1 Introduction

1.1 Overview and Motivation

With the advancement of telecommunication technologies, wireless networking has become ubiquitous owing to the great demand for pervasive mobile applications. The convergence of computing, communications, and media will allow users to communicate with each other and access any content at anytime, anywhere. The future, beyond 5G wireless networks, will support various services such as high-speed access, augmented reality, smart transportation, video conferencing, real-time Internet games, Internet of Things services, smart homes, automated highways, and disaster relief. However, many technical challenges remain to be addressed to make this wireless vision a reality. One prominent issue is devising distributed, self-organizing, and dynamic algorithms for optimizing the performance of the network over time-varying channels and within dense and heterogeneous environments. Examples of such environments in future wireless networks are abundant and they range from dense deployments of small cell networks to massive Internet of Things systems. Therefore, 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 self-organizing wireless networks.

Game theory provides a formal framework with a set of mathematical tools to study the complex interactions among interdependent rational players. For more than a half century, it has led to revolutionary developments in economics and has found important applications in a multitude of disciplines, such as politics, sociology, psychology, and transportation. More recently, there has been a surge in research activities that employ game theory to model and analyze wireless communication systems. Combining game theory with the design of efficient distributed algorithms for emerging wireless networks is desirable and challenging. On the one hand, in a large-scale wireless network, devices will be inherently selfish as they seek to optimize individual quality-of-service (QoS) metrics. For instance, distributed mobile devices tend to maximize their own performance, regardless of how this maximization affects the other users in the network, subsequently giving rise to competing scenarios. Such interdependence and selfishness become more pronounced in large-scale and dense systems such as the Internet of Things or small cell networks. On the other hand, in many practical networking 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. Recently, game theory has been applied to solve many problems in wireless systems, such as power control, resource management, network formation, admission control, and traffic relaying. Game theory provides solid mathematical tools for analyzing competition and cooperation situations between multiple players having individual self-interests that are also coupled across the system. Various solution concepts from game theory provide adequate solutions for communication and networking problems, such as equilibrium solutions that are desirable in competition scenarios because they allow designs that are robust to the deviations by any player. There are many popular wireless and communications applications that have recently explored game-theoretical techniques, including 5G networks, network virtualization, software defined networks, cloud computing, data center, Internet of Things, context-aware networks, green communication, and security-related issues. It has been shown that by using game-theoretical tools, new network design features and properties (e.g., with cooperative and noncooperative behaviors of the wireless entities) can be properly investigated with accurate solution concepts.

Existing game theory books mostly focus on standard game-theoretic constructs, such as static noncooperative games, and as such, they cannot cope with recent networking paradigms such as the Internet of Things or large-scale 5G systems. Therefore, there is a need to develop a comprehensive and useful reference work that can provide a comprehensive treatment of how to adequately apply game theory to the design of wireless communications and networking. The first book, Zhu Han, Dusit Niyato, Walid Saad, Tamer Başar, and Are Hjørungnes, *Game Theory in Wireless and Communication Networks: Theory, Models and Applications*, Cambridge University Press, UK, was published in 2011, which was very well received in both academia and industry.

Since the publication of this first book, there has been significant progress in both game-theoretic approaches and networking applications. In this regard, we have decided to write this second book to cover new advances pertaining to the application of game theory in the context of communications and networking. The book also covers the unprecedented changes in the wireless and communications landscape that have occurred since 2011. The topics range from new concepts from game theory to the state-of-the-art of analysis, design, and optimization of dynamic game-theoretic techniques for wireless networks. The main objectives of this book are as follows:

1. The book introduces new frameworks and tools from game theory while providing an engineering perspective. In particular, we include seven chapters that cover a diversity of new game-theoretic tools that were not covered in our earlier 2011 book. In particular, we provide a clear description of the main game-theoretic entities in a wireless communications environment with a focus on recent and emerging applications (e.g., what are the players, their strategies, utilities, and payoffs, and what is the physical meaning, in a wireless network environment, of different game-theoretic concepts such as equilibria).
2. The book provides an extensive overview of the very recent applications of game theory to wireless communications and networking. Using this overview

of applications, readers can easily understand how game theory can be applied to different wireless systems as well as acquire an in-depth knowledge of the recent developments in this area. In this context, the book provides tutorial-like chapters that explain, clearly and concisely, how game-theoretical techniques can be applied to solving state-of-the-art wireless communication problems. In particular, we study different new scenarios, such as 5G networks, network virtualization, software defined networks, cloud computing, data centers, Internet of Things, context-aware networks, green communication, and security-related issues. The target audiences for this book are the researchers, engineers, undergraduate, and graduate students who are looking for a source to learn game theory from and apply it to solve various multiplayer decision-making problems that arise in wireless and other engineering systems.

