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.

Following the publication of von Neumann and Morgenstern's book, and the seminal work of John Nash, game theory has enjoyed over 65 years of scientific development, and has experienced incessant growth in both the number of theoretical results and the scope and variety of applications. As a recognition of the vitality of the field, a total of three Nobel Prizes have been given in the economic sciences for work primarily in game theory, with the first such recognition given in 1994 to John Harsanyi, John Nash, and Reinhard Selten "for their pioneering analysis of equilibria in the theory of non-cooperative games." The second Nobel Prize went to Robert Aumann and Thomas Schelling in 2005, "for having enhanced our understanding of conflict and cooperation through game-theory analysis." And the most recent one was in 2007, recognizing Leonid Hurwicz, Eric Maskin, and Roger Myerson, "for having laid the foundations of mechanism design theory." We should add to this list of highest-level awards in game theory the Crafoord Prize (the highest prize in the biological sciences), which went to John Maynard Smith (along with Ernst Mayr and G. Williams) in 1991 "for developing the concept of evolutionary biology;" Smith's recognized contributions had a strong game-theoretic underpinning, through his work on evolutionary games and evolutionarily stable equilibrium.

One classical example of game theory is the so-called "Prisoner's Dilemma." This game captures a scenario in which a conflict of interest arises because of the requirement of independent decision-making. The Prisoner's Dilemma pertains to analyzing the decision-making process in the following hypothetical setting. Two criminals are arrested after being suspected of a crime in unison, but the police do not have enough evidence to convict either. Thus, the police separate the two and offer them a deal: if one testifies against the other, he will get a reduced sentence or go free. Here, the prisoners do not have information about each other's "moves," as they would in some social games such as chess. The payoff if they both say nothing (and thus cooperate with each other) is somewhat favorable, since neither can be convicted of the real crime without further proof (though they will be convicted of a lesser crime). If one of them betrays and the other one does not, then the betrayer benefits because he goes free while the other one is imprisoned, since there is now sufficient evidence to convict the silent one. If they both confess, they both get reduced sentences, which can be viewed as a null result. The obvious dilemma is the choice between two options, where a favorable decision, acceptable to both, cannot be made without cooperation.

A representative Prisoner's Dilemma is depicted in Table 1.1. One player acts as the row player and the other the column player, and both have the action options of cooperating (C) or defecting (D). Thus, there are four possible outcomes to the game: $\{(C,C),(D,D),(C,D),(D,C)\}$. Under mutual cooperation, $\{(C,C)\}$, both players will receive a reward payoff of 3. Under mutual defection, $\{(D,D)\}$, both players receive the punishment of defection, 1. When one player cooperates while the other one defects, $\{(C,D),(D,C)\}$, the cooperating player receives a payoff of, 0, and the defecting player receives the temptation to defect, 5.

In The Prisoner's Dilemma example, if one player cooperates, the other player will have a better payoff (5 instead of 3) if he or she defects; if one player defects, the other player will still have a better payoff (1 instead of 0) if he or she also defects. Regardless of the other player's strategy, a player in The Prisoner's Dilemma has an incentive to

Table 1.1 Prisoner's Dilemma.

	Cooperate	Defect
Cooperate	(3,3)	(0,5)
Defect	(5,0)	(1,1)

always select defection, and $\{(D, D)\}$ is an equilibrium. Although cooperation will give each player a better payoff of 3, greediness and lack of trust leads to an inefficient outcome. This simple example shows how the game-theoretic concept of an equilibrium can provide a lot of insight into the outcome of decision-making in an adversarial or conflicting situation.

1.2 Game theory in wireless and communication networks

Recent advances in technology and the ever-growing need for pervasive computing and communication have led to an incessant need for novel analytical frameworks that can be suited to tackle the numerous technical challenges accompanying current and future wireless and communication networks. As a result, in recent years game theory has emerged as a central tool for the design of future wireless and communication networks. This is mainly due to the need for incorporating decision-making rules and techniques into next-generation wireless and communication nodes, to enable them to operate efficiently and meet the users' needs in terms of communication services (e.g., video streaming over mobile networks, ubiquitous Internet access, simultaneous use of multiple technologies, peer-to-peer file sharing, etc.).

