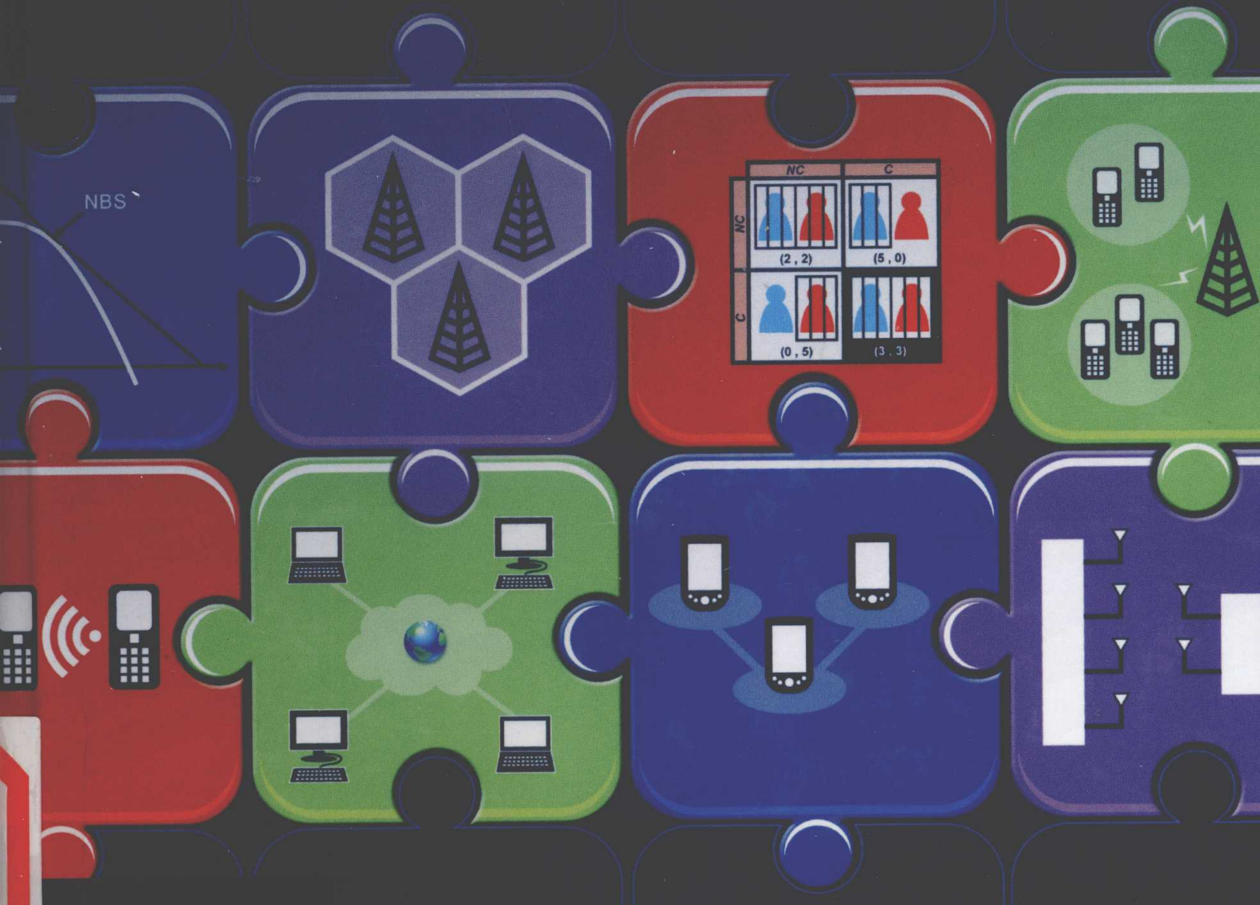
Game Theory

in Wireless and Communication Networks

Theory, Models, and Applications

Zhu Han, Dusit Niyato, Walid Saad,
Tamer Başar, and Are Hjørungnes



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Game Theory in Wireless and Communication Networks

This unified treatment of game theory focuses on finding state-of-the-art solutions to issues surrounding the next generation of wireless and communication networks. Future networks will rely on autonomous and distributed architectures to improve the efficiency and flexibility of mobile applications, and game theory provides the ideal framework for designing efficient and robust distributed algorithms. This book enables readers to develop a solid understanding of game theory, its applications, and its use as an effective tool for addressing various problems in wireless communication and networking.

The key results and tools of game theory are covered, as are various real-world technologies including 3G/4G networks, wireless LANs, sensor networks, cognitive networks, and Internet networks. The book also covers a wide range of techniques for modeling, designing, and analyzing communication networks using game theory, as well as state-of-the-art distributed design techniques. This is an ideal resource for communications engineers, researchers, and graduate and undergraduate students.

