

Cognitive Radio Networking and Security

With the rapid growth of new wireless devices and applications over the past decade, the demand for wireless radio spectrum is increasing relentlessly. The development of cognitive radio networking provides a framework for making the best possible use of limited spectrum resources, and it is revolutionizing the telecommunications industry.

This book presents the fundamentals of designing, implementing, and deploying cognitive radio communication and networking systems. Uniquely, it focuses on game theory and its applications to various aspects of cognitive networking. It covers in detail the core aspects of cognitive radio, including cooperation, situational awareness, learning, and security mechanisms and strategies. In addition, it provides novel, state-of-the-art concepts and recent results. This is an ideal reference for researchers, students, and professionals in industry who need to learn the applications of game theory to cognitive networking.

K. J. RAY LIU is a Distinguished Scholar-Teacher at the University of Maryland, College Park. He is the recipient of numerous honors and awards including the 2009 IEEE Signal Processing Society Technical Achievement Award, IEEE Signal Processing Society Distinguished Lecturer, National Science Foundation Presidential Young Investigator, and various best-paper awards.

BEIBEI WANG is currently a Senior Systems Engineer with Corporate Research and Development, Qualcomm Incorporated. She received her Ph.D. from the University of Maryland, College Park in 2009. Her research interests include dynamic spectrum allocation and management in cognitive radio systems, cooperative communications, multimedia communications, game theory and learning, and network security.

Cognitive Radio Networking and Security

A Game-Theoretic View

K. J. RAY LIU

University of Maryland, College Park

BEIBEI WANG

Qualcomm Incorporated

Cambridge University Press
978-0-521-76231-1 - Cognitive Radio Networking and Security: A Game-Theoretic View
K. J. Ray Liu and Beibei Wang
Frontmatter
[More information](#)

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore,
São Paulo, Delhi, Dubai, Tokyo, Mexico City

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521762311

© Cambridge University Press 2011

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 2011

Printed in the United Kingdom at the University Press, Cambridge

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

Library of Congress Cataloguing in Publication data

Liu, K. J. Ray, 1961–

Cognitive radio networking and security : a game-theoretic view / K. J. Ray Liu,
Beibei Wang.

p. cm.

ISBN 978-0-521-76231-1 (hardback)

1. Cognitive radio networks. 2. Game theory. 3. Computer networks – Security
measures. 4. Wireless communication systems. I. Wang, Beibei. II. Title.

TK5103.4815.L58 2010

621.384–dc22

2010028035

ISBN 978-0-521-76231-1 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.

Cambridge University Press
978-0-521-76231-1 - Cognitive Radio Networking and Security: A Game-Theoretic View
K. J. Ray Liu and Beibei Wang
Frontmatter
[More information](#)

**In memory of my great-grand mother
Lang-Xiang Liu (Kane Koda), August 4, 1899–April 11, 1992, for
the eternal loving bond transcending generations.
I always miss you. – K. J. Ray Liu**

**To my parents, Liangyuan Wang and Shuqin Huang, for their
unconditional love and support. – Beibei Wang**

Contents

<i>Preface</i>	<i>page xiii</i>
Part I Cognitive radio communications and cooperation	1
1 Introduction to cognitive radios	3
1.1 Introduction	3
1.2 Fundamentals	5
1.3 Spectrum sensing and analysis	9
1.4 Dynamic spectrum allocation and sharing	24
1.5 Cognitive radio platforms	39
2 Game theory for cognitive radio networks	46
2.1 Introduction	46
2.2 Non-cooperative games and Nash equilibrium	49
2.3 Economic games, auction games, and mechanism design	67
2.4 Cooperative games	77
2.5 Stochastic games	83
2.6 Summary	86
3 Markov models for dynamic spectrum allocation	87
3.1 Introduction	87
3.2 The system model	88
3.3 Primary-prioritized Markov models	91
3.4 Primary-prioritized dynamic spectrum access	97
3.5 Simulation results and analysis	102
3.6 Summary and bibliographical notes	109
4 Repeated open spectrum sharing games	111
4.1 Introduction	111
4.2 The system model	112
4.3 Repeated spectrum sharing games	113