One of the most popular examples of game theory in wireless networks pertains to modeling the problem of power control in cellular networks using non-cooperative games. For example, in the uplink of a cellular system, researchers and engineers have been concerned with the problem of designing a mechanism that allows the users (utilizing a common frequency such as in a CDMA system) to regulate their transmit power, given the interference that they cause (or that is caused by the other users) in the network. In doing so, wireless researchers were able to draw a striking similarity between the problems of power control and non-cooperative game theory. In a non-cooperative game, a number of players are involved in a competitive situation in which, whenever a player makes a move (or chooses a strategy), this move has an impact (positive or negative) on the utility (e.g., a measure of benefit or gain) of the other players. Similarly, in a power control game, we have a competitive situation in which the transmit power level (strategy) of a wireless user can impact positively or negatively (because of interference) on the transmission rate and quality of service (QoS) of the other users. As a result, solving a power control game has been shown to be equivalent to solving a non-cooperative game, e.g., by finding a Nash equilibrium. Power control is only one example in which game theory can be used to design next-generation wireless and communication networks. In fact, following the early work on non-cooperative games in power control, a plethora of

novel application areas for game theory have emerged in the wireless, communications, and signal processing communities.

The key challenge in applying game theory in a communications context lies in the fact that game theory was essentially developed as a tool to be used in economics and the social sciences. Hence, leveraging game theory for use in engineering applications is accompanied by many difficulties. For instance, researchers interested in applying game-theoretic models to problems in wireless and communication networks face many hurdles in finding accurate models and solutions. This is due to the fact that existing game-theoretic models are not tailored to cope with engineering-specific issues such as modeling time-varying wireless channels, developing performance functions (i.e., utilities) that depend on restrictive communication metrics (e.g., transmission rate, queueing delay, signal-to-noise ratio), and conforming to certain standards (e.g., IEEE 802.16, LTE). This has necessitated a timely, comprehensive reference source that can guide researchers and communications engineers in their quest to find effective analytical models from game theory that can be applied to the design of future wireless and communication networks.

1.3 Organization and targeted audience

Our aim with this book is to provide researchers and engineers working in communications and networking with a comprehensive and detailed introduction to game theory, as relevant to wireless and communication networks. After introducing some fundamentals of wireless networks, the book starts, in Part I, with an in-depth study of important game-theoretic frameworks. In this part of the book, we mainly focus on presenting important classes of games that admit potential applications in wireless and communication networks. In essence, Part I provides a detailed study of a variety of games ranging from classical non-cooperative games to more advanced games such as dynamic games, coalitional games, network-formation games, Bayesian games, evolutionary games, and auction theory. For each type of game, we focus on the fundamental notions, possible solutions, key objectives, and important properties, while highlighting potential application scenarios in a game-theoretic as well as a communications and networking environment. Thus, in each chapter of Part I we start with an overview of the studied class of games, and then delve into key elements such as game components, solution concepts, and mathematical properties of the studied game. In each chapter we provide carefully selected examples from game theory and wireless networks to enable readers to grasp the presented ideas and to start drawing some links between the problems solved in game theory and their counterparts in the communications world. The objective of Part I is, thus, to provide a thorough treatment of the key branches of game theory, while starting to show that such game-theoretic concepts, originally rooted in economics, have a lot to offer in addressing the problems that face researchers and engineers working in wireless and communication networks.

After laying the foundations of game-theoretic techniques and drawing their connections to the wireless and communication worlds, in Part II of the book we start developing

game-theoretic models in a wide range of wireless and communication applications such as cellular and broadband networks, wireless local area networks, multi-hop networks, cooperative networks, cognitive-radio networks, and Internet networks. Each chapter in Part II constitutes a didactic study that explains how game theory can be applied to solve key problems in a state-of-the-art field within wireless and communication networks. In Part II, within every application area we enable readers to understand how, using the game-theoretic techniques studied in Part I, one can solve challenging problems such as resource allocation, MAC (medium access control) protocol design, random-access control, network selection, cooperative routing and packet forwarding, spectrum sensing in cognitive networks, dynamic spectrum access, flow control and routing in Internet networks, a peer-to-peer incentive mechanisms. Within each chapter of Part II, we start by identifying the main technical challenges and problems of the studied application area. Then, after clearly determining the system model of interest, we highlight the problem that needs to be treated, and we map it to a relevant, sufficiently rich class of games as described in Part I. Once the game is formulated by identifying its components, we apply suitable solution concepts and discuss the insights that they yield within the context of the studied problem. We also shed light on potential extensions and future uses of the developed game-theoretic techniques and communication models. In particular, Part II shows how concepts such as the Nash equilibrium, the Stackelberg equilibrium, and evolutionarily stable strategies, can yield meaningful outcomes and implications within a wireless and communication problem. Hence, the objective of Part II is to demonstrate the usefulness of game theory in the design of future wireless and communication networks as well as to provide readers with exhaustive guidelines to enable them to develop networking-oriented game-theoretic approaches using Part I as a basis.

