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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.)

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Table 2
Layered presentation of game theory applications.

OSI Layer	Application field	Specific application
Physical	Power control	Power control for CDMA
		Power control in OFDMA Networks
	Spectrum allocation	Spectrum sharing- Spectrum transactions
	MIMO Systems	Power management in MIMO
	Cooperative communications	Decode-and-forward cooperation
Data link	Medium access control	Access to slotted Aloha
		Random access to the interference channel
Network	Routing	Routing and forwarding
Transport	Call admission control	Request distribution among providers
		Call acceptance based on provider and customer context
	Load control	Termination of sessions based on provider and customer context
	Cell selection	Inter-cell and intra-cell games

aims at demonstrating that game theory may be used to solve problems in all aspects of telecommunications, while allowing for possible combination of game-theoretic frameworks to achieve cross-layer optimization. In most of these games the concept of pricing is also discussed, since pricing constitutes a vital factor in an utility function.

As depicted in Table 2, several application fields are examined under each layer, while interesting approaches are discussed for each field; this however does not imply under any circumstances that no other application fields exist. The authors have simply included the ones they consider most indicative and most helpful for the readers unfamiliar with the usefulness of game theory. In this point the authors would like to note also that processes such as admission control or load control cannot be assigned explicitly to a single layer, since they often deploy cross-layer optimization techniques and could thus involve elements of multiple layers.

4. Physical layer

From a physical layer perspective, performance is generally a function of the estimated signal-to-interference-and-noise ratio (SINR) that players/nodes receive. When the nodes in a network respond to changes in perceived SINR by adapting their signal, a physical layer interactive decision making process occurs. In this frame, game theory can be applied to allocation problems concerning resources such as power or spectrum. A significant aspect that is taken under consideration in these formulations is the interference avoidance.

4.1. Power control

In the power control problem, each user's utility is increasing in his signal-to-interference-and-noise ratio (SINR) and decreasing in his power level [7]. If all other users' power levels were fixed, then increasing one's power would increase one's SINR. However, when a user raises her transmission power, this action increases the interference seen by other users, driving their SINRs down, inducing them to increase their own power levels. MacKenzie and Wicker in [8] formulate a non-cooperative power control game for a CDMA system. Suppose that users transmit information at the rate R bits/s in L bit packets over a spread-spectrum bandwidth of W (Hz). Let p_j be the power transmitted by user j; assuming that users choose their power levels from the set of non-negative real numbers, $p_j \in [0,\infty)$, the signal-to-interference-and noise ratio of user j can be defined as

$$SINR_j = \gamma_j = \frac{W}{R}\cdot\frac{h_j p_j}{\sum_{\forall i\neq j} h_i p_i + \sigma^2}, \quad (1)$$

where h_j is the path gain from user j to the base station and σ^2 is the power of the background noise at the receiver. It is also assumed that the background noise is additive white Gaussian noise (AWGN). The utility function of user j has the unit of bits/J and can be expressed by

$$u_j(p_j,\gamma_j) = \frac{R}{p_j}(1 - 2\cdot BER(\gamma_j))^L, \quad (2)$$

where $BER(j)$ is the bit error rate achieved by a given transmission scheme. If the user's transmit power is too high, then he is squandering precious battery power while having little impact on his bit error rate. The users will attempt to make the best possible choices, taking into account that the other users are doing the same thing. Assuming that the users have complete information about each other and that they are completely rational, according to game theory, they will choose an operating point which is a nash equilibrium. MacKenzie and Wicker [8] also introduce two new types of games: the refereed and the repeated power control games. Gunturi and Paganini in [9] form a similar power control game, which is then expanded to a multi-cell case. Furthermore, Zhu Han et al. in [10] add a virtual referee to the multi-cell power control problem. Interference avoidance is also examined in [11] under the scope of game theory.

Game theory has found similar applications in *Orthogonal Frequency Division Multiplexing Access (OFDMA) networks* as well. In these cases the objective is to minimize the overall transmitted power under rate and power constraints, by adjusting the rate allocation over different sub-channels for different users. The authors of [12] model this problem as a non-cooperative game between users, considering it as a water-filling problem. The solution of the game provides the optimal values for both power and

rate that offer the best utility for a user given the other users' resource allocation. A game-theoretic approach to allocate power in multi-cell OFDM networks through non-cooperative games is also presented in [13].

