

Dynamic Spectrum Access and Management in Cognitive Radio Networks

Are you involved in designing the next generation of wireless networks? With spectrum becoming an ever scarcer resource, it is critical that new systems utilize all available frequency bands as efficiently as possible. The revolutionary technology presented in this book will be at the cutting edge of future wireless communications.

Dynamic Spectrum Access and Management in Cognitive Radio Networks provides you with an all-inclusive introduction to this emerging technology, outlining the fundamentals of cognitive radio-based wireless communication and networking, spectrum sharing models, and the requirements for dynamic spectrum access. In addition to the different techniques and their applications in designing dynamic spectrum access methods, you'll also find state-of-the-art dynamic spectrum access schemes, including classifications of the different schemes and the technical details of each scheme. This is a perfect introduction for graduate students and researchers, as well as a useful self-study guide for practitioners.

Ekram Hossain is an Associate Professor in the Department of Electrical and Computer Engineering at the University of Manitoba, Winnipeg, Canada. He received his Ph.D. in Electrical Engineering from the University of Victoria, Canada, in 2000. His current research interests include design, analysis, and optimization of wireless/mobile communication networks, cognitive radio systems, distributed systems, and mobile computing. Dr. Hossain serves as an Editor for the *IEEE Transactions on Mobile Computing*, the *IEEE Transactions on Wireless Communications*, the *IEEE Transactions on Vehicular Technology*, *IEEE Wireless Communications*, *IEEE Communications Surveys and Tutorials*, and several other international journals. He is a registered professional engineer in the province of Manitoba, Canada.

Dusit Niyato is an Assistant Professor in the Division of Computer Communications, School of Computer Engineering at Nanyang Technological University (NTU), Singapore. He received his Ph.D. from the University of Manitoba, Canada, in 2008. His current research interests include wireless communications and networking.

Zhu Han is an Assistant Professor of Electrical and Computer Engineering at the University of Houston. He was awarded his Ph.D. in Electrical Engineering from the University of Maryland, College Park, and worked for a period in industry as an R & D Engineer for JDS. His research interests include wireless resource allocation and management, wireless communications and networking, game theory, network security, and wireless multimedia.

Dynamic Spectrum Access and Management in Cognitive Radio Networks

EKRAM HOSSAIN

University of Manitoba

DUSIT NIYATO

Nanyang Technological University (NTU)

ZHU HAN

University of Houston



CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom
 One Liberty Plaza, 20th Floor, New York, NY 10006, USA
 477 Williamstown Road, Port Melbourne, VIC 3207, Australia
 314-321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi - 110025, India
 103 Penang Road, #05-06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org

Information on this title: www.cambridge.org/9780521898478

© Cambridge University Press 2009

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2009

A catalogue record for this publication is available from the British Library

Library of Congress Cataloging in Publication data

Hossain, Ekram, 1971–

Dynamic spectrum access and management in cognitive radio networks / Ekram Hossain, Dusit Niyato, and Zhu Han.

p. cm.

Includes Bibliographical References And Index.

ISBN 978-0-521-89847-8 (hardback)

1. Cognitive radio networks. 2. Radio resource management (Wireless communications)

I. Niyato, Dusit. II. Han, Zhu, 1974– III. Title.

TK5103.4815.H67 2009

621.384 – dc22 2009002060

ISBN 978-0-521-89847-8 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication, and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Contents

<i>Preface</i>	<i>page xiii</i>
Part I Introduction	1
1 Wireless communications systems	3
1.1 Radio frequency bands and spectrum management	4
1.1.1 Radio frequency bands	4
1.1.2 Spectrum management	4
1.2 Wireless protocols	6
1.3 Radio propagation characteristics and channel models	9
1.3.1 Radio propagation	9
1.3.2 Channel models	11
1.4 Wireless communications technologies	19
1.4.1 Wireless PAN technologies	19
1.4.2 Wireless LAN technologies	20
1.4.3 Cellular wireless networks	21
1.4.4 Wireless MAN technologies	23
1.4.5 Wireless RAN technology	24
1.5 Advanced wireless technologies	25
1.5.1 OFDM technology	25
1.5.2 MIMO technology	25
1.5.3 Beamforming technique	26
1.5.4 Ultra-wideband technology	26
1.5.5 Cooperative diversity	27
1.6 Multihop wireless networking	27
1.6.1 Wireless sensor networks	28
1.6.2 Wireless ad hoc networks	29
1.6.3 Wireless mesh networks	29
1.7 Radio resource management in wireless networks	30
1.7.1 Admission control	30
1.7.2 Queue management	32
1.7.3 Traffic scheduling	33

