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Spectrum sharing via hybrid cognitive players evaluated by an M/D/1 queuing model

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Abstract

We consider a cognitive wireless network in which users adopt a spectrum sharing strategy based on cooperation constraints. The majority of cognitive radio schemes bifurcate the role of players as either cooperative or non-cooperative. In this work, however, we modify this strategy to one in which players are hybrid, i.e., both cooperative and non-cooperative. Using a Stackelberg game strategy, we evaluate the improvement in performance of a cognitive radio network with these hybrid cognitive players using an M/D/1 queuing model. We use a novel game strategy (which we call altruism) to "police" a wireless network by monitoring the network and finding the non-cooperative players. Upon introduction of this new player, we present and test a series of predictive algorithms that shows improvements in wireless channel utilization over traditional collision-detection algorithms. Our results demonstrate the viability of using this strategy to inform and create more efficient cognitive radio networks. Next, we study a Stackelberg competition with the primary license holder as the leader and investigate the impact of multiple leaders by modeling the wireless channel as an M/D/1 queue. We find that in the Stackelberg game, the leader can improve its utility by influencing followers' decisions using its advertised cost function and the number of followers accepted in the network. The gain in utility monotonically increases until the network is saturated. The Stackelberg game formulation shows the existence of a unique Nash equilibrium using an appropriate cost function. The equilibrium maximizes the total utility of the network and allows spectrum sharing between primary and secondary cognitive users.

Keywords: Cognitive radio, Game theory, Stackelberg games, Spectrum sharing, Performance analysis, Queuing model, Opportunistic scheduling

1 Introduction

Demand is growing rapidly for wireless communication technologies, such as wireless data links, mobile telephones, and wireless medical technologies. This increasing demand places a significant burden on the limited wireless spectrum. Although the dominant spectrum allocation method (i.e., fixed allocations) is easy to implement, it does not maximize channel efficiency since the license holders (primary users) generally do not utilize their allocated spectrum at all times. A primary approach for increasing the efficiency of spectrum allocation is to allow a second group of unlicensed users to use it when the spectrum is idle. The users who wish to use the spectrum but do not have the primary license are called the secondary users, and they can opportunistically access the channel when the primary user is idle [1]. To facilitate this, we introduce a self-organizing mechanism and assess it by modeling the network as a queue that allows both classes of user to wait in a queue to access the channel modeled as a server.

Game theory has played an important role in developing efficient algorithms for sharing a common spectrum between secondary users [2]. Game theory is the study of cooperation and conflict between cognitive decision-makers, which, in this context, are represented by cognitive radios (a radio that changes its transmitter parameters based on feedback from the environment) in a wireless network [3]. Spectrum sharing via game theory occurs in both licensed and unlicensed bands [4] and [5]. Cognitive radio networks can be used for spectrum sharing both in unlicensed and licensed bands by using methods that can combine unused frequency bands and share them

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dynamically [6, 7] and [8]. Heterogeneous wireless systems are an example of unlicensed-band devices that rely on games for spectrum sharing [9]. Cellular operators that use WAN-WiFi are prime candidates for using games to share spectrum in licensed bands. Here, we focus on spectrum sharing in licensed frequency bands with primary users as license holders.

Game theory also plays an important role in deciding how a user must react to an event played by other users in order to maximize its utility (a measure of preferences over some set of strategies) [10, 11]. This decision is made by measuring the user's throughput (packets successfully sent over some specified time frame) and waiting time as metrics for each player's measured cost and gain.

Secondary users can be classified into cooperative and greedy players [12]. Greedy players are not cooperative in the sense that their only objective is to maximize their throughput. In [12], we proposed an "altruistic" user that is cooperative until it senses the presence of a greedy player via observation (for instance, channel usage) similar to [13]. In this situation, the altruistic player will turn into a non-cooperative player to punish the greedy players by jamming the wireless channel. This new altruistic player would subsequently back off when the greedy players act cooperatively with the other players. Adaptive greedy and altruistic players in spectrum-sharing games require an iterative method to study and predict their response. Here, we propose a new equilibrium concept, beyond that of Nash theory, that includes the strategy of a dynamically changing greedy player.