4.2. Spectrum allocation

The spectrum sharing problem addresses the issue of how to allocate the limited available spectrum among multiple wireless devices. The allocation of spectrum should utilize as much of the resource as possible; however, when utilization is maximized, fairness can be compromised. A cooperative game for distributed spectrum sharing is discussed in [14]. According to this approach, the available bandwidth is divided equally into multiple channels. Each node can transmit in any combination of channels at any time and can set its transmit power on each channel. Receiver nodes do not transmit and thus are not considered as players in the game. Let $\chi = \{1,\ldots,K\}$ be the set of available channels, B be the aggregate bandwidth, with each channel having bandwidth B/K, and N be the number of transmitter nodes in the network.

The spectrum sharing game is formulated in [15] as follows: $\mathrm{M} = \{1,\ldots,N\}, P_i^x = \{(p_i^k)k \in x | p_i^k \geqslant 0, \sum_{k \in x} p_i^k < P_{\max}\}$ and $P^x = P_1^x X \ldots X P_N^x$. Let $p \in P^{\chi}$ and $u_i(p) = C_i(p)$, where $C_i(p)$ is the Shannon capacity:

$$C_i(p) = \frac{B}{K} \cdot \sum_{k=1}^{K} \log_2\left(1 + \frac{H_{ii}^k p_i^k}{\frac{\sigma^2}{K} \sum_{\forall j \neq i} H_{ji}^k p_j^k}\right), \tag{3}$$

where p_i^k is the power transmitted by node i on channel k, P_{max} is the maximum transmit power, H_{ji}^k is the channel gain from j to the receiver of i on channel k, and σ^2 is the thermal noise for the entire bandwidth B. Thus, the utility function of node i can be approximated as the Shannon capacity, given that nodes that are far enough away from node i's receivers such that they cause negligible interference, are neglected. Simulations then show that when interference is high, optimal mixed strategies usually involve only a single node transmitting at a time.

Niyato and Hossain [16] consider in their work the problem of spectrum sharing among a primary user and multiple secondary users, forming a model for competitive spectrum sharing among secondary users in cognitive radio networks. The payoff of secondary user i is in this case

$$\pi_\imath(\mathrm{B}) = r_i k_i b_i - b_i \left[x + y\left(\sum_{b_j \varepsilon \mathrm{B}} b_j\right)^{\tau}\right], \tag{4}$$

where b_i is the allocated spectrum size, B is the set of all available strategies, k_i is the average transmission rate, r_i is the revenue, x, y, and τ are non-negative constants, $\tau \geqslant 1$. Similar approaches can be found in [17,18].

A similar problem to spectrum sharing is that of spectrum transactions. Niyato and Hossain [19] study the problem of spectrum pricing in a cognitive radio network where multiple primary service providers compete with each other to offer spectrum access opportunities to the secondary users. Similarly, the authors of [20] address the problem of non-cooperative operators trying to maximize their profits by offering extra spectral resources to other ones. The revenue and costs for primary operator i are calculated in both cases as follows:

$$\begin{aligned} &\mathrm{Re}\, v(i) = c_i M_i, \\ &\mathrm{Cost}(q_i) = c_2 M_i \left(BW_i^{req} - a_i \frac{W_i - q_i}{M_i}\right)^2 \end{aligned} \tag{5}$$

where c_1 and c_2 denote weights for the revenue and cost functions respectively, BW_i^{req} denotes the bandwidth requirement for a primary operator and a_i is the spectral efficiency for primary operator i. Mi is the number of primary connections. Based on the aforementioned model, a game can be formulated where the players are the primary operators offering spectrum. Their strategy may be the price per unit of spectrum p_i and finally the payoff for every operator can be the profit (revenue-costs) after the spectrum transaction. The revenue for every operator can be calculated as:

$$\mathrm{Prof}_i(p) = q_i p_i + \mathrm{Re}\, v_i - \mathrm{Cost}_i, \tag{6}$$

where p_i denotes the set of prices offered by all players in the game and $p = \{p_1,\ldots,p_N\}$ is the set of prices. The best response function of operator i, given a set of prices offered by other primary operators p_i is $B_i(p_i) = \arg\max_{p_i}(\mathrm{Pr}\ of_i(p_i))$.