vi	Contents	
	1.7.4 Medium access control (MAC)	33
	1.7.5 Subcarrier allocation	34
	1.7.6 Power control	34
	1.8 Next generation heterogeneous wireless access networks and cognitive radio	35
	1.9 Summary	38
2	Introduction to cognitive radio	39
	2.1 Software-defined radio	41
	2.2 Cognitive radio features and capabilities	43
	2.2.1 Cognitive radio architecture	43
	2.2.2 Functions of cognitive radio	44
	2.2.3 Dynamic spectrum access	45
	2.2.4 Components of cognitive radio	46
	2.2.5 Interference temperature	47
	2.2.6 Spectrum sensing	50
	2.2.7 Spectrum analysis and spectrum decision	52
	2.2.8 Potential applications of cognitive radio	54
	2.3 Research challenges in cognitive radio	55
	2.3.1 Issues in spectrum sensing	55
	2.3.2 Spectrum management issues	57
	2.3.3 Spectrum mobility issues	58
	2.3.4 Network layer and transport layer issues	59
	2.3.5 Cross-layer design for cognitive radio networks	60
	2.3.6 Artificial intelligence approach for designing cognitive radio	63
	2.3.7 Location-aware cognitive radio	64
	2.4 Cognitive radio architectures for NeXt Generation (XG) networks	66
	2.5 Cognitive radio standardization	67
	2.5.1 IEEE SCC 41	67
	2.5.2 IEEE 802.22 for wireless regional area networks (WRANs)	69
	2.6 Summary	73
	Part II Techniques for design, analysis, and optimization of dynamic spectrum access and management	75
3	Signal processing techniques	77
	3.1 Spectrum sensing	78
	3.1.1 Interference temperature/channel estimation	78
	3.1.2 Detection of spectrum holes	85
	3.1.3 Practical spectrum sensing approaches	88
	3.2 Collaborative sensing	90

3.3	Replacement of sensing devices in secondary users	91
3.3.1	New cognitive cycle with separate sensing devices	92
3.3.2	Remedies for hidden/exposed terminal problems	95
3.4	Filtering and prediction	95
3.4.1	AR, MA, and the ARMA model	96
3.4.2	Wiener filter	97
3.4.3	LMS filter	99
3.4.4	RLS filter	101
3.4.5	Kalman filter	104
3.5	Compressed sensing	106
3.5.1	Basic technology	106
3.5.2	Applications	108
3.6	Summary	109
4	Optimization techniques	110
4.1	Constrained optimization	110
4.1.1	Basic definition	111
4.1.2	Lagrangian method	113
4.1.3	Optimality	115
4.1.4	Primal-dual algorithm	118
4.2	Linear programming and the simplex algorithm	119
4.3	Convex programming	122
4.3.1	Quadratic, geometric, and semi-definite programming	122
4.3.2	Gradient method, Newton method, and their variations	124
4.4	Non-linear programming	127
4.4.1	Barrier/interior-point method	128
4.4.2	Monte Carlo method	129
4.4.3	Simulated annealing	130
4.4.4	Genetic algorithm	131
4.5	Integer programming	131
4.5.1	General formulation	132
4.5.2	Knapsack problem	135
4.5.3	Relaxation and decomposition	138
4.5.4	Enumeration technique: branch-and-bound	139
4.5.5	Cutting plane algorithms based on polyhedral combinatorics	142
4.6	Dynamic programming and the Markov decision process	144
4.6.1	General definition of dynamic programming	144
4.6.2	Markov decision process	146
4.6.3	Examples in wireless networks	148
4.7	Stochastic programming	149
4.7.1	Problem definition	150
4.7.2	Recourse	152
4.8	Summary	153