viii	Contents	
	4.4 Cooperation with optimal detection	118
	4.5 Cheat-proof strategies	122
	4.6 Simulation results	127
	4.7 Summary and bibliographical notes	132
5	Pricing games for dynamic spectrum allocation	133
	5.1 Introduction	133
	5.2 The system model	134
	5.3 Pricing-game models	135
	5.4 Collusion-resistant dynamic spectrum allocation	139
	5.5 Simulation results	151
	5.6 Summary and bibliographical notes	154
6	A multi-winner cognitive spectrum auction game	155
	6.1 Introduction	155
	6.2 The system model	157
	6.3 One-band multi-winner auctions	160
	6.4 Multi-band multi-winner auctions	168
	6.5 Simulation results	171
	6.6 Summary	176
7	Evolutionary cooperative spectrum sensing games	177
	7.1 Introduction	177
	7.2 The system model and spectrum sensing game	179
	7.3 Evolutionary sensing games and strategy analysis	184
	7.4 Simulation results and analysis	194
	7.5 Summary and bibliographical notes	199
8	Anti-jamming stochastic games	200
	8.1 Introduction	200
	8.2 The system model	202
	8.3 Formulation of the stochastic anti-jamming game	205
	8.4 Solving optimal policies of the stochastic game	211
	8.5 Simulation results	215
	8.6 Summary and bibliographical notes	225
9	Opportunistic multiple access for cognitive networks	226
	9.1 Introduction	226
	9.2 Network and channel models	228
	9.3 Multiple relays for the primary network	231
	9.4 Opportunistic multiple access for secondary nodes	237

Contents	ix
9.5 Summary and bibliographical notes	245
Part II Resource awareness and learning	247
10 Reinforcement learning for energy-aware communications	249
10.1 Introduction	249
10.2 The Markov decision process and dynamic programming	251
10.3 Reinforcement learning	252
10.4 Throughput maximization in point-to-point communication	254
10.5 Multi-node energy-aware optimization	262
10.6 Discussion	266
10.7 Summary and bibliographical notes	268
11 Repeated games and learning for packet forwarding	270
11.1 Introduction	270
11.2 The system model and design challenge	271
11.3 The repeated-game framework and punishment analysis	275
11.4 Self-learning algorithms	285
11.5 Simulation results	290
11.6 Summary and bibliographical notes	296
12 Dynamic pricing games for routing	297
12.1 Introduction	297
12.2 The system model	299
12.3 Pricing game models	302
12.4 Optimal dynamic pricing-based routing	306
12.5 Simulation studies	317
12.6 Summary and bibliographical notes	323
13 Connectivity-aware network lifetime optimization	325
13.1 Introduction	325
13.2 The system model and problem formulation	327
13.3 Facts from spectral graph theory	329
13.4 Keep-connect algorithms	331
13.5 The upper bound on the energy consumption	335
13.6 The distributed implementation and learning algorithm	340
13.7 Simulation results	342
13.8 Summary	349
14 Connectivity-aware network maintenance and repair	350
14.1 Introduction	350

x	Contents	
	14.2 The system model	352
	14.3 Network maintenance	355
	14.4 Lifetime-maximization strategies	357
	14.5 Network repair	360
	14.6 Simulation results	361
	14.7 Summary and bibliographical notes	368
	Part III Securing mechanism and strategies	371
15	Trust modeling and evaluation	373
	15.1 Introduction	373
	15.2 The foundations of trust evaluation	375
	15.3 Attacks and protection	383
	15.4 Trust-management systems in ad hoc networks	388
	15.5 Simulations	391
	15.6 Summary and bibliographical notes	397
16	Defense against routing disruptions	399
	16.1 Introduction and background	399
	16.2 Assumptions and the system model	401
	16.3 Security mechanisms	403
	16.4 Security analysis	408
	16.5 Simulation methodology	410
	16.6 Performance evaluation	412
	16.7 Summary and bibliographical notes	417
17	Defense against traffic-injection attacks	420
	17.1 Introduction	420
	17.2 Traffic-injection attacks	421
	17.3 Defense mechanisms	423
	17.4 Theoretical analysis	428
	17.5 Centralized detection with decentralized implementation	437
	17.6 Simulation studies	439
	17.7 Summary and bibliographical notes	443
18	Stimulation of attack-resistant cooperation	444
	18.1 Introduction	444
	18.2 The system model and problem formulation	445
	18.3 System description	448
	18.4 Analysis under attacks	457
	18.5 Simulation studies	460
	18.6 Summary and bibliographical notes	466