4.3. MIMO systems

The authors of [21] consider interference characterization and management in wireless ad hoc networks using Multiple Input Multiple Output (MIMO) techniques. According to this approach, power allocation in the ith link is modeled as non-cooperative games using the simple utility function $u_i = C_i - \gamma_i p_i$ where γ_i is a scaling factor so that the two terms in the previous equation have the same units, C_i is the achievable data rate of the link and p_i is the link transmit power.

Similarly, in [22] non-cooperative games are formulated, in which the players are the links and the payoff functions are the rates on each link. The solution to the problem is considered as the water-filling solution, while the nash equilibrium, according to the authors, is considered as fixed-point.

4.4. Cooperative communications

Chen and Kishore [23] have developed a cooperative game-theoretic analysis of decode and forward cooperative communications for additive white Gaussian noise (AWGN) and Rayleigh fading channels, as two-state Markov models. According to this model, the terminals, which constitute the players, communicate over orthogonal channels to a common destination node. The authors propose two alternatives for the payoff: it may be considered equal to the Shannon capacity or to the transmission reliability, which is equal to 1 minus the bit error rate. The games are assumed to be monitored by an entity which either rewards or punishes nodes (by increasing or reducing the transmission power respectively) based on their behavior.

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5. Data link layer

Game theory applications regarding the data link layer involve the medium access control problem. In these games, selfish users seek to maximize their utility by obtaining an unfair share of access to the channel. This action, though, decreases the ability of other users to access the channel.

5.1. Medium access control

A fine example of such games is the work of MacKenzie and Wicker [3,24], who model random access to slotted Aloha. According to this case, users wish to transmit as soon as possible. However, if multiple users try to transmit simultaneously, all accesses will fail. Additionally, unsuccessful attempts to transmit may cost. In slotted Aloha, time is divided into slots and through a specific method of synchronization. All users know where the slot boundaries are located; when a user wishes to access the shared channel he waits until the next slot boundary and then he starts attempting to transmit. If two or more users try to transmit in the same slot, the users become "backlogged" and must try to repeat the transmission in a future slot.

Let $G(n)$ be the game in which there are currently n users. In each stage of $G(n)$ each of the players must decide whether to transmit (T) or wait (W). If one player decides to transmit and the rest decide to wait, the player who transmits will receive a payoff of 1, and each of the other $(n-1)$ players will play $G(n-1)$ in the next period. If either no users transmit or more than one user transmit, all players will play $G(n)$ again in the next period. Players place a lower value on payoffs in later stages than on current payoffs. This is represented by a per period discount factor $d < 1$. Let $u_{i,n}$ represent user i's utility from playing $G(n)$ and let K be a random variable denoting the number of other users who transmit in a given slot. The utility functions for each action are then [24]:

$$u_{i,n}(T) = \frac{P[K=0]}{1-\delta \cdot P[K>0]},$$
$$u_{i,n}(W) = \frac{\delta \cdot P[K=1]}{1-\delta \cdot P[K\neq 1]} u_{i,n-1}. \quad (7)$$

This game has symmetric nash equilibrium strategies. Simeone et al. [25] discuss a game formulation of a basic two-by-two interference channel with random packet arrivals and random access. In this model, time is slotted and transmission of each packet takes one slot. Let us assume that in this non-cooperative game transmitter i transmits with probability $p_i^{(1)}$ if the other transmitter has no packet in queue, and $p_i^{(2)}$otherwise. The set of all feasible transmission probabilities is defined as

$$P_i(\boldsymbol{\rho}_\mathbf{j}) = \left\{ \boldsymbol{\rho}_\mathbf{i} = \left[p_i^{(1)} p_i^{(2)}\right]^T : 0 \leqslant p_i^{(1)}, p_i^{(2)} \leqslant 1 \right\}, \quad (8)$$

under the constrains

$$p_i^{(1)} = 0 \Rightarrow p_i^{(2)} > 0, \quad p_i^{(2)} = 0 \Rightarrow p_i^{(1)} > 0,$$
$$p_i^{(2)} = 0 \Rightarrow p_j^{(2)} > 0. \quad (9)$$

