understand and position themselves in this hot area of ad hoc and sensor networks, but will also allow them to develop new capabilities, enhance skills, share expertise, consolidate knowledge and encourage further development of the area by identifying key problems, analyzing them and designing new and innovative solutions and applications.

Carlos de Moraes Cordeiro
Dharma Prakash Agrawal

Acknowledgements for the Second Edition

The second edition of this book would not have been possible without the help from numerous individuals. Thanks are due to Weihuang Fu in collecting material and extensive inputs for the Chapter on Wireless Mesh Networks. Both Talmai Oliveira and Aparna Venkataraman helped in completing the page numbers for the index section.

A number of graduate students have read different versions of the drafts and helped improve the overall quality of this textbook. Our sincere thanks are due to Amitabh Mishra, Dushan Aththidiyavidanalage, Vaibhav Pandit, Nishan Weragama, Yang Chi Yang, Jung Hyun Jun, Sansit Sharma, Weihuang Fu, Sriram Narayanan, Narendra Katneni, and Avani Dalal.

Finally, we express our gratitude to the authorities of Intel Corporation and the University of Cincinnati for their encouragement in writing this second edition. The help by the staff of our publisher at the World Scientific Inc. is also very much appreciated.

Carlos de Morais Cordeiro
Dharma Prakash Agrawal

Acknowledgements for the First Edition

This book would not have been possible without the help from numerous individuals. A number of colleagues have read different versions of the drafts and helped improve the overall quality of this textbook. Our sincere thanks are due to Dave Cavalcanti, Hrishikesh Gossain, Anup Kumar, and Ashok Roy, for many helpful suggestions on different topics. Vivek Jain, Anurag Gupta, Anindo Mukherjee, Demin Wang, Yun Wang, and Qi Zhang provided useful material and references for some important concepts. Many thanks are also due to Torsha Banerjee, Ratnabali Biswas, Yi Cheng, Kaushik Chowdhury, Bing He, Nagesh Nandiraju, Lakshmi Santhanam and Haitang Wang for final proofreading of different chapters and identifying the index terms. Last, but not the least, our sincere thanks go to Abhishek Jain for going through the tiring process of proof-reading, updating diagrams, and performing endless painstaking corrections.

The authors would like to thank their families for enduring lonely evenings, weekends, and working vacations for the past two years while we have been busy writing this book. Finally, we express our gratitude to the authorities of Philips Research North America and the University of Cincinnati for their encouragement in writing this textbook. The help by the staff of our publisher at the World Scientific Inc. is also very much appreciated.

Carlos de Morais Cordeiro
Dharma Prakash Agrawal

Contents

Preface to the Second Edition	vii
Preface to the First Edition	ix
Acknowledgements for the Second Edition	xiii
Acknowledgements for the First Edition	xv
1. Introduction.....	1
1.1 Introduction.....	1
1.2 The Communication Puzzle.....	4
1.3 Applications of MANETs.....	6
1.4 Challenges.....	8
1.4.1 Scalability	8
1.4.2 Quality of Service	9
1.4.3 Client-Server Model Shift.....	9
1.4.4 Security	10
1.4.5 Interoperation with the Internet.....	10
1.4.6 Energy Conservation	11
1.4.7 Node (MH) Cooperation	11
1.4.8 Interoperation.....	12
1.5 Book Organization.....	12
1.6 Conclusions and Future Directions	16
Homework Questions/Simulation Projects	16
References	16
2. Routing in Ad hoc Networks.....	18
2.1 Introduction.....	18
2.2 Topology-Based versus Position-Based Approaches.....	19
2.3 Topology-Based Routing Protocols.....	20
2.3.1 Proactive Routing Approach.....	20
2.3.2 Reactive Routing Approach	26
2.3.3 Hybrid Routing Approach.....	34
2.3.4 Comparison.....	40
2.4 Position-Based Routing	40