Contents		xi
19	Optimal strategies for stimulation of cooperation	468
	19.1 Introduction	468
	19.2 Optimal strategies in packet-forwarding games	469
	19.3 System description and the game model	477
	19.4 Attack-resistant and cheat-proof cooperation-stimulation strategies	479
	19.5 Strategy analysis under no attacks	483
	19.6 Strategy analysis under attacks	485
	19.7 Discussion	487
	19.8 Simulation studies	489
	19.9 Summary	495
20	Belief evaluation for cooperation enforcement	496
	20.1 Introduction	496
	20.2 The system model and game-theoretic formulation	497
	20.3 Vulnerability analysis	500
	20.4 A belief-evaluation framework	502
	20.5 Simulation studies	512
	20.6 Summary and bibliographical notes	517
21	Defense against insider attacks	519
	21.1 Introduction	519
	21.2 System description and the game model	520
	21.3 Defense strategies with statistical attacker detection	525
	21.4 Optimality analysis	533
	21.5 Performance evaluation	538
	21.6 Summary	544
22	Secure cooperation stimulation under noise and imperfect monitoring	545
	22.1 Introduction	545
	22.2 Design challenges and game description	546
	22.3 Attack-resistant cooperation stimulation	551
	22.4 Game-theoretic analysis and limitations	555
	22.5 Simulation studies	557
	22.6 Discussion	567
	22.7 Summary and bibliographical notes	569
	<i>References</i>	570
	<i>Index</i>	598

Preface

Recent increases in demand for cognitive radio technology have driven researchers and technologists to rethink the implications of the traditional engineering designs and approaches to communications and networking. One issue is that the traditional thinking is that one should try to have more bandwidth, more resources, and more of everything, while we have come to the realization that the problem is not that we do not have enough bandwidth or resources. It is rather that the bandwidth/resource utilization rates in many cases are too low. For example, the TV bandwidth utilization nowadays in the USA is less than 6%, which is quite similar to that in most developed countries. So why continue wanting to obtain more new bandwidth when it is indeed a scarce commodity already? Why not just utilize the wasted resource in a more effective way?

Another reconsideration is that often one can find the optimization tools and solutions employed in engineering problems being too rigid, without offering much flexibility, adaptation, and learning. The super highway is a typical example in that, during traffic hours, one direction is completely jammed with bumper-to-bumper cars, while the other direction has few cars with mostly empty four-lane way. That is almost the case for networking as well. Rigid, inflexible protocols and strategies often leave wasted resources that could otherwise be efficiently utilized by others. It was recognized that traditional communication and networking paradigms have taken little or no situational information into consideration by offering cognitive processing, reasoning, learning, and adaptation. Along the same lines, such awareness also drives us to seek an optimization tool to better enhance cooperation and resolve conflict with learning capability.

In the past decade we have witnessed that the concept of cognitive networking and communications has offered a revolutionary perspective in the design of modern communication infrastructure. By cognitive communications and networking we mean that a communication system is composed of elements that can dynamically adapt themselves to the varying conditions, resources, environments, and users through interacting, learning, and reasoning to evolve and reach better operating points or a better set of system parameters to enhance cooperation and resolve conflict, if any. Those factors can include awareness of channel conditions, energy efficiency, bandwidth availability, locations, spectrum usage, and the connectivity of a network, to name just a few. Such design with awareness of situations, resources, environments, and users forms the core concept of the emerging field of cognitive communications and networking. Many new ideas have thus been inspired and have blossomed.

Cognitive radio, a special case of cognitive networking, has received a lot of attention recently. In contrast to traditional radio, cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment and can adaptively change its operating parameters on the basis of interactions with the environment and users. With cognitive radio technology, future wireless devices are envisioned to be able to sense and analyze their surrounding environment and user conditions, learn from the environmental variations, and adapt their operating parameters to achieve highly reliable communications and efficient utilization of the spectrum resources.

In a cognitive network, nodes are intelligent and have the ability to observe, learn, and act to optimize their performance. Since nodes generally belong to different authorities and pursue different goals, fully cooperative behaviors cannot be taken for granted. Instead, nodes will cooperate with others only when cooperation can improve their own performance. Often nodes with such selfish behaviors are regarded as rational. Therefore, a key problem in cognitive networks is how to stimulate cooperation among selfish nodes. To address the interactions of the dynamics among conditions, resources, environments, and users, game theory has naturally become an important emerging tool that is ideal and essential in studying, modeling, and analyzing the cognitive interaction process. This is especially true because a rational user in a cognitive network often behaves selfishly to maximize his/her own utility or welfare. There is of course no surprise here, since game theory has been a core tool in the study of economics and business/social models, in particular in the understanding of cooperation, interaction, and conflict, via which strategies and mechanisms can be developed to offer flexible and adaptable solutions.