Assuming that the state (backlog) of the system at the tth slot is described by a variable $S\ (t)$ that takes values in the set $S = \{S1, S2, S3, S4\} = \{(0,0), (1,0), (0,1), (1,1)\}$, where each tuple describes the backlog of the two transmitters (1 means that the transmitter has a packet to transmit, while 0 mean it does not), the payoff is modeled as

$$R_i(\mathbf{p}) = \pi_{q(i)}(\mathbf{p}) p_i^{(1)} \rho^{(1)} + \pi_4(\mathbf{p})[p_i^{(2)}(1-p_j^{(2)})\rho^{(1)} + p_i^{(2)} p_j^{(2)} \rho^{(2)}, \quad (10)$$

where $q\ (1) = 2$, $q\ (2) = 3$ and $\pi_{q(i)}(\mathbf{p}) = P\ [S\ (t) = S_k]$, $k = 1,2,3,\ 4$ are steady state probabilities.

6. Network layer

Functionalities of the network layer include the establishment of routes and the forwarding of packets along those routes. In most cases game theory may be applied to aid a node in determining which the optimal route is or deciding whether it should forward a received packet or not. The latter are referred to as forwarding games. Game theory is a valuable asset in this context due to the fact nodes need to decide individually on their actions, while maintaining knowledge on the behavior of others. Since each node wishes to preserve its energy in order to be able to send as much traffic as possible, forwarding a packet for another node is not rational, at least at first glance.

6.1. Routing and forwarding

The games formulated here are non-cooperative and take place between a pair of nodes, denoted as i and $-i$. Variations such as Min–Max games or Bottleneck games can be also formulated [26]. In the routing problem, the source nodes can be viewed as the players in the game. The action set available to each player is the set of all possible paths from the source to the destination. In wireless ad hoc networks for example, nodes communicate with far off destinations using intermediate nodes as relays. Since wireless nodes are energy constrained, it may not be in the best interest of a node to always accept relay requests. On the other hand, if all nodes decide not to expend energy in relaying, then network throughput will drop dramatically. For this reason, ad hoc and peer-to-peer networks sometimes operate as voluntary resource sharing networks, relying on users' willingness to spend their own resources for the common good [27]. In [28] the utility function of such a game is modeled as $U_j\ (s) = a_j(s) + \beta_j(s)$, where $a_j(s) = a_j\left(\sum_{i\in N, i\neq j} s_i\right)$ is the benefit accrued by a user from others' sharing of their resources and $\beta_j(s) = \beta_j(s_j)$ is the benefit (or cost) accrued by sharing one's own resources with others, s being the joint action taken by all players ($s = 0$ stands for sharing and $s = 1$ for not sharing). The latter may be negative, since there may be a cost to participating in the network (such as faster depletion of a node's energy resources) or positive, if financial incentives for participation exist or if the user derives satisfaction in doing so.

Concerning forwarding games, a wide variety of utility functions has been proposed in this context; the majority of them consider metrics such as the node's forwarding ratio and energy consumption. For example, DARWIN [29]

considers the following payoff, given that α is the reward a node receives for forwarding a packet and p_i is the probability that node i drops a packet.

$$u_i = 1 + \frac{1}{2a-1}p_i - \frac{2a}{2a-1}p_{-i}. \quad (11)$$

7. Transport layer

At the transport layer, game-theoretic models have been mainly developed to analyze the effectiveness of congestion control algorithms. Congestion avoidance control refers to controlling the load of the network by restricting the admission of new user's sessions and resolving the unwanted overload situations. Admission control and load control constitute key mechanisms regarding Radio Resource Management (RRM).

7.1. Call admission control

Admission control takes place each time a new session request is received and decides whether it should be allocated resources or be rejected due to lack of resources. Its basic goal in cellular networks is to control the admission of new sessions within the network with the goal of maintaining the load of the network within some boundaries. The decision about the target network can be based on either user or network/operator criteria [30–32]. Fig. 1 depicts two different types of this kind of game, which will be analyzed in this section.

7.1.1. Provider vs. provider

In this kind of games the networks constitute the players. As individual players in the game, the access networks will try to choose the request that best fits their characteristics. Such a game may be played in rounds. In each round of the game the networks must decide which request will maximize their payoff and then select it. Once a request is selected it is removed from the set of service requests and the game is repeated, until all requests have been selected. A typical example can be found in [33]. The proposed game is non-zero-sum and non-cooperative, since a player is unable to bind and enforce agreements with other players.

