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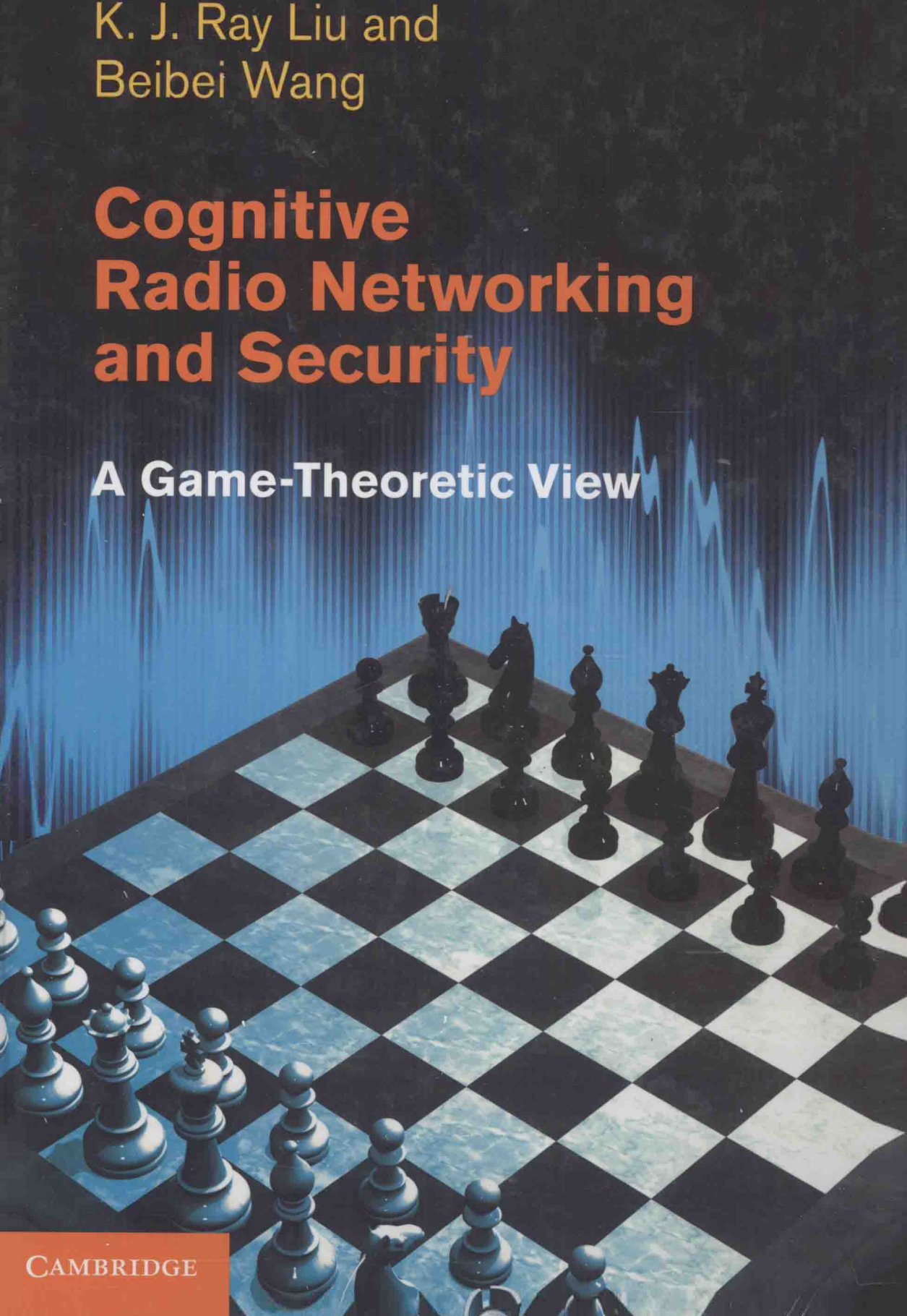
A Game-Theoretic View



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A Game-Theoretic View

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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.

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

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

Contents

Part I

Cognitive radio communications and cooperation

1 Introduction to cognitive radios

With the rapid deployment of new wireless devices and applications, the last decade has witnessed a growing demand for wireless radio spectrum. However, the policy of fixed spectrum assignment produces a bottleneck for more efficient spectrum utilization, such that a great portion of the licensed spectrum is severely under-utilized. The inefficient usage of the limited spectrum resources has motivated the regulatory bodies to review their policy and start to seek innovative communication technology that can exploit the wireless spectrum in a more intelligent and flexible way. The concept of cognitive radio was proposed to address the issue of spectrum efficiency and has been receiving increasing attention in recent years, since it equips wireless users with the capability to optimally adapt their operating parameters according to the interactions with the surrounding radio environment. There have been many significant developments in the past few years concerning cognitive radios. In this chapter, the fundamentals of cognitive radio technology, including the architecture of a cognitive radio network and its applications, are introduced. The existing works on spectrum sensing are reviewed, and important issues in dynamic spectrum allocation and sharing are discussed in detail. Finally, an overview on implementation of cognitive radio platforms and standards for cognitive radio technology is provided.

1.1 Introduction

The usage of radio spectrum resources and the regulation of radio emissions are coordinated by national regulatory bodies such as the Federal Communications Commission (FCC). The FCC assigns spectrum to licensed holders, also known as *primary users*, on a long-term basis for large geographical regions. However, a large portion of the assigned spectrum remains under-utilized as illustrated in Figure 1.1 [114]. The inefficient usage of the limited spectrum necessitates the development of dynamic spectrum access techniques, where users who have no spectrum licenses, also known as *secondary users*, are allowed to use the temporarily unused licensed spectrum. In recent years, the FCC has been considering more flexible and comprehensive uses of the available spectrum [116], through the use of *cognitive radio* technology [284].

Cognitive radio is the key enabling technology that enables next-generation (xG) communication networks, also known as dynamic spectrum access (DSA) networks, to utilize the spectrum more efficiently in an opportunistic fashion without interfering