5	Game theory	155
5.1	Basics of game theory	156
5.2	Non-cooperative static game	159
5.2.1	Normal form of static game	160
5.2.2	Nash equilibrium, Pareto optimality, and mixed strategy	161
5.2.3	Social optimum: price of anarchy and referee-based game	163
5.3	Dynamic/repeated game	164
5.3.1	Sequential game and extensive form	165
5.3.2	Tit-for-tat and trigger-price strategy	167
5.3.3	Stochastic game	169
5.4	Bargaining game	170
5.4.1	Solution of bargaining games	170
5.4.2	Applications of bargaining games	172
5.5	Coalition game	174
5.5.1	Characteristic function and core	174
5.5.2	Fairness	175
5.5.3	Merge/split algorithm	177
5.6	Game with imperfect information	178
5.6.1	Bayesian game in normal form	179
5.6.2	Bayesian game in extensive form	181
5.7	Other special types of games	183
5.7.1	Zero-sum game	183
5.7.2	Potential game	185
5.7.3	Super-modular game	186
5.7.4	Correlated equilibrium	188
5.8	Summary	189
6	Intelligent algorithms	191
6.1	Machine learning	191
6.1.1	Supervised learning	192
6.1.2	Unsupervised learning	197
6.1.3	Reinforcement learning	198
6.2	Reinforcement learning models and algorithms	198
6.2.1	Value function	200
6.2.2	Dynamic programming	201
6.2.3	Monte Carlo methods	203
6.2.4	Temporal-difference learning	204
6.2.5	Learning in games	205
6.3	Applications of machine-learning techniques in wireless communications and networking	208
6.3.1	Neural network and cognitive radio	208
6.3.2	Q-learning and dynamic channel assignment	209

6.3.3	Q-learning and pricing in cognitive radio	210
6.3.4	Radio environment map and learning algorithms	211
6.4	Genetic algorithms	213
6.5	Fuzzy logic	216
6.5.1	Fuzzy set	216
6.5.2	Fuzzy operation	217
6.5.3	Fuzzy rule	217
6.5.4	Fuzzy logic control	217
6.5.5	Applications of fuzzy logic control to cognitive radio	218
6.6	Summary	220
Part III	Dynamic spectrum access and management	221
7	Dynamic spectrum access: models, architectures, and control	223
7.1	Spectrum access models	223
7.1.1	Exclusive-use model	224
7.1.2	Shared-use model	226
7.1.3	Spectrum commons model	227
7.2	Dynamic spectrum access architecture	229
7.2.1	Infrastructure-based versus infrastructureless cognitive radio network	229
7.2.2	Centralized versus distributed dynamic spectrum access	230
7.2.3	Inter- and intra-RAN dynamic spectrum allocation	231
7.3	Spectrum sensing	232
7.3.1	Design tradeoff in spectrum sensing	235
7.3.2	Cooperative centralized spectrum sensing	237
7.3.3	Cooperative distributed spectrum sensing	238
7.3.4	Spectrum sensing using sensor networks	239
7.3.5	Spectrum sensing and prediction	240
7.3.6	Spectrum sensing standards	242
7.4	Medium access control for dynamic spectrum access	243
7.4.1	Optimal decision on spectrum sensing and spectrum access	245
7.4.2	Multichannel and multiuser MAC	250
7.4.3	Spectrum allocation and scheduling	259
7.4.4	Spectrum trading	264
7.4.5	Performance analysis of cognitive MAC protocols	266
7.5	Open issues in dynamic spectrum access	272
7.6	Summary	273
8	Centralized dynamic spectrum access	274
8.1	Introduction	274
8.2	Optimization-based approach	274
8.2.1	Quality of service (QoS)-constrained dynamic spectrum access	274

x	Contents	
	8.2.2 Primary-prioritized dynamic spectrum access	276
	8.2.3 Dynamic control of open spectrum management	278
	8.2.4 Joint admission control and power allocation for dynamic spectrum access	280
	8.2.5 Power and rate control for dynamic spectrum access	281
	8.2.6 Coordinated dynamic spectrum access in cellular networks	283
	8.2.7 Collaboration and fairness in spectrum allocation	285
	8.2.8 Spatio-temporal dynamic spectrum allocation	286
	8.2.9 Dynamic spectrum allocation among network service providers	288
	8.2.10 Coordinated dynamic spectrum access	289
	8.2.11 Cooperative game for dynamic spectrum access	291
	8.2.12 Transmission scheduling via spectrum server	292
	8.2.13 Spectrum sensing and access scheduling	294
	8.2.14 Joint spectrum allocation and routing	296
	8.2.15 DSA based on the water-filling algorithm	297
	8.3 Auction-based approach	297
	8.3.1 General framework of spectrum auction	298
	8.3.2 Multibid auction for dynamic spectrum allocation	300
	8.3.3 Dynamic spectrum allocator knapsack auction	301
	8.3.4 Weighted proportional fair spectrum allocation	302
	8.3.5 Bilateral bargain in spectrum access	303
	8.4 Summary	305
9	Distributed dynamic spectrum access: cooperative and non-cooperative approaches	306
	9.1 Cooperative and optimization-based distributed dynamic spectrum access	308
	9.1.1 Power and admission control of cognitive radio with antenna arrays	308
	9.1.2 Genetic algorithm to optimize distributed dynamic spectrum access	312
	9.1.3 Distributed spectrum sharing based on cooperative game	313
	9.1.4 Optimal channel sensing and allocation in cognitive radio mesh network	315
	9.1.5 Cooperative spectrum sharing using repeated game	318
	9.1.6 Cooperative strategy for distributed spectrum sharing	320
	9.2 Non-cooperative distributed dynamic spectrum access	322
	9.2.1 Decentralized channel selection for QoS-sensitive cognitive radio networks	322
	9.2.2 Joint distributed power control and channel selection in CDMA cognitive radio networks	323
	9.2.3 Random access and interference channel in cognitive radio networks	325
	9.2.4 Dynamic channel selection in multihop networks	328