7.1.2. Customer vs. provider

The main goal of such schemes is to maximize not only the QoS offered to customers, but also the provider's gain, therefore balancing the interests of both parties. Such an attempt has been modeled in [34–36]. The authors there consider that each customer has a contract with a specific service provider, thus him being the default network choice ("home" provider); nevertheless, if case of insufficient resources, the customer is free to pursue higher QoS at another provider, given that there is some kind of federation agreement between the visited and the home provider as in roaming (possibly under a small monetary penalty).

Suppose that there are N users and M service providers, which means that each user at any time can choose any provider, giving a total of M^Npossible states. Each user-provider combination is considered as a two-player game $G_j, 1 \leqslant j \leqslant M$. The proposed game is *non-cooperative* because, on the one hand, the service providers wish to maximize their revenue and, on the other hand, the users wish to maximize the quality of service received, keeping at the same time the expenses as low as possible. Since these two goals are obviously contradictory, the players do not have the slightest motivation to cooperate. The game is also *nonzero-sum*, since an increase in one player's payoff does not imply a decrease in the other player's payoff.

The user's revenue expresses in monetary value the quality of service offered to him, taking into account the cost, and may be modeled as $R = U{\cdot}q - C$, where U expresses the customer's utility function, q is a constant factor mapping the utility value to monetary value and C is the cost of the service from the customer's point of view [34–36]. It is also assumed that the provider's billing scheme takes into account the QoS percentage offered to customers, meaning that the customer pays an amount proportional to the level of QoS he receives.

In bibliography, in most cases, user satisfaction is monitored through utility. For instance, in [12], utility is approximated by a sigmoid function as $U = \frac{1}{1+e^{-a(b-Pb)}}$where

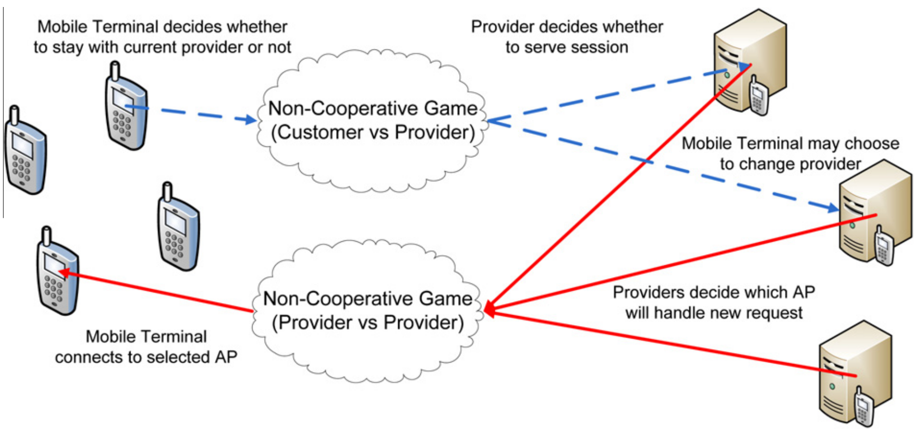

Fig. 1. Call admission control games.

P_b is the packet blocking probability and a, b are constants which determine the steepness and the center of the curve. Exact user utility functions can be obtained through field tests and user surveys.

As far as the solution of the game is concerned, two cases are distinguished. Assuming the case where the system is not full, the user request will be accepted and the probability that a customer leaves is near to zero. In this case there is a nash equilibrium, when the service provider accepts the request while the user remains with the provider. Assuming now the case where the system is loaded to a certain extent or even overloaded, the user request may be not accepted and the probability that a customer leaves is non zero. Even in this case, there is also a pure strategy nash equilibrium which depends on the relation between some terms in the payoffs. The new request is accepted if the revenue generated from admitting the request is greater than the possible revenue loss is the user leaves. Otherwise, the provider is better to reject the request.

7.2. Load control

The scheme described previously for admission control has also been expanded for load control in [36]. The main difference is that this game is played periodically while the sessions are running. Through this process it is possible to terminate sessions that greedily consume the system's resources, causing this way degradation to the QoS offered to the rest of the customers and thus reducing the provider's total revenue. Moreover, unsatisfied customers are granted the opportunity to seek more efficient networks, based on their preferences.