We believe that this follow-up book will be useful to a broad spectrum of readers, particularly from the wireless communications and networking field. The material from the book can be used to design and develop more efficient, scalable, and robust communication protocols.

To summarize, the key features of this book are

1. An extensive overview on the recent advances in game theory, that have occurred in the recent past.
2. A unified view of novel game-theoretical approaches for wireless networks
3. Comprehensive treatment of state-of-the-art distributed techniques for today's wireless communication problems
4. Coverage of a wide range of techniques for modeling, design, and analysis of wireless networks using game theory
5. Identifying the key research issues related to wireless game theory applications

1.2 Intended Book Audience

Given the incessantly increasing popularity of game theory in the wireless communications and networking research community, reference works that provide a comprehensive introduction to the analytical aspects and the applications of game theory are needed. Notably, engineers and researchers in the wireless communication community seek a reference that can integrate the notions from game theory and wireless engineering, while emphasizing how game theory can be applied in wireless networks from an engineering perspective. The primary audience for this book will comprise

1. Communications engineers interested in studying the new tools of distributed optimization and management in wireless networking systems
2. Researchers interested in the state-of-the-art research on distributed algorithm design, cooperation, and networking for a wide range of wireless communication applications

3. Graduate and undergraduate students interested in acquiring comprehensive information on the design and evaluation of game-theoretical approaches to find suitable topics for their dissertations

1.3 Organization

The design, analysis, and optimization of distributed wireless networks require multidisciplinary knowledge, namely, knowledge of wireless communication and networking, signal processing, artificial intelligence, decision theory, optimization, game theory, and economics. Therefore, a book covering the basic concepts/theories for designing dynamic spectrum access methods, the state-of-the-art of technologies, and the related information will be very useful in designing future wireless communication systems and services. These are the primary motivations for writing this book.

Accordingly, there are two main objectives for writing this book. The first objective is to introduce novel game-theoretic techniques and their applications for designing distributed and efficient solutions for a number of diverse wireless communication and networking problems. The second objective is to present the state-of-the-art game-theoretic schemes in networking. This includes classifications of different schemes and the technical details for each scheme. To achieve the preceding objectives, the book will comprise two parts, as described next:

Part I: Theory

Before discussing how to apply game theory to different wireless network problems, the choice of a design technique is crucial and must be emphasized. In this context, this part presents different new game-theoretic techniques, which can be applied to the design, analysis, and optimization of wireless networks.

Chapter 2. Matching Games: The goal of Chapter 2 is to demonstrate the effectiveness of matching theory, a powerful game-theoretic and operational research framework, for solving a wide range of wireless resource allocation problems in a distributed manner. Matching theory, as a Nobel Prize-winning framework, has already been widely used in many economic applications. More recently, matching theory has been shown to have a promising potential for modeling and analyzing wireless resource allocation problems due to following reasons: (1) it offers suitable models that can inherently capture many features of various wireless communication problems; (2) it has the ability to use notions, such as preference relations, to model complex system requirements; (3) it provides low-complexity and near-optimal matching algorithms while guaranteeing system stability. Specifically, in this chapter, an overview of basic concepts, classifications, and models of matching theory is provided. Furthermore, comparisons with existing centralized/distributive mathematical solutions of resource allocation problems in wireless networks are conducted.

Chapter 3. Contract Theory: The aim of Chapter 3 is to introduce the framework of contract theory as an effective approach for designing incentive mechanisms for a wide range of application scenarios in wireless networks. In contract theory, participants are offered properly designed rewards based on their performances to encourage better participation. Particularly, contract theory is an efficient tool in dealing with asymmetric information between employer/seller(s) and employee/buyer(s). In wireless networks, the employer/seller(s) and employee/buyer(s) can take on different roles depending on the scenario under consideration. Thus, there is a great potential to utilize the ideas, methods, and models of contract theory to design efficient wireless network mechanisms. An overview of basic concepts, classifications, and models of contract theory is provided. Furthermore, comparisons with existing methods of economics in wireless networks are conducted.