In recent years, it has found a major engineering challenge in the emerging development of cognitive communications and networking. In a certain sense, what is taking place in cognitive communications and networking can be viewed as a kind of information game, where optimal policies, strategies, and protocols are developed from the signals/information obtained by users through interaction, cooperation, or competition of communication/networking devices, rather than economic and financial games being played in human society. Not only can traditional games be leveraged to apply to various networking scenarios, but also new games can be developed, since wireless communication is interference-limited instead of quantity-limited as is the case for most economic models. Therefore we are seeing the new era of information games emerging and unfolding.

This book aims at providing a comprehensive coverage of fundamental issues on cooperation, learning, adaption, and security that should be understood in the design, implementation, and deployment of cognitive communication and networking systems, with a focus on game-theoretical approaches. Most of the material stems from our research over the past decade pursuing the realization of cognitive communications and secure networking. A goal of the book is to provide a bridge between advanced research on the one hand and classroom learning and self-study on the other by offering an emphasis on systematic game-theoretical treatments of cognitive communications and networking. In particular, we partition the book into three parts.

In Part I, we address the issues relating to cognitive radio communications and user cooperation. The users in a cognitive network will be assumed to be rational when cooperating with others, i.e., they behave selfishly in maximizing their own interest. In Chapter 1 we provide an introductory overview and survey of cognitive radio technology and related technical issues, including spectrum sensing, dynamic spectrum sharing and allocation, and cognitive radio platforms and standards, followed by a tutorial on fundamentals of game theory for cognitive networking in Chapter 2. We then focus on each important component of cognitive radio technology with more detailed treatments. Chapter 3 introduces Markov models for efficient dynamic spectrum allocation. Chapter 4 considers repeated open spectrum sharing games with cheat-proof strategies. The concept of pricing games is studied in Chapter 5 for dynamic spectrum allocation. A multi-winner spectrum auction game is presented in Chapter 6 to address the interference-limited situation of wireless communications. An evolutionary cooperative spectrum sensing game is then introduced in Chapter 7 in order for the reader to understand the best strategy for cooperation and its evolution when the situation is changing. It is followed by discussion of a stochastic anti-jamming game to design the optimal adaptive defense strategies against cognitive malicious attackers in Chapter 8. Finally, the issue of opportunistic multiple access for cognitive networks with cooperation of relays is studied in Chapter 9.

In Part II, the focus is on resource awareness and learning. The discussion is extended beyond the narrow definition of a cognitive radio to the general notion of cognitive wireless communications and networking. Various situational awareness and learning scenarios are considered. In Chapter 10, reinforcement learning for energy awareness is discussed. Chapter 11 considers a repeated game framework and learning for cooperation enforcement. Dynamic pricing games for routing are studied in Chapter 12. A graph-theoretical connectivity-aware approach for network lifetime optimization is presented in Chapter 13, followed by the issues relating to graph-theoretic network maintenance and repair in Chapter 14.

Because of the interactions and cooperation in cognitive networks, security becomes a major issue. Therefore Part III is dedicated to the consideration of a securing mechanism and strategies. However, since there is no consensus notion of a security paradigm yet in this arena, there are three main themes in this part: trust modeling and evaluation, defense mechanisms and strategies, and game-theoretical analysis of security. Some users who are attackers are assumed to be malicious, i.e., their goal is to damage the system's performance, instead of maximizing their own interest. Since security in centralized systems is less of an issue, most of the chapters are formulated in terms of distributed ad hoc networking. First information-theoretical trust models and an evaluation framework are presented in Chapter 15 for network security, followed by some defenses against a series of attacks such as routing disruption attacks in Chapter 16 and injecting traffic attacks in Chapter 17. Attack-resistant mechanisms and optimal strategies for cooperation stimulation are considered in Chapters 18 and 19, respectively. Finally, statistical securing approaches for cooperation stimulation and enforcement under noise and imperfect monitoring situations are presented in the next three chapters, with Chapter 20 focusing on belief evaluation and vulnerability analysis,

Chapter 21 on defense against insider attacks, and Chapter 22 on secure cooperation stimulation.

This book is intended to be a textbook or a reference book for graduate-level courses on wireless communications and networking that cover cognitive radios, game theory, and/or security. We hope that the comprehensive coverage of cognitive communications, networking, and security with a holistic treatment from the view of information games will make this book a useful resource for readers who want to understand this emerging technology, as well as for those who are conducting research and development in this field.

This book could not have been made possible without the research contributions by the following people: Charles Clancy, Amr El-Sherif, Zhu Han, Ahmed Ibrahim, Zhu Ji, Charles Pandana, Karim Seddik, Yan Sun, Yongle Wu, and Wei Yu. We also would like to thank all the colleagues whose work enlightening our thoughts and research made this book possible. We can only stand on the shoulders of giants.

K. J. Ray Liu
Beibei Wang