According to this scheme, if the QoS of at least one service type is found below the acceptance threshold, then the *global load control game* is triggered, during which games are played between the provider and all running sessions. This game may result in either disappointed customers leaving the provider or the provider terminating unprofitable customers. If either one decides that a connection should be terminated, then the session ends and the customer is prompted to another service provider. Penalty is submitted only if the customer chooses to leave willingly. On the other hand, if the global game is not triggered and at least one session presents a QoS below the acceptance threshold, then the *local load control game* is triggered. In this case, a game is played between the provider and each session that triggered the game, leaving the other sessions unaffected. This type of game may also result in some sessions being terminated.

7.3. Cell selection

Cell selection is responsible for guaranteeing the required QoS by always keeping the mobile camped on a mobile station with good enough quality. The goal of cell selection procedures is to determine which base station is the optimal choice. Gao et al. [37] formulate the cell selection problem as the two-tier game. In the first tier, i.e., in inter-cell game, the mobile stations select the cell according to the optimal cell selection strategy derived from the expected payoff. In the second tier, i.e., in intra-cell game, the mobile stations choose the proper time–frequency resource in the serving cell to achieve the highest payoff.

8. Discussion

In this section the authors discuss certain issues that are relevant with the application of game theory in wireless network. Table 3 summarizes the key elements of the games described throughout the previous sections.

8.1. Challenges in the use of game theory

The use of game theory in wireless networks unfortunately comes with a set of challenges, the most important of which are the following ones:

- *Assumption of rationality*
  Game theory is founded on the hypothesis that each player plays rationally and thus seeks his best interest in a rational manner. When dealing with nodes or terminals however this behavior cannot be always guaranteed.
- *Assumption of willingness to cooperate*
  In cooperative games it is assumed that players will collaborate in order to maximize their profits. A significant problem is that players sometimes choose to behave selfishly or even cheat in order to optimize their own profit. For this reason, in certain occasions, incentive mechanisms for cooperation, as well as disincentives against cheating need to be formulated.
- *Choice of utility functions/ payoff calculation*
  This is unquestionably the most challenging part of a game-theoretic framework, since the utility function interprets the player's perception of performance and satisfaction. Utility functions also show the trade-offs the player is willing to make, usually between acquiring more resources and saving money.
- *Not guaranteed existence of equilibrium*
  In game-theoretic formulations an analysis is often required to check if they reach a nash equilibrium. Even if an equilibrium is reached however, the existence of multiple equilibria is not always excluded. In such case the most efficient and stable one has to be sought.

8.2. Cooperation incentives

In several cases, optimization issues require collaboration among nodes. Nevertheless, cooperation cannot be taken for granted; even though in most cases players do obtain the optimal result by sharing resources with others, in certain cases it is not clear enough for them why they should not act selfishly or even not try to cheat. Nodes exhibiting such behavior are termed *selfish* and *malicious* correspondingly. The basic idea for node punishment is that nodes should be rewarded or penalized based on their behavior. Nodes that offer resources should be aided. On the other hand, selfish nodes should be gradually isolated from the network.

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Table 3
Collective information on game theory applications.

Specific application	Objective	Game type	Players
Power control for CDMA	Set transmission power in order to maximize SNIR with minimum interference.	Non-cooperative	Users/terminals
Power control in OFDMA networks	Minimize the overall transmitted power under rate and power constraints.	Non-cooperative	Users/terminals
Spectrum sharing – spectrum transactions	Distribute spectrum to maximize utilization and fairness.	Cooperative/ non-cooperative	Users/terminals, service providers
Power management in MIMO	Power allocation in links to minimize interference.	Non-cooperative	Links
Decode-and-forward cooperation	Power allocation problem	Cooperative/ non-cooperative	Users/terminals
Access to slotted Aloha	Model random access to slotted Aloha to minimize collisions.	Non-cooperative	Users/terminals
Random access to the interference channel	Share access to an interference channel	Non-cooperative	Users/terminals
Routing and Forwarding	Decide if a packet from another node should be forwarded or not. Choose the optimal path.	Non-cooperative	Users/terminals
Request distribution among providers	Distribute service requests among a set of providers in an optimal way.	Non-cooperative	Service Providers
Call acceptance based on provider and customer context	Decide if acceptance of a service request would be beneficial to both players – Selection of the optimal Service Provider.	Non-cooperative	Service provider – User/ terminal
Termination of sessions based on provider and customer context	Decide if termination of an ongoing session would be beneficial to either player.	Non-cooperative	Service provider – User/ terminal
Inter-cell and intra-cell games	Decide which cell can best fulfill service requirements.	Non-cooperative	Service provider – User/ terminal, service providers

In wireless networks, *incentive mechanisms* may be applied to urge players to cooperate instead of pursuing their own interest. Reputation and pricing are the main concepts around which cooperation incentive mechanisms are built, providing respectively *reputation-based* and *credit-based* mechanisms.