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Are Hjørungnes was a Professor in the Faculty of Mathematics and Natural Sciences at the University of Oslo, Norway. He was a Senior Member of the IEEE and received his Ph.D. from the Norwegian University of Science and Technology in 2000.

While on a sabbatical at the University of Hawaii, our colleague and co-author, Dr. Are Hjørungnes, went missing and passed away during a mountain run on the island of Oahu. Words fail to express our sadness and sorrow in losing our dear friend. Are, you will remain forever engraved in our hearts and memories, as the Viking who was stronger than life itself. We will always remember your openness, great spirit, and technical brilliance. We would like to dedicate this book to you, as your efforts and perseverance were instrumental in the completion of this work.

May your soul rest in peace.
ZH, DN, WS, TB

To my daughter, Melody Han — Zhu Han
To my family — Dusit Niyato
To my wife Mary and my son Karim — Walid Saad
To my wife, Tangül — Tamer Başar
To my grandmother, Margit — Are Hjørungnes

Preface

With the recent advances in telecommunications technologies, wireless networking has become ubiquitous because of the great demand created by pervasive mobile applications. The convergence of computing, communications, and media will allow users to communicate with each other and access any content at any time and at any place. Future wireless networks are envisioned to support various services such as high-speed access, telecommuting, interactive media, video conferencing, real-time Internet games, e-business ecosystems, smart homes, automated highways, and disaster relief. Yet many technical challenges remain to be addressed in order to make this wireless vision a reality. A critical issue is devising *distributed* and *dynamic* algorithms for ensuring a robust network operation in time-varying and heterogeneous environments. Therefore, in order to support tomorrow's wireless services, it is essential to develop efficient mechanisms that provide an optimal cost-resource-performance tradeoff and that constitute the basis for next-generation ubiquitous and autonomic wireless networks.

Game theory is a formal framework with a set of mathematical tools to study the complex interactions among interdependent rational players. For more than half a century, game theory has led to revolutionary changes in economics, and it has found a number of important applications in politics, sociology, psychology, communication, control, computing, and transportation, to list only a few. During the past decade, there has been a surge in research activities that employ game theory to model and analyze modern communication systems. This is mainly due to (i) the emergence of the Internet as a global platform for computation and communication, which has sparked the development of large-scale, distributed, and heterogeneous communication systems; (ii) the deregulation of the telecommunications industry, and the dramatic improvement in computation power, which has made it possible for various network entities to make independent and selfish decisions; and (iii) the need for robust designs against uncertainties, e.g., in security situations that can sometimes be modeled as games of users with malicious intent.

Consequently, combining game theory with the design of efficient distributed algorithms for wireless networks is desirable but at the same time challenging. On the one hand, wireless network users are generally selfish in nature. For instance, distributed mobile users tend to maximize their own performance, regardless of how this maximization affects the other users in the network, subsequently giving rise to competitive scenarios. On the other hand, in some scenarios, cooperation is required among wireless network users for performance enhancement. These situations recently motivated researchers and engineers to adopt game-theoretic techniques for characterizing competition and cooperation in wireless networks. As a result, game theory has been applied to solve many problems in wireless systems, e.g., those that arise in power control, network formation, admission control, cognitive radio, and traffic relaying. In fact, game theory provides solid mathematical tools for analyzing competition and cooperation in an ensemble of multiple players having individual self-interests. Various solution concepts from game theory are highly appropriate for communications and networking problems, such as equilibrium solutions that are desirable in competitive scenarios, since they lead to designs that are robust to the deviations made by any player. There are many popular wireless and communications applications that have recently explored game-theoretic techniques, including, but not limited to, cognitive radio, heterogeneous wireless networks, cellular networks, cooperative networks, and multi-hop networks. It is now commonly acknowledged that within the rich landscape of game theory, new aspects of network design (e.g., with cooperative and non-cooperative behaviors of the wireless entities) can be investigated using appropriate solution concepts.

Although game theory has been applied to wireless communications and networking for many years, there are only a few books that allow researchers, engineers, and graduate/undergraduate students to study game theory from an engineering perspective. On the one hand, most of the existing game theory books focus on the mathematical and economical aspects, which are considerably different from the engineering (and particularly the application-oriented) perspective. On the other hand, the wireless communications and networking books focus mainly on system optimization or control techniques while overlooking distributed algorithms. In addition, the cooperative and non-cooperative behaviors of the network entities (e.g., users or service providers) cannot be modeled and analyzed effectively using the techniques presented in these books. Therefore, there is a need to develop a comprehensive and useful reference source that can provide complete coverage on how to adequately apply game theory to the design of wireless communications and networking.