In the literature, spectrum allocation has been modeled with various pricing schemes as a non-cooperative game, with each cognitive radio acting as a player. References [14] and [15] propose a price-based spectrum-management system using a water-filling algorithm. Their algorithm employs a distributed pricing procedure that leads to an improved Nash equilibrium solution compared to iterative water-filling [16]. However, our proposed pricing scheme to be used in the utility function, based on primary users only, is intuitively more realistic since the primary users are the license holders. A game-theoretic model is presented in [17] that achieves the optimal pricing for spectrum sharing based on competition between multiple primary users to give spectrum access to secondary users. However, here, we assume a generalized distributed system that uses a single pricing model for each primary user. Yet, to address the secondary users' competition to maximize their spectrum access, we offer different pricing functions based on the traffic on the network and other variables such as available spectrum.

An extensive survey presented in [18] reviews the state-of-the-art and advances in cognitive-radio medium access control protocols. A stochastic geometry framework that captures the performance of an asynchronous ALOHA network in which a subset of nodes operates in full-duplex mode is presented in [19]. Compared to [20] and [21], in which an altruistic player can regain access to shared spectrum in an asynchronous ALOHA network, [19] only allows licensed primary users to access the network. In order to evaluate our game theory modeling approach, we used a queuing analysis that is used in [22]. The opportunistic access used for the performance analysis in [22] does not consider different cost functions or pricing schemes, number of primary or secondary cognitive users, or congestion. An M/G/1 queuing system (a queue model in which arrivals are Markovian and service times have a general distribution with a single server) containing one primary and multiple secondary users is presented in [23]. Here, we use an M/D/1 queuing system, merely to be used for analysis. Secondary users can gain access to the spectrum through an amplify-and-forward time-division multiple-access protocol. Our method is more generalized in that it supports multiple primary users as well as general cost functions that are not imposing any performance requirement for secondary users such as amplify and forward.

In this paper, we investigate a Stackelberg competition with the primary user as leader and find that in the Stackelberg game, the leader can improve its utility by influencing the follower's decision using its advertised cost function and the number of followers accepted into the network. For a given stable system and for feasible transmission rate sets, based on the number of primary and secondary users, we find a Nash equilibrium for primary and secondary users. We study a network of cognitive radios competing to access the spectrum that are either cooperative or non-cooperative. We introduce a hybrid player, i.e., one which is both cooperative and non-cooperative. Using a Stackelberg game strategy, we evaluate the improvement in performance of the cognitive players using an M/D/1 queuing model. We use altruism to monitor the spectrum usage and find the non-cooperative players. We also study a Stackelberg competition with primary users as leaders and investigate the impact of multiple leaders by modeling the wireless channel as an M/D/1 queue.

The remainder of this paper is organized as follows. In Section 2, we describe the game with a greedy and normal player and demonstrate that a vigilante player mitigates the impact of a greedy player. We then describe the M/D/1 queuing modeling and the proposed cooperation scheme. In Section 3, we formulate and solve a Stackelberg game with the primary user as the leader and employ a Vickrey auction between secondary users. In Section 4, we provide the numerical results for several communication scenarios and observe the impact of the network parameters in each case. In Section 5, we discuss our results and conclusions.

2 Problem definition

We study various generalizations of fundamental communication models for cognitive radios, using new equilibrium concepts beyond Nash theory that can capture the realistic aspects of spectrum sharing. We consider two cognitive-radio player types in which only the primary user has access rights to radio resources as shown in Fig. 1. Both primary and secondary cognitive users have data to transmit using the spectrum, which is modeled as a server in our queuing model presented in Fig. 1. Cognitive users participating in a Stackelberg game are selfish in the sense that they will act to maximize their respective utilities, i.e., minimizing the time in the queue. The primary and secondary users are leader and follower, respectively, in a Stackelberg game, and the follower will control the game by advertising its strategy (Fig. 1) to the follower. As it can be seen in the figure, both players are competing to access the server (spectrum) to transmit their data, but the leader can influence the strategy that the follower chooses by advertising its parameters.

Below, we first introduce a vigilante player to cope with a greedy player that maximizes its utility function by transmitting more than its allocation. Second, we focus on a queuing analysis of opportunistic access in cognitive radios. All variables used in this paper are defined in Table 1.