Credit-based systems have been used widely in routing formulations. The basic idea of these systems is to use notional credit, monetary or otherwise, to pay off users for forwarding packets coming from other users. This acts as a compensation for transmission and battery costs. These credits can then be used to forward their own packets through other users, resulting in an incentive to act as relay points. Users who do not cooperate will not be able to use the network themselves, having not earned any credits. One of the most well known credit-based schemes called Sprite [38] uses the idea of credit to solve the problem of routing in ad hoc networks of self-interested nodes. The basic advantage of credit based systems is that they succeed in a large scale to stimulate cooperation in networks with selfish nodes. Moreover, credits are useful when an action and its reward are not simultaneous.

On the other hand, reputation management systems can be categorized in centralized and decentralized and the reputation is estimated either in a central hub station or at each node individually. In the context of wireless networks, reputation reflects the player's willingness to contribute to the whole network by sharing resources, for instance to forward packets or not. The most accepted game theoretic framework that is used to analyze reputation is that of repeated games. Reputation systems may find application in self-organized networks, such as 4G, where there are various heterogeneous components. One of the main advantages of this kind of incentives is that it relies on observations from multiples sources, instead on the judgment of a single entity; it is therefore a rather subjective means of evaluation, relatively resistant to the diffusion of false information from a small number of lying nodes. CONFIDANT [39] is a protocol which detects and isolates misbehaving nodes. In this approach nodes have a monitor for observations, reputation records for first-hand and trusted second-hand observations, trust records to control trust given to received warnings, and a path manager for nodes to adapt their behavior according to reputation. On the other hand, in OCEAN [40] only first-hand observations are considered.

8.3. Game theory and 4G

Cooperation is the major issue in such self-organized communication systems, because users/nodes are concerned mostly for their own profits. They usually show selfish behavior which is catastrophic for the connectivity and the whole throughput of the wireless mesh network. The success of 4G will consist in the combination of network and terminal heterogeneity, as stated in [15,41,42]. Network heterogeneity guarantees ubiquitous connection and provision of common services to the user, ensuring at least the same level of QoS when passing from one network's support to another one. Moreover, due to the simultaneous availability of different networks, heterogeneous services will also be provided to the user [43,44]. The concept of node cooperation introduces a new form of diversity that results in an increased reliability of the communication, leading both to the extension of the coverage and the minimization of the power consumption. In fact, mobile terminals are less susceptible to the channel variations and shadowing effects and can transmit at lower power levels in order to achieve a certain throughput, thus increasing their battery life. Furthermore, cooperative

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transmission strategies may increase the end-to-end capacity and hence the spectral efficiency of the system [45].

Throughout the modeled games and applications highlighted so far, is should be clear how game-theoretic solutions may effectively predict/simulate realistic user behavior in competitive or cooperative scenarios. Since in 4G the most efficient allocation of resources is required, user cooperation may be modeled according to the principles of game theory. The authors envision a novel future architecture where users may form freely and dynamically resource sharing groups, where users are expected to share as many resources they see best for their own interests. Game-theoretic backgrounds can easily fabricate mechanisms for rewarding generous users or punishing selfish ones. Another possible application of game theory in 4G involves the resource or even client exchange among different networks or even providers, as discussed in previous Sections.

9. Concluding remarks

In this survey the authors have attempted to demonstrate how game theory can be applied to wireless networking. Following a layered perspective, it has been explained how to capture wireless networking problems in game-theoretic formulations, emphasizing on which game type best suits each application field and on how the corresponding utility function may be constructed. The purpose of this survey was to guide the interested readers familiar with computer science through the basics of both non-cooperative and cooperative game theory and to help them integrate this fascinating tool into their own studies.

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