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Game theory for cognitive radio networks: An overview

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ABSTRACT

Cognitive radio technology, a revolutionary communication paradigm that can utilize the existing wireless spectrum resources more efficiently, has been receiving a growing attention in recent years. As network users need to adapt their operating parameters to the dynamic environment, who may pursue different goals, traditional spectrum sharing approaches based on a fully cooperative, static, and centralized network environment are no longer applicable. Instead, game theory has been recognized as an important tool in studying, modeling, and analyzing the cognitive interaction process. In this tutorial survey, we introduce the most fundamental concepts of game theory, and explain in detail how these concepts can be leveraged in designing spectrum sharing protocols, with an emphasis on state-of-the-art research contributions in cognitive radio networking. Research challenges and future directions in game theoretic modeling approaches are also outlined. This tutorial survey provides a comprehensive treatment of game theory with important applications in cognitive radio networks, and will aid the design of efficient, self-enforcing, and distributed spectrum sharing schemes in future wireless networks.

1. Introduction

Cognitive radio technology [1] is emerging in recent years as a revolutionary communication paradigm, which can provide faster and more reliable wireless services by utilizing the existing spectrum band more efficiently [2,3]. A notable difference of a cognitive radio network from traditional wireless networks is that users need to be aware of the dynamic environment and adaptively adjust their operating parameters based on the interactions with the environment and other users in the network. Traditional spectrum sharing and management approaches, however, generally assume that all network users cooperate unconditionally in a static environment, and thus they are not applicable to a cognitive radio network.

In a cognitive radio network, users are intelligent and have the ability to observe, learn, and act to optimize their performance. If they belong to different authorities and pursue different goals, e.g., compete for an open unlicensed band, fully cooperative behaviors cannot be taken for granted. Instead, users will only cooperate with others if cooperation can bring them more benefit. Moreover, the surrounding radio environment keeps changing, due to the unreliable and broadcast nature of wireless channels, user mobility and dynamic topology, and traffic variations. In traditional spectrum sharing, even a small change in the radio environment will trigger the network controller to re-allocate the spectrum resources, which results in a lot of communication overhead. To tackle the above challenges, game theory has naturally become an important tool that is ideal and essential in studying, modeling, and analyzing the cognitive interaction process, and designing efficient, self-enforcing, distributed and scalable spectrum sharing schemes.

Game theory is a mathematical tool that analyzes the strategic interactions among multiple decision makers. Its history dates back to the publication of the 1944 book *Theory of Games and Economic Behavior* by J. von Neumann and O. Morgenstern, which included the method for finding mutually consistent solutions for two-person zero-sum

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games and laid the foundation of game theory. During the late 1940s, cooperative game theory had come into being, which analyzes optimal strategies for groups of individuals, assuming that they can enforce collaboration between them so as to jointly improve their positions in a game. In early 1950s, J. Nash developed a new criterion, known as Nash equilibrium, to characterize mutually consistent strategies of players. This concept is more general than the criterion proposed by von Neumann and Morgenstern, since it is applicable to non-zero-sum games, and marks a quantum leap forward in the development of non-cooperative game theory. During the 1950s, many important concepts of game theory were developed, such as the concepts of the core, the extensive-form games, repeated games, and the Shapley value. Refinement of Nash equilibriums and the concepts of complete information and Bayesian games were proposed in the 1960s. Application of game theory to biology, i.e., the evolutionary game theory, was introduced by J. M. Smith in the 1970s, during which time, the concepts of correlated equilibrium and common knowledge were introduced by R. Aumann. Starting from the 1960s, game theorists have started to investigate a new branch of game theory, mechanism design theory, focusing on the solution concepts for a class of private information games. In nowadays, game theory has been widely recognized as an important tool in many fields, such as social sciences, biology, engineering, political science, international relations, computer science, etc., for understanding cooperation and conflict between individuals.

In cognitive radio networks, network users make intelligent decisions on their spectrum usage and operating parameters based on the sensed spectrum dynamics and actions adopted by other users. Furthermore, users who compete for spectrum resources may have no incentive to cooperate with each other and instead behave selfishly. Therefore, it is natural to study the intelligent behaviors and interactions of selfish network users from a game theoretic perspective.