2.1 Vigilante player

All players in this setup are considered secondary cognitive players. We desire a wireless network with only one visible greedy player for any specific cell. We assume that a cognitive network with M players can be divided into m cells each with N_i players in ith cell as shown in Fig. 2. Without loss of generality, we assume that there are the same number of cognitive radios on average in each cell, i.e., the N_i terms are equal. This simplifies our study of movement of a greedy player and its impact on our proposal because only N_i players will be affected by the greedy player. The greedy player is defined as one that is not transmitting with probability $1/N_i$ in its current cell and uses the following for updating its transmitting probability in a slotted ALOHA accessing scheme:

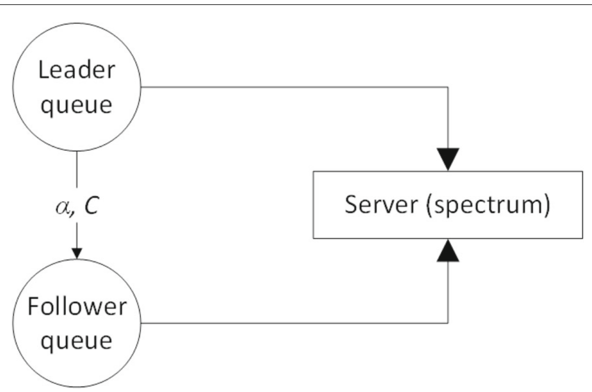

Fig. 1 Queuing model of primary user as a leader and secondary user as a follower in Stackelberg game

Table 1 Summary of variables used in paper

A_i	Total number of normal players in ith cell
B_i	Total number of players that are not vigilante in ith cell
C	Cost function
e_g	The aggressiveness of the greedy player
e_v	The aggressiveness of the vigilante player
i	Cell indicator
M	Total number of players in network
m	Total number of cells in network
N_i	Total number of players in ith cell
n_p	Number of primary players
n_s	Number of secondary players
P_g	Transmitting probability of greedy player
P_n	Transmitting probability of normal player
P_v	Transmitting probability of vigilante player
Q_g	Throughput of greedy player
Q_n	Throughput of normal player
Q_v	Throughput of vigilante player
u_g	Greedy utility function
u_p	Primary utility function
u_s	Secondary utility function
u_v	Vigilante utility function
W_p	Primary waiting time
W_s	Secondary waiting time
α_p	Share of bandwidth used by primary
α_s	Share of bandwidth used by secondary
λ_p	Packet rate for the primary
λ_s	Packet rate for the secondary
μ	Server rate or bandwidth

$$P_g(t+1) = e_g P_g(t) : (P_g(t+1) < 1), \tag{1}$$

where e_g is used to model the aggressiveness of the greedy player and the : condition denotes that probability cannot exceed 1. Other models are possible, but Eq. 1 adequately models a greedy player that aggressively updates its transmission probability. By using the throughput

$$Q_g = P_g \prod_{A} (1 - P_a), \tag{2}$$

where A is all players except the greedy player and P_a is the transmission probability for those players, one can define

