

Preface

Game theory is the formal studies of decision-making among multiple autonomous players who have common or conflicting interests and whose interactions influence the outcomes obtained by each participant. It has found its applications in the areas of telecommunication engineering since the early 1990s, for solving problems such as flow control and routing. In recent years, game-theoretical approach to radio resource allocation is one of the most extensively investigated research topics in wireless communications. A significant number of scientific papers and books, as well as special journal issues (e.g., the *IEEE Journal on Selected Areas in Communications* and the *IEEE Journal on Selected Topics in Signal Processing*) have been dedicated to this topic.

In some interactive scenarios involving selfish decentralized individuals, game theory helps us formulate analytical models so that we can examine the possible final outcomes and study the stability conditions of these outcomes. This is important in devising good strategies, which we ultimately hope will lead the system to these stable, efficient states at which the overall performance is improved and sustainable compared to a randomized, uncontrolled operating state. To this end, it is essential to emphasize the need to establish the existence of Nash equilibria in wireless communication games, one of which will be chosen as the final stable operating point of the system. The system exhibits a preferable and desirable property, if only one unique Nash equilibrium exists and any initially adopted strategy profile of players is able to converge to this Nash equilibrium by applying some iterative dynamics.

Existence and convergence of Nash equilibrium do not always apply to any arbitrary utility functions and strategy sets. However, there are special types of games, including *potential games*, where at least a pure-strategy Nash equilibrium is guaranteed to exist and can be reached with certain classes of learning dynamics such as the best responses. In a potential game formulation, one can identify a special function called the *potential function*, which changes values whenever there is a change in the utility of any single player due to his/her own strategy deviation, according to some predefined relationships. As such, the game's equilibria can often be associated with the optimum points of this potential function. Potential games

are first studied by Monderer and Shapley [11]. Due to their desirable properties, they have been adopted to model radio resource allocation problems. Despite the promising number of applications in several wireless communications problems, it seems that the means to formulate a problem as a potential game is still vastly done through the process of trials and errors, with most applications being limited to a few known utility functions. In fact, there lacks a unifying framework in order for us to gain an in-depth insight in order to better exploit this very useful technique. For example, the overarching question of whether or not there is a systematic method to identify and to define the potential function of a game is still unanswered. Alternatively, how one can generalize and establish new potential game models for existing practical problems is another complicated and challenging problem. To the best of the authors' knowledge, there are dozens of textbooks that present excellent accounts of the use of game theory for wireless communications. Nevertheless, potential games often only receive a one-chapter treatment at best. No books or monographs are available to address the aforementioned concerns.

In this monograph, we attempt at a complete treatment of potential game theory and its applications in radio resource management for wireless communications systems and networking. We hope to pave the way to more extensive and rigorous research findings on a topic whose capacity for practical applications is potentially huge but yet not fully exploited. First and foremost, a generalized and rigorous mathematical framework on potential games will be presented. Consequently, we will discuss new as well as existing findings on the formulation of potential games and their applications in solving a variety of wireless communications problems.

The monograph is comprised of five chapters and is divided into two parts:

- In *Part I—Theory*, the purpose is to introduce the necessary background, as well as the notations and concepts used in game theory. In particular, we document our studies of a class of games known as potential games, which have found useful applications in the context of radio resource allocation. The materials covered in Part I will lay the fundamentals for the actual applications presented in Part II. Part I consists of two chapters:
 - Chapter 1 serves as a concise introductory text to game theory. It reviews the most elemental concepts and building blocks in game theory. We put an emphasis on the use of iterative decision dynamics in myopic computation of Nash equilibria, which is a process often employed in practical applications. The discussion is facilitated with a series of toy examples in order to have a better understanding of the abstract concepts.
 - Chapter 2 is the focal point of the monograph where theoretical treatments on potential games and our contributions to the literature on this topic are presented. Besides theoretical definition and characterization, we also give a very detailed and rigorous discussion on the questions of how to identify whether a game is a potential game, how to find the corresponding potential function, and how to formulate the utility function so that the resulting game is a potential game. The chapter is a cornerstone of the monograph, which serves as a basis for all subsequent discussions.

- *Part II—Applications* looks into a variety of practical problems in wireless resource allocation which can be formulated as potential games. In this part, we present our own results as well as summarize existing related works. It includes three chapters:
 - Chapter 3 uses game-theoretical approaches to achieve fair and efficient spectrum access schemes for the distributed OFDMA network consisting of transmit-receive pairs which exploits spatial frequency reuse. We discuss how a potential game can be formulated, the behaviors of strategy domination, and how it can be overcome, as well as an analysis of the price of anarchy. The system performance when best-response algorithm is used will be evaluated.
 - Chapter 4 looks at the subcarrier allocation problem for a downlink multicell multiuser OFDMA network where a potential game is also formulated. We propose our iterative algorithm for obtaining the Nash equilibria and address several performance issues such as fairness for edge-users as well as when the system is overloaded. Numerical results show the improvement in efficiency and fairness of this approach over existing schemes.
 - Chapter 5 gives a summary of existing approaches that apply potential games in solving wireless communications and networking problems, focusing on the formulations using exact potential games and pseudo-potential games. A non-exhaustive list of selected applications discussed in this chapter includes Menon et al. [9], Buzzi et al. [2], Neel et al. [12], Babadi et al. [1], Scutari et al. [14], Perlaza et al. [13], Mertikopoulos et al. [10], Xu et al. [16], Heikkinen [3], and Xiao et al. [15], to name a few.

This monograph is helpful for engineering students at the graduate and advanced undergraduate levels to learn and understand the fundamentals of potential game theory. It is also intended to introduce researchers and practitioners on how this theory can be used to solve the practical radio resource allocation problems. Researchers, scientists, and engineers in the fields of telecommunication, wireless communications, computer sciences, and others will certainly benefit from the contents of the book.

Chapters 3 and 4 of this monograph make use of materials that have been published in the authors' earlier papers [5–8], as well as the first author's Ph.D. thesis [4].

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