2.4.1 Principles and Issues	40
2.4.2 Location Services	41
2.4.3 Forwarding Strategies	47
2.4.4 Comparisons	57
2.5 Other Routing Protocols	62
2.5.1 Signal Stability Routing	62
2.5.2 Power Aware Routing	63
2.5.3 Associativity-Based Routing	63
2.5.4 QoS Routing	64
2.6 Conclusions and Future Directions	69
Homework Questions/Simulation Results	70
References	71
3. Broadcasting, Multicasting and Geocasting	74
3.1 Introduction	74
3.2 The Broadcast Storm	76
3.2.1 Broadcasting in a MANET	77
3.2.2 Flooding-Generated Broadcast Storm	78
3.2.3 Rebroadcasting Schemes	80
3.3 Multicasting	90
3.3.1 Issues in Providing Multicast in a MANET	91
3.3.2 Multicast Routing Protocols	91
3.3.3 Comparison	115
3.4 Geocasting	116
3.4.1 Geocast Routing Protocols	117
3.4.2 Comparison	125
3.5 Conclusions and Future Directions	125
Homework Questions/Simulation Projects	127
References	127
4. Wireless LANs	130
4.1 Introduction	130
4.2 Why Wireless LANs	131
4.3 Transmission Techniques	132
4.3.1 Wired Networks	132
4.3.2 Wireless Networks	133
4.4 Medium Access Control Protocol Issues	138
4.4.1 Hidden Terminal Problem	138
4.4.2 Reliability	140
4.4.3 Collision Avoidance	141
4.4.4 Congestion Avoidance	141
4.4.5 Congestion Control	142

4.4.6 Energy Efficiency	142
4.4.7 Other MAC Issues.....	143
4.5 The IEEE 802.11 Standard for Wireless LANs	143
4.5.1 Network Architecture.....	146
4.5.2 The Physical Layer	147
4.5.3 The MAC Layer.....	159
4.5.4 Security	169
4.5.5 The IEEE 802.11e MAC Protocol	174
4.5.6 A Glimpse on Past and Present IEEE 802.11 Efforts.....	178
4.6 Enhancements to IEEE 802.11 MAC.....	178
4.6.1 Power Control	180
4.6.2 Spatial Reusability	184
4.6.3 QoS Provisioning.....	189
4.7 Conclusions and Future Directions	191
Homework Questions/Simulation Projects	192
References.....	193
5. Wireless PANs	196
5.1 Introduction.....	196
5.2 Why Wireless PANs	197
5.3 The Bluetooth Technology.....	198
5.3.1 History and Applications	199
5.3.2 Technical Overview	200
5.3.3 The Bluetooth Specifications	206
5.3.4 Piconet Synchronization and Bluetooth Clocks	209
5.3.5 Master-Slave Switch	210
5.3.6 Bluetooth Security	211
5.4 Enhancements to Bluetooth	217
5.4.1 Bluetooth Interference Issues.....	217
5.4.2 Intra and Inter Piconet Scheduling.....	223
5.4.3 Bridge Selection.....	234
5.4.4 Traffic Engineering	236
5.4.5 QoS and Dynamic Slot Assignment.....	239
5.4.6 Scatternet Formation.....	241
5.5 The IEEE 802.15 Working Group for WPANs.....	243
5.5.1 The IEEE 802.15.3.....	244
5.5.2 The IEEE 802.15.4.....	246
5.6 Comparison between WPAN Systems.....	251
5.6.1 Range	252
5.6.2 Data Rate.....	252
5.6.3 Support for Voice.....	252
5.6.4 Power Management	253

5.6.5 Comparison and Summary of Results	253
5.7 Conclusion and Future Directions.....	254
Homework Questions/Simulation Projects	255
References.....	255
6. Wireless Mesh Networks	259
6.1 Introduction.....	259
6.2 Network Architecture.....	261
6.3 Challenging Technologies.....	264
6.3.1 MR Deployment.....	264
6.3.2 IGW Deployment.....	265
6.3.3 Channel Assignment	266
6.4 Other Issues.....	269
Homework Questions/Simulation Projects	269
References.....	269
7. Directional Antenna Systems	270
7.1 Introduction.....	270
7.2 Antenna Concepts	272
7.2.1 Gain.....	273
7.2.2 Radiation Pattern.....	274
7.2.3 Beam Width	275
7.3 Evolution of Directional Antenna Systems.....	275
7.3.1 Sectorized Antenna Systems	275
7.3.2 Diversity Antenna Systems	275
7.3.3 Smart Antenna Systems	276
7.4 Advantages of Using Directional Antennas	279
7.5 Directional Antennas for Ad Hoc Networks	280
7.5.1 Antenna Models	281
7.6 Protocol Issues on the Use of Directional Antennas	284
7.6.1 Directional Neighborhood.....	284
7.6.2 New Types of Hidden Terminal Problems.....	286
7.6.3 Deafness.....	289
7.7 Broadcasting	291
7.7.1 Broadcasting Protocols	292
7.8 Medium Access Control	297
7.8.1 Single Channel.....	298
7.8.2 Multi-Channel.....	308
7.8.3 Other Protocols	310
7.9 Routing	312
7.9.1 Protocols	312
7.10 Conclusions and Future Directions	315