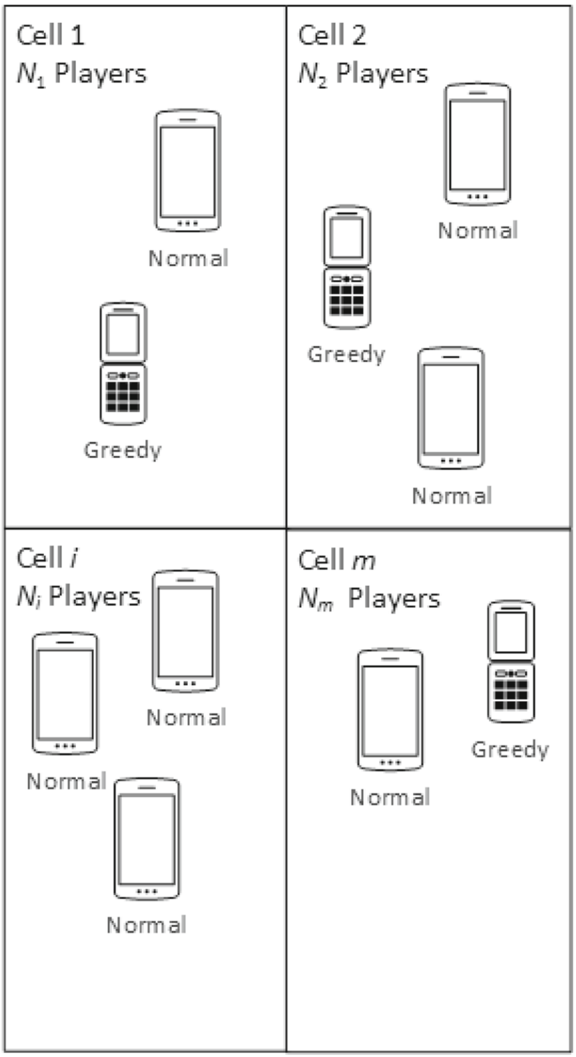

Fig. 2 Cognitive network with M players can be divided into m cells each with N_i players

a basic utility function for the greedy player that needs to be minimized, i.e.,

$$U_g = 1 - Q_g. \tag{3}$$

A vigilante player can be defined with an altruistic approach to jam the shared resource causing the greedy player to lower its transmission probability with a similar transmission probability to Eq. 1. Assume, if

$$Q_v = P_v \prod_B (1 - P_b) < Q_n, \tag{4}$$

where Q_n is the throughput of a normal player in the absence of a greedy or vigilante player [24], B is all players except the vigilante player, and P_b is the transmission probability of those players, then the vigilante player uses the following to update its transmission probability:

$$P_v(t + 1) = e_v P_v(t) : (P_v(t + 1) < 1) , \tag{5}$$

where e_v is an aggressiveness factor used to cope with the greedy player. Define $Q_v = P_v \prod_B (1 - P_b)$ as the throughput of the vigilante player, where B represents other players in the same cell as the vigilante player. The vigilante player acts as greedy to make the nodes cooperate rather than maximizing its throughput, so the vigilante player's utility function is defined as

$$u_v = |Q_v - Q_n| , \tag{6}$$

where Q_n represents a throughput for a cooperative player without any greedy or vigilante players. Assuming an approximation of a throughput, we can find the following equation for the choice of e_g for the greedy player to minimize its utility function based on full knowledge of the game played by the vigilante player:

$$\frac{du_g}{de_g} = 0 \rightarrow e_g = e_v \frac{N}{N - 1}, \tag{7}$$

where the vigilante player is aware of e_g because of the nature of Stackelberg games, and N is total number of cognitive radios in the corresponding cell.

In our model, one must assume that a greedy player is able to move between the geographical cells; in which case, it can move from a cell with an active vigilante player to a cell in which the presence of a vigilante player is unknown. Once moved, then a cooperative player will turn into a vigilante player, and the same cyclic behavior occurs. If the greedy player is static, i.e., not able to move between cells, then it cannot achieve more than its share because of the presence of an active vigilante player. We investigate these behaviors and show that the same cyclic behavior happens in the new cell.

2.2 M/D/1 queueing model

Here, we show that the problem of spectrum sharing between multiple primary and secondary users can be analyzed by a queuing model. We assume a channel with accessible bandwidth of μ and two virtual queues for primary (leader) and secondary (follower) users, as leader and follower shown in Fig. 1. A Poisson process is assumed for packet arrival times with a uniform packet size, and we use a modified M/D/1 (queue in which arrivals are governed by a Markovian process, service rate is fixed, and has a single server) queuing system to analyze the network performance. We use the waiting time to correlate our game theory approach with the M/D/1 queuing model. The expected waiting time for a stable queue is positive and finite. Waiting time is one of the parameters used to define the utility function in our Stackelberg game. In a Stackelberg game, the follower chooses its game strategy to maximize its utility based on the leader's advertised strategy. That means the leader and follower play a sequential game in which the follower must react optimally to a strategy imposed by the leader. Furthermore, the leader is capable of calculating the follower's best response to any imposed plan. As a result, the leader chooses a strategy to maximize its utility knowing the follower's reaction [25]. For the M/D/1 queuing system and a primary user, we know that [26] (for our model, we employ a Poisson distribution as this is simpler, yet can be shown to be equivalent to Markovian)

$$W_p = \frac{1}{2(\mu - \lambda_p)} \frac{1}{2\mu}, \tag{8}$$

where W_p is the expected delay in the queue for the primary user, λ_p is packet rate for the primary, and μ is the server rate or, in this model, the spectrum bandwidth. By assuming that the primary user is going to auction the spectrum access to a secondary user, we can define