In a nutshell, the main goal of the book is to formalize the use of game theory in wireless and communication networks, by providing not only an introduction to the fundamental branches of game theory but also a thorough and instructive treatment on developing game-theoretic techniques for analyzing state-of-the-art and emerging communications and networking applications. The main goal of the book can, thus, be summarized in the following three objectives:

- The first objective is to provide a general introduction to wireless communications and networking while pinpointing the most recent developments and challenges. These aspects are discussed, in detail, throughout the book.
- The second objective is to introduce different game-theoretic techniques and their applications for designing distributed and efficient solutions for a diverse number of wireless communications and networking problems. This is mainly dealt with in Part I of the book.
- The third objective is to provide a didactic study of how game theory can be leveraged for use in state-of-the-art and emerging applications in wireless and communication networks. This includes identifying key problems in a variety of communications applications, linking them to game-theoretic frameworks, and studying the properties and implications of the solutions and outcomes.

By achieving these objectives, the book enables the reader to clearly identify the links and connections between the technical challenges looming in future wireless communication networks and the classical economics-oriented applications of game theory. In particular, in recent years, engineers and researchers in the wireless communication community have been seeking a reference source, such as this book, that integrates the notions of game theory and of wireless engineering, while emphasizing how game theory can be applied in wireless networks from an engineering perspective. This book serves this purpose, and is intended, primarily, for the following audience:

- communications engineers interested in studying the new tools of distributed optimization and management in wireless networking systems
- researchers interested in state-of-the-art research on distributed algorithm design, cooperation, and networking for a wide range of wireless communication applications
- graduate and undergraduate students interested in obtaining comprehensive information on the design and evaluation of game-theoretic approaches to find suitable topics for their dissertations.

1.3.1 Timeliness of the book

Because of the rapid growth in communication networks and its projected evolution, a broad range of novel technical challenges are emerging daily. This requires solid and robust analytical frameworks, such as game theory, that can enable researchers in the wireless and communications industry to overcome these challenges. Hence, this book constitutes a timely contribution, for the following reasons:

Promising distributed game-theoretic approaches for future wireless networks. In recent years, there has been an unprecedented increase in consumer demand for wireless services. This growing demand has led to the emergence of large-scale wireless networks that cover huge areas and that are expected to meet stringent quality-of-service (QoS) requirements. In this regard, wireless network entities such as base stations are unable to cope with this growth, which requires such entities to gather a large amount of information from the network (e.g., channel conditions, users' actions, etc.), which in turn yields extensive complexity, overhead, and signaling. Consequently, devising distributed solutions and algorithms constitutes a promising direction for the efficient design of future wireless networks. Nonetheless, deriving distributed algorithms for wireless networks is accompanied by several challenging issues. On the one hand, wireless network users are generally selfish. For instance, distributed mobile users tend to maximize their own performance, regardless of how this maximization affects the other users in the network, giving rise to competing scenarios. On the other hand, in some scenarios, cooperation is required among wireless network users in order to achieve the best performance. These situations recently motivated researchers and engineers to adopt game-theoretic techniques for characterizing competition and cooperation in wireless networks. As an example, distributed resource allocation can be modeled as a game that deals largely with how rational and intelligent individuals interact with each other in an effort to achieve

their own goals in terms of sharing the network resources. In this game, each mobile user is self-interested and will attempt to optimize its own benefit. In brief, applying game theory in future wireless networks presents many advantages:

