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A survey on game theory applications in wireless networks

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ABSTRACT

While the Quality of Service (QoS) offered to users may be enhanced through innovative protocols and new technologies, future trends should take into account the efficiency of resource allocation and network/terminal cooperation as well. Game theory techniques have widely been applied to various engineering design problems in which the action of one component has impact on (and perhaps conflicts with) that of any other component. Therefore, game formulations are used, and a stable solution for the players is obtained through the concept of equilibrium. This survey collects applications of game theory in wireless networking and presents them in a layered perspective, emphasizing on which fields game theory could be effectively applied. To this end, several games are modeled and their key features are exposed.

1. Introduction

Game theory is a discipline aiming to model situations in which decision makers have to make specific actions that have mutual – possibly conflicting – consequences [1]. It has been used primarily in economics, in order to model competition between companies. In the context of wireless networks, game theory may be used as a tool for forming cooperation schemes among entities such as nodes, terminals or network providers. During the last years, game theory has also been applied to networking, in most cases to solve routing and resource allocation problems in a competitive environment. Recently, its application was introduced in wireless communications: the decision makers in the game are rational users or networks operators who control their communication devices. These devices have to cope with a limited transmission resource (i.e., the radio spectrum) that imposes a conflict of interests [2]. In this article we describe how game-theoretic frameworks can be set up to address several issues in wireless networks and survey recent advances in this area, highlighting applicability to problems such as power control, spectrum allocation call admission control, medium access control and routing, among others. Emphasis is placed on which type of game is most appropriate for each case, as well as on which element should be considered in the development of utility functions; to this end several examples of such functions are exposed.

2. Game theory basics

2.1. Basic concepts

This section demonstrates the fundamentals of game theory. For further details the reader is prompted at [1,3,4]. Game theory is related to the actions of decision

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makers who are conscious that their actions affect each other. A game consists of a principal and a finite set of *players* N = {1,2,...,N}, each of which selects a *strategy* $s_i \in S_i$ with the objective of maximizing his *utility* u_i. The utility function u_i (s): S → R represents each player's sensitivity to everyone's actions.

According to the above, a game can be modeled as $G = (P, A, S_i, \pi_{ij})$ where:

- $P = \{1,\ldots,n\}$ denotes the set of players
- $A = \{1,\ldots,n\}$ denotes the available resources in the game (action set)
- S_i denotes the set of strategies for player *i*, i.e. all possible choices from set A
- π_{ij} denotes the payoff assigned to player *i* after choosing resource *j*.

Table 1 presents a mapping between the basic components of a game and the entities of wireless networks.

Two types of games are distinguished: in *non-cooperative* games, each player selects strategies without coordination with others. The strategy profile **s** is the vector containing the strategies of all players: $s = (s_i),\ i \in \mathbf{N} = (s_1, s_2, \ldots, s_N)$. On the other hand, in a **cooperative game**, the players cooperatively try to come to an agreement, and the players have a choice to bargain with each other so that they can gain maximum benefit, which is higher than what they could have obtained by playing the game without cooperation [5]. Let $N = \{1,2,\ldots,N\}$ be a set of *n* players. Non-empty subsets of N, $S, T \subseteq N$ are called a *coalition*. The coalition form of an *n*-player game is given by the pair (N, u), where *u* is the characteristic function [6]. A coalition that includes all of the players is called a grand coalition. The characteristic function assigns each coalition *S* its maximum gain, the expected total income of the coalition denoted $u(S)$. The *core* is the set of all feasible outcomes that no player or coalition can improve upon by acting for themselves. The objective is to allocate the resources so that the total utility of the coalition is maximized. In wireless networks the formation of coalitions involves the sharing of certain resources; however, as the costs of such resource sharing outweigh the benefits perceived by the nodes, users are less likely to participate, compromising overall network goals.

2.2. Nash equilibrium

The equilibrium strategies are chosen by the players in order to maximize their individual payoffs. In game theory, the nash equilibrium is a solution concept of a game involving two or more players, in which no player has anything to gain by changing only his own strategy unilaterally. If each player has chosen a strategy and no player can benefit by changing his strategy while the other players keep theirs unchanged, then the current set of strategy choices and the corresponding payoffs constitute a nash equilibrium. Some games can be solved by iterated dominance, which systematically rules out strategy profiles. A pure strategy s_i is strictly dominated for player *i* if there exists $s_i' \in S_i$ such that $u_i(s_{i'}, s_{-i}) > u_i(s_i, s_{-i})\ \forall\ s_{-i} \in S_{-i}$. It is customary to denote by s_{-i} the collective strategies of all players except player *i*.

2.3. Mixed strategies

When a player makes a decision, he can use either a pure or a mixed strategy. If the actions of the player are deterministic, he is considered to use a pure strategy. If probability distributions are defined to describe the actions of the player, a mixed strategy is used. We denote a mixed strategy available to player *i* as σ_i. We denote by $\sigma_i(s_i)$ the probability that σ_i assigns to s_i. Clearly, $\sum_{s_j \in S_i} \sigma_i(S_i) = 1$. Of course, a pure strategy s_i is a degenerate case of a mixed strategy σ_i, where $\sigma_i(s_i) = 1$. The space of player *i*'s mixed strategies is Σ_i. As before, a mixed strategy profile $\sigma = (\sigma_1, \sigma_2, \ldots, \sigma_N)$ and the Cartesian product of the Σ_i forms the mixed strategy space Σ.

2.4. Repeated games

In strategic or static games, the players make their decisions simultaneously at the beginning of the game. On the contrary, the model of an extensive game defines the possible orders of the events. The players can make decisions during the game and they can react to other players' decisions. Extensive games can be finite or infinite. A class of extensive games is repeated games, in which a game is played numerous times and the players can observe the outcome of the previous game before attending the next repetition.

3. Game theory in wireless networks: a layered perspective

As stated in the introduction of the present article, the author's intention is to collect a wide spectrum of game theory applications in wireless networks. In order to provide a coherent presentation and point out the various fields of application, the latter have been categorized under corresponding OSI Layers. The adopted layered perspective

Table 1
Mapping of game theory elements to networks.

Game component	Entities, processes or elements of wireless networks
Players	Network nodes, service providers or customers
Resources	All kinds of resources needed by nodes to communicate successfully (spectrum, power, bandwidth, etc.), income
Strategies	A decision regarding a certain action of the player, depending on the application field (forward packet, set power level, accept new call, etc.)
Payoffs	Estimated by utility functions, based on QoS merits (delay, throughput, SNR, etc.)