$$n_p\alpha_p + n_s\alpha_s = 1, \tag{9}$$

where α_p is the share of bandwidth used by a primary user, α_s is the share of bandwidth used by a secondary user, n_p is the number of primary users, and n_s is the number of secondary users. These coefficients must add up to one in order to fully utilize the spectrum bandwidth available to the cognitive radios. We define the utility function of the leader to share the spectrum as

$$u_p(\alpha_p, \lambda_p, \mu, n_s, n_p) = -\ln(W_p) - \ln(\alpha_p/n_t)C(n_s, n_p, \mu), \tag{10}$$

where $C(n_s, n_p, \mu)$ is the cost function used by the primary user to advertise the excess bandwidth available to the followers. We can define a simple cost function to capture the impact of n_s on the cost by a logarithmic function as

$$C_1(n_s) = \ln(1 + n_s). \tag{11}$$

In Section 4, a comprehensive discussion for the choice of cost functions and their impact on the Stackelberg game is presented. The follower, or the secondary user, in the Stackelberg game uses the following as its utility function (since waiting time in the queue has a negative impact on the utility):

$$u_s(W_s, n_s) = n_s - \ln(W_s). \tag{12}$$

To find the Nash equilibrium, both primary and secondary users will gain no additional access to bandwidth (server) by moving from the point defined by (α_p, α_s). As a result we have:

$$\frac{\partial u_p(\alpha_p, \lambda_p, \mu, n_s, n_p)}{\partial \alpha_p} = 0 \tag{13}$$

and

$$\frac{\partial u_s(W_s, n_s)}{\partial \alpha_s} = 0. \tag{14}$$

To ensure the M/D/1 queue is stable, the pair of points found in Eqs. 13 and 14 must mutually lie in the set:

$$0 \le \alpha_p, \alpha_s \le 1, \tag{15}$$

$$\alpha_p\mu \le \lambda_p, \text{and} \tag{16}$$

$$\alpha_s\mu \le \lambda_s. \tag{17}$$

3 System model

Below, we first study a game with three players who desire to maximize their utility functions, each using a unique strategy. Then, we formulate and solve a Stackelberg game for the communication scenario described in Section 2.2 with the primary license holder and secondary users as leader and followers of the Stackelberg game, respectively.

3.1 Game with three players

Without loss of generality, the utility functions defined in Section 2.1 are simplified versions of the utility functions defined in [24]. Based on different pairs of (e_v, e_g), one can see either a cyclic behavior for the throughput of the players [24] or a Nash equilibrium [27]. For the case of reaching an equilibrium, the vigilante player uses most of the shared bandwidth, which keeps the greedy player from increasing its transmission probability and, as a result, there is no fair resource sharing for cooperative players to use.

By moving from a cell that has an active vigilante player, the greedy player can minimize its utility function. In a distributed cognitive network, a predefined radio node in each cell can be considered/assigned as a vigilante player. For a dynamic greedy player, the measured throughput that is an indicator of e_v is used to calculate the best e_g and/or best time to move to a new cell.

By introducing a vigilante player and using non-traditional game strategy for decision-making, we hope to improve the performance of a cognitive radio network. To date, the application to cognitive radio networks of a hybrid player, which is both cooperative and non-cooperative, has not been studied significantly. We propose a play strategy (i.e., altruism) to police a wireless network. Using this new player, we will test a series of predictive algorithms to investigate a potential improvement in wireless channel utilization by punishing the non-cooperative players. Then, we will use this strategy to demonstrate the application of a vigilante player in an M/D/1 queue.

The mean value of a received signal in a certain frequency range is an indicator of the presence of a primary user. Since malicious users are more effective in acting in a cooperative manner with other malicious users to change the mean and make a false pretense that a primary user is active, one can suggest finding these users in an iterative manner [28]. With this method, one can find their intention for changing the mean by averaging their advertised signal power and treating them as a separate group inside each cell, which is plausible since one can argue that by introducing a fusion center, the algorithm will be capable of disregarding the malicious users as a group. If a user is falsely accused of being malicious due to multipath fading and/or shadowing, it can be reclassified as a normal user if the weight assignment method is implemented [27].