The importance of studying cognitive radio networks in a game theoretic framework is multifold. First, by modeling dynamic spectrum sharing among network users (primary and secondary users) as games, network users' behaviors and actions can be analyzed in a formalized game structure, by which the theoretical achievements in game theory can be fully utilized. Second, game theory equips us with various optimality criteria for the spectrum sharing problem. To be specific, the optimization of spectrum usage is generally a multi-objective optimization problem, which is very difficult to analyze and solve. Game theory provides us with well defined equilibrium criteria to measure game optimality under various game settings. Third, non-cooperative game theory, one of the most important branch of game theory, enables us to derive efficient distributed approaches for dynamic spectrum sharing using only local information. Such approaches become highly desirable when centralized control is not available or flexible self-organized approaches are necessary.

In this tutorial survey, we aim at providing a comprehensive treatment of game theory oriented towards their applications to cognitive radio networks in recent years. Considering game theory is still rarely taught in engineering or computer science curricula, we assume that the reader has very little background in this area. Therefore, we start each section by introducing the most basic game theoretic concepts, and then address how these concepts can be leveraged in designing efficient spectrum sharing schemes from a network designer's perspective. The organization of the tutorial survey is illustrated in Fig. 1, where the game theoretic spectrum sharing schemes are classified into four categories. We first discuss non-cooperative spectrum sharing games in Section 2, since networks users are mostly assumed to be selfish and only aim at maximizing their own spectrum usage. Then, we talk about the

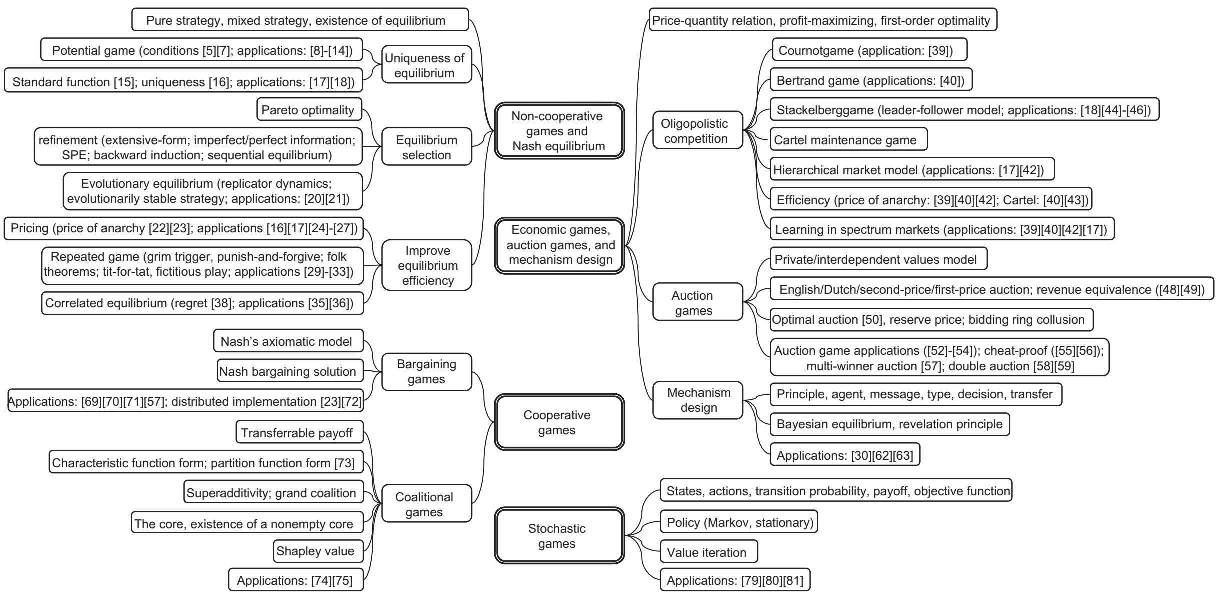

Fig. 1. Four categories of the game theoretic spectrum sharing approaches.