In this regard, this book not only focuses on the description of the main aspects of game theory in the context of wireless communications, but also provides an extensive review of the applications of game theory in wireless communications and networking problems. In a nutshell, it provides a comprehensive treatment of game theory in wireless communications and networking. The topics range from the basic concepts of game theory to the state of the art of analysis, design, and optimization of game-theoretic techniques for wireless and communication networks. The three main objectives of this book are as follows:

- This book introduces the basics of game theory from an engineering perspective. In particular, the basics of game theory are explained and discussed in the context of wireless communications and networking. For example, the book provides a clear description of the main game-theoretic entities in a communication environment (e.g., the players, their strategies, utilities and payoffs, and the physical meaning, in a wireless network environment, of the different game-theoretic concepts such as equilibria).
- This book provides an extensive review/survey of the applications of game theory to wireless communications and networking. With this review/survey of applications,

readers can understand how game theory can be applied in different wireless systems and can acquire an in-depth knowledge of the recent developments in this area. In this context, this book presents tutorial-like chapters that explain, clearly and concisely, how game-theoretic techniques can be applied to solving state-of-the-art wireless communications problems. In particular, the benefits of using game theory in wireless communications environments are emphasized. The target audience of this book are researchers, engineers, and undergraduate and graduate students who are looking for a self-contained book from which to learn game theory and its application to multi-player decision-making problems in wireless and other engineering systems.

- Most of the research in this field has been focused on applying standard game-theoretic models and techniques to several limited topics, such as power control in wireless networks and routing in wire-line networks. However, game theory is a very powerful tool and can help us better understand many other aspects of communication networks. The goals of this book are to provide the fundamental concepts of game theory and also to bring together the state-of-the-art research contributions that address the major opportunities and challenges of applying game theory in wireless engineering problems. The applications presented here are varied and cover a significant part of the most recent challenges and problems in wireless communications and networking systems. In this respect, we believe that this book will be useful to a variety of readers from the wireless communications and networking fields. The material from this book can be used to design and develop more efficient, scalable, and robust communication protocols.

To summarize, the key features of this book are

- a unified view of game-theoretic approaches to wireless networks
- comprehensive treatment of state-of-the-art distributed techniques for wireless communications problems
- coverage of a wide range of techniques for modeling, designing, and analyzing of wireless networks using game theory
- an outline of the key research issues related to wireless applications of game theory.

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1 Introduction

1.1 Brief introduction to the history of game theory

Game theory can be viewed as a branch of applied mathematics as well as of applied sciences. It has been used in the social sciences, most notably in economics, but has also penetrated into a variety of other disciplines such as political science, biology, computer science, philosophy, and, recently, wireless and communication networks. Even though game theory is a relatively young discipline, the ideas underlying it have appeared in various forms throughout history and in numerous sources, including the Bible, the Talmud, the works of Descartes and Sun Tzu, and the writings of Charles Darwin, and in the 1802 work *Considérations sur la Théorie Mathématique du Jeu* of André-Marie Ampère, who was influenced by the 1777 *Essai d'Arithmétique Morale* of Georges Louis Buffon. Nonetheless, the main basis of modern-day game theory can be considered an outgrowth of three seminal works:

- Augustin Cournot's *Mathematical Principles of the Theory of Wealth* in 1838, which gives an intuitive explanation of what would, over a century later, be formalized as the celebrated Nash equilibrium solution to non-cooperative games. Furthermore, Cournot's work provides an evolutionary or dynamic notion of the idea of a "best response," i.e., situations in which a player chooses the best action given the actions of other players, this being so for all players.
- Francis Ysidro Edgeworth's *Mathematical Physics* (1881), which demonstrated the notion of competitive equilibria in a two-person (as well as two-type) economy, and Emile Borel's *Algebre et Calcul des Probabilites* (*Comptes Rendus Academie des Sciences*, volume 184, 1927), which provided the first insight into mixed strategies, i.e., that randomization may support a stable outcome.
- While many other contributors hold places in the history of game theory, it is widely accepted that modern analysis started with John von Neumann and Oskar Morgenstern's 1944 book, *Theory of Games and Economic Behavior*, and was given its modern methodological framework by John Nash's seminal work on non-cooperative games and bargaining, which had von Neumann and Morgenstern's results as a first building block. It is worth mentioning that some two decades prior to this, in 1928, John von Neumann himself had resolved completely an open fundamental problem in zero-sum games, that *every finite two-player zero-sum game admits a saddle point in mixed strategies*, which is known as the *Minimax Theorem* [492]—a result which Emile Borel had conjectured to be false eight years earlier.