	Contents	xi
9.2.5	Genetic algorithm-based competitive power allocation for dynamic spectrum access	329
9.2.6	Cognitive medium access and coexistence with WLAN	331
9.2.7	Time domain spectrum allocation	335
9.3	Summary	337
10	Distributed dynamic spectrum access: learning algorithms and protocols	338
10.1	Learning-based distributed dynamic spectrum access	338
10.1.1	Distributed resource management in multihop cognitive radio networks	338
10.1.2	Opportunistic channel selection based on the fuzzy learning algorithm	341
10.1.3	Distributed dynamic spectrum access based on no-regret learning	344
10.1.4	Agent-based dynamic spectrum access	346
10.1.5	Biologically inspired dynamic spectrum access	349
10.1.6	Secondary spectrum access	351
10.1.7	Distributed rule-regulated spectrum sharing	354
10.1.8	Game theory-based spectrum etiquette	356
10.1.9	Opportunistic channel selection in cooperative mobility networks	359
10.2	Distributed signaling protocols for cognitive radio networks	360
10.2.1	Channel evacuation protocol	360
10.2.2	Distributed channel management in uncoordinated wireless environment	362
10.2.3	Spectrum-aware on-demand routing protocol	365
10.2.4	Optimization of the transmission period	366
10.3	Summary	368
11	Economics of dynamic spectrum access: spectrum trading	369
11.1	Introduction to spectrum trading	369
11.1.1	Classification and taxonomy of spectrum trading	373
11.1.2	Radio resource pricing	375
11.1.3	Authentication, authorization, and accounting in spectrum trading	376
11.2	Economic theories in dynamic spectrum access	378
11.2.1	Utility theory	378
11.2.2	Market-equilibrium	385
11.2.3	Oligopoly market	386
11.2.4	Auction theory	393
11.3	Spectrum trading and dynamic spectrum access	397
11.3.1	Double auction-based pricing for dynamic spectrum access	397
11.3.2	Sequential and concurrent auction for dynamic spectrum access	398

xii	Contents	
	11.3.3 Dynamic spectrum allocation via spectrum server	400
	11.3.4 Techno-economic model for dynamic spectrum access	402
	11.3.5 Spectrum leasing through cooperation	403
	11.3.6 Improving the efficiency of spectrum access by using pricing	405
	11.3.7 Spectrum pricing competition based on Hotelling's model	407
	11.3.8 Pricing and admission control	408
	11.4 Summary	409
12	Economics of dynamic spectrum access: applications of spectrum trading models	410
	12.1 Dynamic competitive spectrum sharing: Cournot model	410
	12.1.1 System model	411
	12.1.2 Non-cooperative game formulation for spectrum sharing	412
	12.1.3 Dynamic game model	413
	12.1.4 Performance evaluation results	416
	12.2 Bertrand competition, market-equilibrium pricing, and cooperative spectrum pricing	418
	12.2.1 System model and pricing schemes	419
	12.2.2 Utility and spectrum demand of secondary users	421
	12.2.3 Revenue and cost functions for a primary service provider	422
	12.2.4 Spectrum supply, spectrum demand, and market-equilibrium	422
	12.2.5 Non-cooperative game formulation for Bertrand competition	423
	12.2.6 Cooperative spectrum pricing based on optimization	424
	12.2.7 Distributed algorithms for the pricing schemes	425
	12.2.8 Information exchange protocol	427
	12.2.9 Performance evaluation results	428
	12.3 Collusion in competitive spectrum pricing	430
	12.3.1 Formulation of a repeated game	430
	12.3.2 Performance evaluation results	432
	12.4 Economic model for spectrum sharing in IEEE 802.22 WRANs	433
	12.4.1 System model for spectrum trading in IEEE 802.22 WRANs	434
	12.4.2 Selection of service providers	435
	12.4.3 Non-cooperative game formulation of joint spectrum bidding and service pricing	437
	12.4.4 Performance evaluation results	438
	12.5 Open research issues	440
	12.6 Summary	440
	<i>References</i>	442
	<i>Index</i>	484