- Local information-based decisions and distributed implementation: By using game-theoretic approaches, individual mobile users optimize their performance by taking individual decisions based on the local observation of a well-defined game's outcome. As a result, by adopting game-theoretic models, there is no need for collecting global information and conducting optimization in a centralized manner.
- More robust outcomes: In large-scale wireless networks, adopting centralized solutions for optimizing performance may yield inefficient results owing to errors occurring during the complex information-gathering phase. In contrast, local information is generally more reliable and accurate. Hence, in many situations, the outcome of distributed game approaches is more robust than that of centralized solutions.
- Convenient approaches for solving problems of a combinatorial nature: Traditional optimization techniques such as mathematical programming require handling combinatorial problems that are inherently hard to manipulate. In game theory, most problems are naturally studied in a discrete form, which is relatively easy to analyze. For example, in a cognitive-radio network, analyzing the spectrum access strategy of the unlicensed user using game theory is tractable, while solving this problem in a centralized manner with reasonable complexity is not feasible in many cases.
- Rich mathematical and analytical tools for optimization: Game theory provides a variety of analytical and mathematical tools for adequately analyzing the outcome of well-defined classes of games. For instance, in non-cooperative games, static games (i.e., games in which decisions are made only once) can be solved using well-defined notions such as the best-response function and the Nash equilibrium. Moreover, in dynamic games (i.e., games in which decisions are made dynamically, evolving with time), various concepts and solutions can be applied (e.g., behavioral equilibria, repeated-game solutions). In addition, whenever cooperation between players is required, cooperative game theory provides a rich framework suitable for such an analysis. Finally, auction theory as well as other game-theoretic concepts can be applied for efficient and robust mechanism design in various situations (e.g., bidder/seller games).

Most existing game theory books are oriented toward economic aspects, and most existing network optimization books focus on centralized approaches. In the current market, most books dealing with game theory and its applications draw their applications from economics. As a result, such books are difficult for engineers to understand and use, because of unfamiliar terminology as well as a significant number of assumptions (e.g., demand/supply and transferable money) that are fundamentally different from engineering problems. In addition, most existing books dealing with wireless network optimization study centralized approaches such as constrained optimization. Consequently, there is a gap between understanding game theory and applying it to

the design of next-generation wireless networks. Moreover, designing game-theoretic solutions for wireless networks requires interdisciplinary knowledge from multiple scientific and engineering disciplines to achieve the desired design objectives. Therefore, a unified treatment of this subject area is desirable. In this regard, this book aims to fill this void in the literature by closely combining game-theoretic approaches with wireless network design problems. Briefly, this book will provide a unified reference source on the application of game theory to wireless networks, tailored to the technical needs of engineers.

Emergence of new wireless applications and services. The emergence of a large class of wireless applications requiring distributed solutions is a motivation for the application of game theory. A few of these emerging wireless applications are as follows:

- Cognitive radios: The introduction of cognitive radios in future wireless networks faces several challenges that require a broad range of analytical tools from game theory such as non-cooperative games and mechanism design. For example, the spectrum can be accessed by non-cooperative multiple unlicensed users, or it can be traded among licensed and unlicensed users.
- Cooperative communication: Recently, there has been a growing interest in studying cooperative scenarios in wireless networks. It has been shown that, through cooperation, the wireless network performance can be significantly improved. Hence, cooperative communication is rapidly emerging as a pillar technology in next-generation wireless networks, and it has already been incorporated in various standards, such as the IEEE 802.16 WirelessMAN (WiMAX) family of broadband networks. The introduction of cooperative communication in wireless networks faces several challenges (deriving autonomous and distributed cooperative strategies, analyzing users' interactions, etc.) that can only be analyzed by solid and robust analytical tools such as game theory.
- Autonomic communication in heterogeneous networks: Currently, a broad range of wireless-network standards exists (UMTS, LTE, WiMAX, etc.), with each type of network having its own characteristics. Consequently, there is a need to produce wireless devices that can autonomously operate within heterogeneous environments, allowing for interoperability between these wireless standards. Autonomic communications aims to: (i) provide distributed algorithms that can ease the burden of managing complex and heterogeneous networks, and (ii) provide large-scale networks that are self-configuring, self-organizing, and able to learn and adapt to their environments (changes in topology, technologies, service requirements, etc.). Clearly, game theory is the natural tool for achieving these objectives of autonomic communications.
- Wireless intelligent transportation system: A wireless intelligent transportation system (ITS) refers to an integrated wireless communication and software system that facilitates information exchange and processing for improving the safety and the efficiency of vehicle transportation. Since mobility is a key feature in such a communication environment, a distributed and efficient wireless communication system can improve

system performance. For example, the vehicular node can relay safety-related data of other nodes, or the vehicular nodes can download data from a roadside unit. If the vehicular nodes have self-interests, radio resource management based on a game model would be required to obtain equilibrium solutions. Essentially, an equilibrium solution must be obtained as quickly as possible because the connection duration of vehicular nodes is very short, owing to the high mobility of the vehicles. In this case, speed of convergence will be crucial for the rational vehicular node to access the radio resources required for supporting wireless ITS services.