3.2 Stackelberg game in M/D/1 queue

In our Stackelberg game, in order to have a stable queue, the validity and stability of spectrum sharing assessed via the M/D/1 queuing system needs to be investigated in terms of the number of primary and secondary users as leaders and followers, respectively. By having more than one primary user, it is intuitive to show that the M/D/1 queue with a constant μ will be unstable for a larger set of λ_p. A similar argument applies for followers with λ_s. This will lead to a feasible set tighter than Eqs. 15, 16, and 17 redefined using Eq. 9, i.e.,

$$0 \leq n_p\alpha_p, n_s\alpha_s \ \leq \ 1, \tag{18}$$

$$\alpha_p\mu \ \leq \ n_p\lambda_p, \text{and} \tag{19}$$

$$\alpha_s\mu \ \leq \ n_s\lambda_s. \tag{20}$$

This tighter feasible set requires a careful consideration for the number of followers admitted to the queue to ensure that it remains stable. A network can estimate the number of secondary users it can accept based on multiple variables such as the number of primary users, service rate, and request rates by primary and secondary users. Cost functions used in Eqs. 13 and 14 can be chosen to prioritize one or more variables mentioned above and/or, by using a Vickrey auction, the highest bidder will win and then the leader's strategy will adopt to that. The existence of Nash equilibrium in this tighter feasible set will allow the network to share unused spectrum with the followers with a gain in spectrum usage advertised by the cost function to the leaders by transmitting that cost function. By defining the set of pairs (α_p, α_s) satisfying Eqs. 15, 16, and 17 as set A, it is easy to show that the Nash equilibrium point for the leader of the Stackelberg game can be found from:

$$\alpha_p = \begin{cases} \frac{\lambda_p(C-1)}{\mu(C-2)} & \text{if } \alpha_p \in A \\ 1/n_p & \text{if } \alpha_p \notin A \end{cases}, \tag{21}$$

where C is the cost function for that pair, for example, the simple cost function defined in Eq. 11. If there is no answer for α_p, then the primary user has no motive to share the spectrum because it makes the network unstable.

The Stackelberg game using three types of secondary users introduced in Section 3.1, and a primary user as follower will result in a cyclic behavior. The leader cannot stop a greedy player, instead it will not share the spectrum when the network is saturated, according to Eq. 21. In this scenario, the vigilante player will force the greedy player to move to another cell.

4 Numerical analysis

Here, we present the simulation results of cyclic behavior of the three players' utility functions introduced in Section 2.1. Then, we introduce the numerical analysis of a Stackelberg game introduced in Section 2.2 with parameters inside the feasible set defined in Section 3.2.

4.1 Cyclic behavior for vigilante player

Via numerical analysis, we study the movement of a greedy player and the correlation between e_v and the average throughput of a greedy player based on the number of cooperative players in a cell. First, without loss of generality in our numerical simulation, we specify ten cells with $N = 5$ players in each cell assuming one will turn vigilante if its throughput is less than Q_n. The vigilante player always assumes that this decrease in its utility function is due to presence of a greedy player. If this assumption is wrong due to transmission error, the vigilante player will turn to normal in the next iteration according to the algorithm. The turned node will then follow Eq. 5 as its transmission probability. In order to clearly see the changes in throughput, we use $e_g = 1.1$ and $e_v = 1.3$ (assuming $e_v \geqslant e_g > 1$); the sudden decrease in throughput for the greedy player leads the dynamic greedy player to change cells to minimize its utility function as seen in Fig. 3. Each cycle represents a migration from a cell.

To study the effect of e_v, we assumed a greedy player with $e_g = 1.2$ for updating its transmission probability (Eq. 1) in a cell of N nodes from 5 to 45. After sensing the presence of a vigilante player, the greedy player will move to a neighboring cell. Different values for e_v that do not cause a desired Nash equilibrium are shown in Fig. 4. As it can be seen from Fig. 4, less aggressive vigilante players ($e_g = 1.2, e_v = 1.2$) will cause the greedy player to stay in a cell and, as a result, its utility function will be minimized allowing greater throughput. More aggressive vigilante players ($e_g = 1.2, e_v = 1.5$) cause the greedy players to switch cells and, in a new cell, it takes time for the greedy player to minimize its utility function, which when minimized leads to less throughput for others. If a greedy player were static, the behavior would not be cyclic and would be represented by the first "hump" only (i.e., time slot 0–17 in Fig. 3).