Preface

Frequency spectrum is a limited resource for wireless communications and may become congested owing to a need to accommodate the diverse types of air interface used in next generation wireless networks. To meet these growing demands, the Federal Communications Commission (FCC) has expanded the use of the unlicensed spectral band. However, since traditional wireless communications systems also utilize the frequency bands allocated by the FCC in a static manner, they lack adaptability. Also, many studies show that while some frequency bands in the spectrum are heavily used, other bands are largely unoccupied most of time. These potential spectrum holes result in the under-utilization of available frequency bands.

The concepts of software-defined radio and cognitive radio have been recently introduced to enhance the efficiency of frequency spectrum usage in next generation wireless and mobile computing systems. Software radio improves the capability of a wireless transceiver by using embedded software to enable it to operate in multiple frequency bands using multiple transmission protocols. Cognitive radio, which can be implemented through software-defined radio, is able to observe, learn, optimize, and intelligently adapt to achieve optimal frequency band usage. Through dynamic spectrum access, a cognitive wireless node is able to adaptively and dynamically transmit and receive data in a changing radio environment. Therefore, techniques for channel measurement, learning, and optimization are crucial in designing dynamic spectrum access schemes for cognitive radio under different communication requirements.

In fact, cognitive radio based on dynamic spectrum access has emerged as a new design paradigm for next generation wireless networks. Cognitive radio aims at maximizing the utilization of the limited radio bandwidth while accommodating the increasing number of services and applications in wireless networks. The driving force behind this cognitive radio technology is the new spectrum licensing paradigm initiated by the FCC, which will be more flexible to allow unlicensed (or secondary) users to access the spectrum as long as the licensed (or primary) users are not interfered with. This new spectrum licensing paradigm will improve the utilization of the frequency spectrum and enhance the performance of wireless systems. Dynamic spectrum access (DSA) or opportunistic spectrum access (OSA) is the key approach in a cognitive radio network which is adopted by a cognitive radio user (i.e. an unlicensed user) to access the radio spectrum opportunistically. Development of dynamic spectrum access-based cognitive radio technology has to deal with technical and practical considerations as well as regulatory requirements. Therefore, there is increasing interest in this technology from

researchers in both academia and industry, and engineers in the wireless industry, as well as from spectrum policy makers.

Design, analysis, and optimization of dynamic spectrum access require multidisciplinary knowledge, namely, knowledge of wireless communication and networking, signal processing, artificial intelligence (e.g. for learning), decision theory, optimization, and economic theory. A comprehensive introduction to the dynamic spectrum access and spectrum management problem in a cognitive radio network therefore needs to cover the basic concepts/theories for designing dynamic spectrum access methods as well as state-of-the-art of dynamic spectrum access and management methods.

This book provides a comprehensive treatment of the dynamic spectrum access and spectrum management problem in cognitive radio networks. The topics covered include the following: introduction to cognitive radio and the basic concepts of dynamic spectrum access; the analysis, design, and optimization of dynamic spectrum access techniques for cognitive radio; and state-of-the-art of dynamic spectrum access techniques. The key features of this book are as follows:

- a unified view of dynamic spectrum access for cognitive radio networks,
- coverage of a wide range of techniques for design, analysis, and optimization of dynamic spectrum access for cognitive radio networks,
- comprehensive treatment of state-of-the-art dynamic spectrum access techniques, and
- outlining the key research issues related to dynamic spectrum access.