- Multi-hop communications: The service area and throughput of a wireless network can be improved by using multi-hop communication (e.g., ad hoc and mesh network). Various wireless technologies will support multi-hop communication (e.g., IEEE 802.16). In such a network, wireless nodes interact with one another to relay their data to the destination. If these wireless nodes have self-interests, the data relaying behavior of each node can be modeled using game theory. The equilibrium relaying strategy will provide a stable solution for each wireless node in a multi-hop network. Moreover, several other aspects of multi-hop communication can be modeled using game theory, including distributed topology design and distributed relaying.
- Mobile wireless multimedia network: With the need to support multimedia applications, wireless networks have to be designed to provide QoS guarantee and reliable multimedia communication. In this case, the multimedia users can have heterogeneous QoS requirements that the radio resource management algorithm is required to handle adequately. In this context, game theory can be applied to wireless multimedia networks to obtain a fair and efficient solution for radio resource sharing between the mobile multimedia users.

Applications of game-theoretic concepts in traditional wireless systems. Game-theoretic techniques can be readily applied to traditional wireless communication systems to achieve a better flexibility of radio resource usage so that system performance can be improved while the signaling overhead is reduced. For example, load balancing/dynamic channel selection in traditional cellular wireless systems and WLANs, distributed subcarrier allocation in orthogonal frequency-division multiplexing (OFDM) systems, transmit power control in ultra wideband (UWB) systems, and spectrum access for cognitive radios can be achieved by using distributed game-theoretic techniques.

1.3.2 Outline of the book

To achieve the aforementioned objectives, the book is organized as follows.

In Chapter 2, we first study the basic characteristics of wireless channels. Then we introduce different wireless access technologies (e.g., cellular wireless, WLAN, WMAN, WPAN, and WRAN technologies) and the related standards. Some typical wireless networks such as ad hoc/sensor networks will also be presented. This includes the basic components, features, and potential applications. Then, advanced wireless technologies such as OFDM, MIMO, and cognitive radio are discussed. For distributed

implementation, the research challenges in the different layers of the protocol stack are discussed.

Part I: Fundamentals of game theory

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

- In Chapter 3, the best-known type of games (i.e., non-cooperative games) is discussed. Various non-cooperative static games, in which multiple users (or players) are selfish and engage in a non-cooperative competition, are presented. We define and discuss the celebrated Nash equilibrium concept. We also pursue our discussion by introducing and presenting dynamic and repeated games. Unlike static games in which players are involved in the decision process once, dynamic games study the evolution of the process of decision-making of the players, taking into account the presence or lack of information. For instance, when the players are allowed to act multiple times, the behavior of these players can be analyzed using various concepts from repeated or dynamic games. The solution concept of subgame-perfect equilibrium is defined for dynamic games. In addition, for repeated games, we present a number of different strategies (e.g., trigger and punishment) that can be adopted by the users. Some special game concepts are finally discussed, such as the potential game, the Stackelberg game, the correlated equilibrium, the supermodular game, and the Wardrop equilibrium.
- In Chapter 4, game models (i.e., Bayesian and learning games) with incomplete information are discussed. In general, Bayesian games are adequate for modeling scenarios in which the players lack some necessary information when making their strategic choices. Bayesian games can be used to capture this incompleteness of information. With Bayesian games, a player can develop a belief about the payoffs and strategies of other players. Alternatively, the player can implement learning algorithms to gain knowledge of the game and the environment so that a suitable equilibrium solution can be reached. Accordingly, we provide a clear introduction to Bayesian and learning games, while outlining their significance in wireless and engineering problems. Finally, we provide several examples of Bayesian game approaches such as the packet-forwarding game, the K-player Bayesian water-filling game, the channel-access game, the bandwidth auction game, and the network game.
- Chapter 5 covers differential games which extend static non-cooperative game theory by adopting the methods and models developed in optimal control. Differential-game theory provides a means of obtaining the equilibrium solution for rational entities with time-varying objectives or payoff functions and evolving states as well as information. Two major approaches to optimal-control theory are the *dynamic programming* introduced by Bellman and the *maximum principle* introduced by Pontryagin. These approaches have been adopted in differential game theory in which the payoff for a player depends on (i.e., is constrained by) the state, which evolves over time. The