Chapter 4. Stochastic Games: Stochastic games are games in which the decisions and outcomes of the game are governed by uncertainty in the environment. In our first book (2011), we provided only a very brief overview on stochastic games. In Chapter 4, we expand substantially on this discussion and delve into the details of various types of dynamic, stochastic games that include basic stochastic games as well as more advanced constructs such as mean-field games, which enables the analysis of massive networks with an infinite number of players.

Chapter 5. Games with Bounded Rationality: Most existing game-theoretic techniques, such as those covered in our first book, typically focus on players that are completely rational. In other words, players always conform to the rules of the game and are not influenced by real-world behavioral considerations or computational/cognitive limitations. However, there has been a sizeable recent literature that revisits game-theoretic solutions while relaxing the rationality assumption and assuming that players may not conform to prescribed game rules due to irrational behavior, their limited cognitive or computational capabilities, or other environmental factors. The study of such situations is typically carried out using games with bounded rationality. In Chapter 5, we cover the main tenets of game theory with bounded rationality, with a focus on the Nobel Prize-winning framework of prospect theory.

Chapter 6. Learning in Games: Learning (in the context of games) refers to the process that game-theoretic decision makers can use to interact and reach the sought equilibria, in a distributed manner. The main goal of learning in games is to study the behavior of the players and to understand when, or whether, play might converge to equilibrium. In Chapter 6, we cover a broad range of learning algorithms that range from simple best response dynamics and fictitious play to more advanced reinforcement learning and neural network approaches.

Chapter 7. Equilibrium Programming with Equilibrium Constraints: An equilibrium problem with equilibrium constraints (EPEC) is a new class of mathematical programs that often arise in engineering and economics applications. In our 2011 book, the well-known Stackelberg game (single-leader-multi-follower game) was formulated as an optimization problem called a mathematical program with equilibrium constraints (MPEC), in which followers' optimal strategies are solutions of complementarity problems or variational inequality problems based on the leader's strategies. In Chapter 7, we study how to utilize the existing results for formulating a variety of networking problems.

Chapter 8. Miscellaneous Games: Beyond the previously mentioned new types of game theory approaches, there are other, miscellaneous types of games. In Chapter 8, we briefly overview some special types of games such as zero-determinant games and social choice theory.

Part II: Applications

This part of the book deals with the modeling, design, and analysis of game-theoretical schemes in communication and networking applications. Different game models that were applied to solve a broad range of major problems in wireless and communication networks are discussed. Moreover, in this part, major research issues and challenges are also identified. This second part is comprised of seven chapters, whose descriptions follow.

Chapter 9. Applications of Game Theory in the Internet of Things: The Internet of Things (IoT) is an emerging concept and paradigm that allows a number of devices to be connected through the Internet. IoT has a great potential for improving resource efficiency and utilization, increasing revenue and profit, and enhancing service quality of many applications including logistics, manufacturing, transportation, and healthcare. The devices or objects can be sensors to collect sensing data. The sensing data will be transferred for storage or processing to support IoT applications and services. IoT is designed by integrating several technologies including sensor networks, wired/wireless communications and networking, and data center and cloud computing to meet business needs and user requirements. Additionally, multiple parties and entities are involved in IoT systems. In Chapter 9, game theory is used to address various IoT resource management issues such as sensing task allocation, sensing service pricing, QoS provisioning for IoT wireless communication, congestion control, and crowd-sensing incentive mechanisms.

Chapter 10. Applications of Game Theory in Network Virtualization: Network virtualization and software defined networks (SDNs) are emerging approaches to improve network service quality, efficiency, reliability, and security. In SDNs, network functions are separated into control plane and data plane. Therefore, the controller can dynamically adjust network operations according to the system environments and user requirements. Additionally, the concept of network virtualization allows network resources to be virtualized and used adaptively. In Chapter 10, game theory has been applied to address various issues, especially bandwidth allocation, optimal routing, and pricing of the virtualized resources. Moreover, wireless network virtualization and wireless SDNs are introduced. Several novel game-theoretic approaches are developed to analyze competition in wireless systems with virtualization and SDN capabilities.