The book is divided into three parts: Part I (Introduction), Part II (Techniques for design, analysis, and optimization of dynamic spectrum access and management), and Part III (Dynamic spectrum access and management). Part I comprises Chapters 1 and 2, which provide an introduction to the different wireless technologies and cognitive radio networks. The topics covered include the basics of cellular wireless, wireless local area network (WLAN), wireless metropolitan area network (WMAN), wireless personal area network (WPAN), wireless regional area network (WRAN) technology and related standards; the basic components, features, and potential applications of cognitive radio; an introduction to dynamic spectrum access; the motivations for cognitive radio-based wireless access technology; and the research issues in the different layers of the protocol stack for a cognitive radio network.

In Part II, different techniques which can be applied to the problem of the design, analysis, and optimization of dynamic spectrum access mechanisms in cognitive radio networks are introduced. In Chapter 3, the signal processing techniques (e.g. techniques for parameter estimation, filtering, and prediction) which are required for a wireless node to observe and gain knowledge of the ambient radio environment in order to access the radio spectrum dynamically are described. Optimization techniques, which are useful to obtain the optimal dynamic spectrum management scheme, are discussed in Chapter 4. Major variations of optimization techniques (e.g. unconstrained and constrained optimization, non-linear optimization, combinatorial optimization) are presented. Also, stochastic optimization based on dynamic programming, the Markov decision process (MDP), and stochastic programming for dynamic spectrum access in a random radio environment are discussed. In Chapter 5, game theory techniques are discussed in the

context of designing dynamic spectrum access methods. Game theory is an attractive tool to model the dynamic spectrum sharing problem in a cognitive wireless network. The basics of different game theory models, namely, non-cooperative, repeated, cooperative (i.e. bargaining and coalition), and evolutionary game models are presented. Intelligent algorithms (i.e. learning techniques) are fundamental to cognitive radio design, and provide the ability to observe, learn, plan, and optimize the decision of dynamic spectrum access in a cognitive radio network. An introduction to different machine learning techniques including supervised learning, unsupervised learning, and reinforcement learning is provided in Chapter 6. Example applications of these techniques are discussed in the context of cognitive radio. Intelligent techniques based on genetic algorithms and fuzzy control are also discussed.

Part III deals with the modeling, design, and analysis of dynamic spectrum access and management schemes in cognitive radio networks. In Chapter 7, different models of spectrum access/sharing are discussed. Different approaches for spectrum sensing, which is a key component of dynamic spectrum access, are reviewed. A comprehensive review of the different medium access control (MAC) protocols developed for dynamic spectrum access is presented. Dynamic spectrum access and management architectures can be either centralized or distributed. In the centralized approach, a central controller collects information about the radio environment and controls the spectrum access by cognitive radio users. In Chapter 8, different schemes for centralized dynamic spectrum access are reviewed. Chapter 8 also introduces the concept of spectrum auction, which requires a centralized auctioneer for dynamic spectrum access and management. If there is no central controller available in a cognitive radio network, the cognitive radio users have to make their spectrum access decisions independently in a distributed manner. Chapter 9 introduces the concept of distributed dynamic spectrum access. Two major approaches to distributed dynamic spectrum access, namely, the cooperative and the non-cooperative approach are discussed. Chapter 10 deals with the application of learning algorithms in distributed dynamic spectrum access. The signaling protocols required to support distributed spectrum access are also reviewed. While dynamic spectrum access and management can be designed by considering only the technical issues, the economic issues are also important, especially under the new spectrum licensing paradigm. Chapters 11 and 12 address the economic aspects of spectrum sharing and management in a cognitive radio network. Chapter 11 introduces the concept of spectrum trading and reviews the different spectrum trading schemes. Through spectrum trading, the licensed users (or primary service provider) are able to sell a portion of the unused spectrum to the unlicensed users (or secondary service provider). The basic economic theories which can be used in dynamic spectrum access are reviewed. Chapter 12 provides an extensive review of economics-inspired dynamic spectrum access and management models. The first two models are based on competitive dynamic spectrum access and pricing. The concept of *collusion* among cognitive radio users in the context of spectrum trading is discussed. A spectrum trading model for IEEE 802.22-based wireless regional area networks (WRANs) is presented.

To use this book, if the reader is familiar with wireless technologies and the concept of cognitive radio, the first chapter can be skipped. Also, if the reader is an experienced

researcher, some of the chapters in Part II can also be skipped. Since each chapter is quite independent, skipping any chapter will not affect following the rest of the book.

The authors would like to acknowledge the research support from Telecommunications Research Laboratory (TRLabs), Winnipeg, Canada, the Natural Sciences and Engineering Research Council (NSERC) of Canada, and Boise State University, Idaho, USA, during the writing of this book.