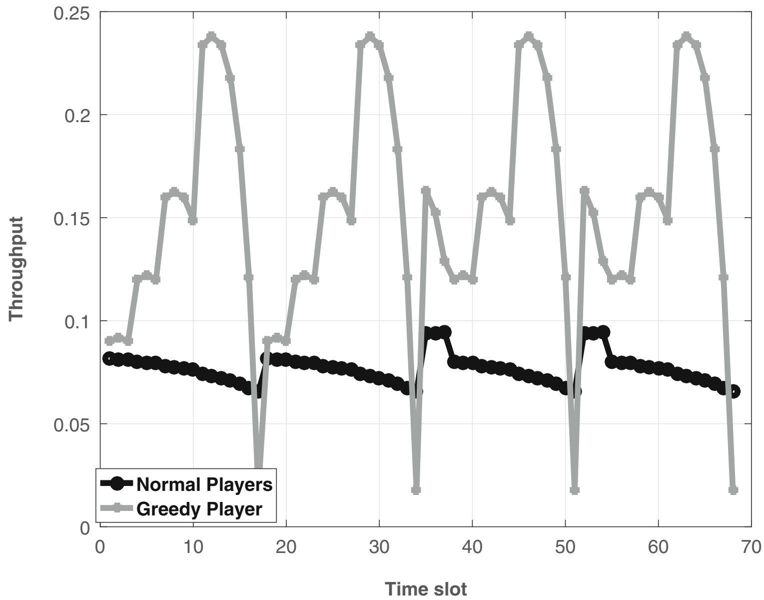

Fig. 3 The cyclic behavior of a moving greedy player's throughput compared to average throughput of static normal players in an affected cell

4.2 Spectrum sharing performance analysis of a Stackelberg game using an M/D/1 queueing model

For the Stackelberg game's Nash equilibrium analysis, we first present the simulation results analyzed via an M/D/1 queue, with one primary user as the leader, and then extend the results with multiple leaders. We evaluate the utilities of the leader and follower at the equilibria found in Sections 2.2 and 3.2. We omit the equilibria found in the feasible set defined by Eqs. 15, 16, and 17 when the utility function for both leaders and followers yields zero. As shown later in this section, this happens when the network is close to saturation. The available bandwidth is between 40 to 160 kbps (we use actual numbers to compare the results for different scenarios). We vary the remaining parameters, such as the number of primary and secondary users (n_p, n_s), cost function, and accessible spectrum μ, in order to assess their impact on the utilities.

Figure 5 shows the utilities resulting from the Stackelberg game's Nash equilibrium, defined in Section 3.2 with the scenario presented in Section 2.2, with the simple cost function of Eq. 11. For this set of analyses, there is only one primary user as a leader, and the number of secondary users varies from 1 to 20. In this Stackelberg game, as the number of secondary users increases,

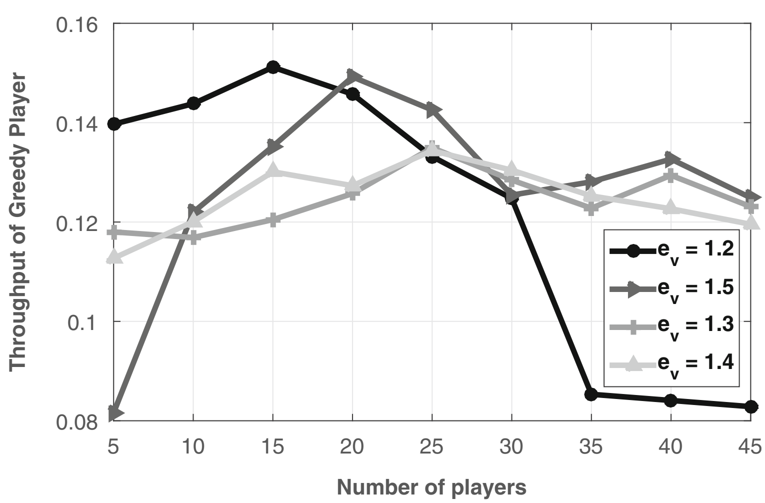

Fig. 4 Effect of a vigilante player's aggression coefficient, e_v, on the throughput of a moving greedy player