Chapter 11. Applications of Game Theory in Cloud Networking: Cloud Networking considers the network beyond the data centers with the aim of providing both on-demand computing and network resources. With cloud networking, resources and services can be provisioned from interconnecting distributed data centers owned by one or multiple providers, called cloud data center networking. The cloud resources and services can also be integrated with mobile networks, i.e., mobile cloud networking. Moreover, edge computing models are deployed in cloud networking to bring the cloud resources and services close to users, and thus minimize overall costs, jitter, latencies, and network load. In Chapter 11, game theory has been used to optimize pricing strategies of cloud providers, bandwidth and task allocation in cloud data center networking, mobile cloud computing, edge computing, and cloud-based multimedia services.

Chapter 12. Applications of Game Theory in Context-Aware Networks and Mobile Services: Context-aware Networks are networks that are able to acquire and utilize context information extracted from mobile devices and mobile users to improve data transfer performance and mobile service satisfaction. User context information such as type of applications can be used along with location information. Context information can be obtained more easily from a smartphone that is equipped with numerous sensors, e.g., accelerometers, video, and camera. A major application of context-aware networks is mobile social networks in which mobile users utilize social tie information to help information dissemination. Moreover, context-aware networks allow the customization of mobile services to suit the need and requirements of distinct users, increasing the network utility and resource utilization. In Chapter 12, game theory is used to address, for example, competitive resource allocation issues for quality-of-experience (QoE) support, resource allocation of small cell networks taking social metrics into account, and social learning for community detection.

Chapter 13. Applications of Game Theory for Green Communication Networks: Green Communications pertains to the design of wireless communication systems that are energy efficient. It has been estimated that worldwide telecommunication networks account for close to 1000 Terawatt-hours of electricity annually only for the network infrastructure, and thus energy management is one of the significant costs for network operators. Energy challenges become more crucial for mobile devices whose battery energy supply is very limited. In Chapter 13, a number of approaches have been proposed to reduce the energy consumption of the network infrastructure and mobile devices, many of which are related to transmission control. While optimization is a typical approach for minimizing energy consumption of wired and wireless networks, due to the presence of multiple decision makers, game-theoretic approaches are also apropos. For example, noncooperative games can provide a suitable framework to study energy-efficient interference management problems. Meanwhile, cooperative base station approaches whose goal is to minimize the energy consumption at the wireless infrastructure level can also be studied using game theory. Moreover, game-theoretic frameworks are also suitable to study energy harvesting scenarios in which base stations or devices use alternate forms of renewable energy to power their systems.

Chapter 14. 4G, 5G, and Beyond: Modern wireless cellular networks have witnessed an unprecedented evolution from classical, centralized, and homogenous architectures to a mix of heterogeneous technologies, in which the network devices are densely and randomly deployed in a decentralized architecture. This shift in network architecture requires network devices to become more autonomous, which causes noncooperative behaviors. To cooperate with one another, the need for smart and autonomic network designs has become a central research issue in a variety of applications and scenarios. In Chapter 14, we include examples such as next-generation heterogeneous dense cell networks, LTE-Unlicensed networks or device-to-device communication networks, in which the mobile devices must be able to interact, co-exist, meet stringent QoS requirements, and self-adapt to uncertainties and time-varying environments. Incorporating self-organizing capabilities in heterogeneous wireless systems motivates the development of innovative analytical techniques, such as game theory, which is expected to play a critical role toward deploying intelligent, distributed, and flexible networked systems in which devices can make independent and rational strategic decisions, smartly adapting to their environment.

Chapter 15. Security: Security is one of the major challenges of tomorrow's wireless networks. Given the adversarial nature of security scenarios, it is natural to model security problems using game theory. In Chapter 15, we study a number of emerging security problems for future wireless networks. First, we analyze the problem of security for cyber-physical drone delivery systems, while focusing on games with bounded rationality. Then, we analyze the emerging paradigm of moving target defense in wireless networks, using stochastic games. We conclude the discussion on security with an overview on how contract theory can be used for critical infrastructure protection.

In a nutshell, this book constitutes a complete and comprehensive reference on a plethora of advanced game-theoretic frameworks and their applications in wireless communications and networking. Furthermore, with the aforementioned structure of the book, which separates theory from applications, the material in the book will be easy to follow and understand.