Homework Questions/Simulation Projects	316
References.....	316
8. Cognitive Radio and Networks	318
8.1 Introduction.....	318
8.2 Cognitive Radio and Networks	319
8.3 Spectrum Access Models	320
8.4 Cognitive Radio Technologies and Challenges	323
8.5 The IEEE 802.22 Standard.....	325
8.5.1 TV Band and PUs	325
8.5.2 Applications of IEEE 802.22	326
8.5.3 Reference Architecture	326
8.5.4 The IEEE 802.22 Physical (PHY) Layer	327
8.5.5 The IEEE 802.22 Medium Access Control (MAC) Layer...	333
8.5.6 Spectrum Management Model	342
8.5.7 Spectrum Sensing.....	346
8.6 Other Activities.....	356
8.6.1 IEEE 802.22.1 and IEEE 802.22.2.....	356
8.6.2 IEEE SCC 41	356
8.6.3 IEEE 802.11af.....	357
8.7 Conclusions and Future Directions	357
Homework Questions/Simulation Projects	358
References.....	358
9. TCP over Ad Hoc Networks.....	360
9.1 Introduction.....	360
9.2 TCP Protocol Overview	361
9.2.1 Designed and Fine-Tuned to Wired Networks.....	362
9.2.2 TCP Basics.....	362
9.2.3 TCP Header Format	364
9.2.4 Congestion Control	367
9.2.5 Round-Trip Time Estimation	369
9.3 TCP and MANETs.....	370
9.3.1 Effects of Partitions on TCP	372
9.3.2 Impact of Lower Layers on TCP.....	375
9.4 Solutions for TCP over Ad Hoc	388
9.4.1 Mobility-Related	389
9.4.2 Fairness-Related.....	395
9.5 Conclusions and Future Directions	401
Homework Questions/Simulation Projects	403
References.	404

10. Applications of Sensor Networks.....	406
10.1 Introduction.....	406
10.2 Applications of WSNs	408
10.3 DARPA Efforts towards Wireless Sensor Networks	410
10.4 Body Area Network	411
10.5 Habitat Monitoring.....	412
10.6 The Grand Duck Island Monitoring Network.....	413
10.6.1 Architecture.....	413
10.6.2 A Remote Ecological Micro-Sensor Network.....	414
10.6.3 Environmental Monitoring.....	415
10.6.4 Environmental Observation and Forecasting System.....	416
10.6.5 Drinking Water Quality	417
10.6.6 Disaster Relief Management	417
10.6.7 Soil Moisture Monitoring.....	418
10.7 Health Care Monitoring	418
10.8 Building, Bridge, and Structural Monitoring	419
10.9 Smart Energy and Home/Office and Industrial Assembly.....	420
Lines Applications	
10.10 Greenhouse Monitoring	421
10.11 Unusual Applications of WSNs	422
10.12 Conclusions and Future Directions	423
Homework Questions/Simulation Projects	424
References.....	424
11. Sensor Networks Design Considerations	427
11.1 Introduction.....	427
11.2 Empirical Energy Consumption.....	429
11.3 Sensing and Communication Range	431
11.4 Design Issues	434
11.4.1 Challenges.....	436
11.5 Localization Scheme	440
11.6 Clustering of SNs.....	442
11.6.1 Architecture of WSNs.....	444
11.6.2 Network Lifetime.....	445
11.6.3 Physical Layer.....	447
11.7 MAC Layer	447
11.7.1 Design Issues	449
11.7.2 MAC Protocols	450
11.7.3 The Sensor-MAC	450
11.8 The Self-Organizing MAC for WSNs and the Eaves-drop-.....	452
And-Register Protocol	
11.8.1 SMACS	453