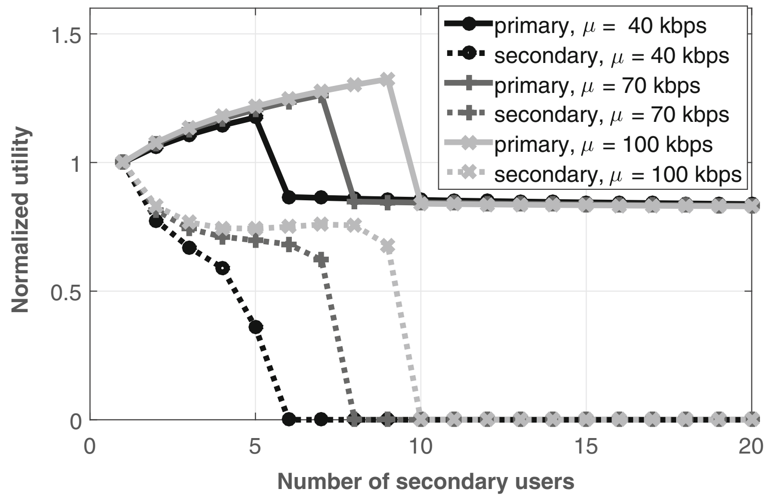

Fig. 5 The two players' normalized utilities versus the number of secondary users with $n_p = 1$, $\lambda_p = 10$ kbps, $\lambda_s = 1$ kbps and different μ ranging from 40 to 100 kbps for the Stackelberg games in Section 3.2 and cost function defined with Eq. 11

their utility decreases while the leader's utility increases until the cognitive network is saturated. It is intuitive to show that the follower's utility functions decrease because of competition to access the limited spectrum with the fellow followers, and it gets increasingly critical when μ decreases for the constant $\lambda_p = 10$ kbps, $\lambda_s = 1$ kbps. In this scenario, the best approach by the leader is to admit as many secondary cognitive nodes in the cell based on the available μ, until its normalized utility function has an optimum. For $n_s = 5, 7$, and 9, this happens for $\mu = 40$, 70, and 100 kbps, respectively.

Figure 6 shows how the utility function reacts by varying the number of primary users in order to observe the impact of the number of leaders in the Stackelberg game. To satisfy the feasible set defined by Eqs. 15, 16, and 17, the server rate μ varies from 100 to 160 kbps. This range will delay the saturation and will let us understand the impact of the number of leaders in the game. As before, $\lambda_p = 10$ kbps, and $\lambda_s = 1$ kbps, but the number of secondary users is constant, $n_s = 3$. In this case, the main reason for the decrease in the normalized utility is the competition to access the network between the primary users; when the cognitive network is saturated, there will be no utility for the secondary users. The saturation for $\mu = 100$, 130, and 160 kbps happens at $n_p = 7, 8$, and 9, respectively.

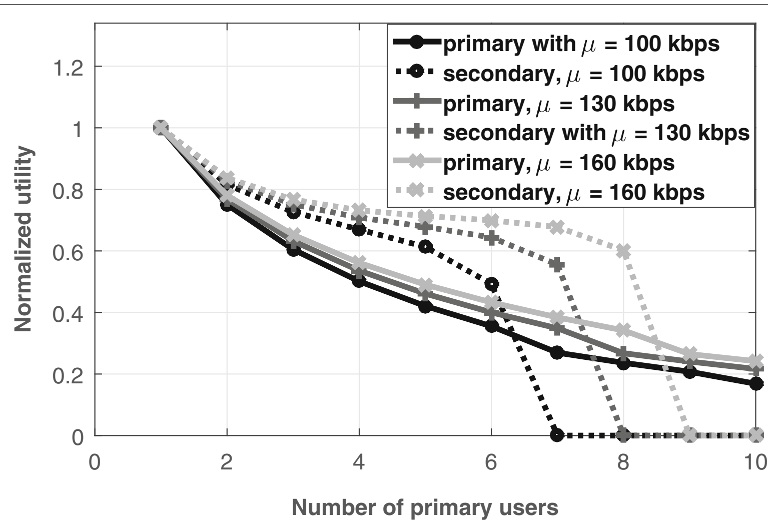

Fig. 6 The two players' normalized utilities versus the number of primary users with $n_s = 3$, $\lambda_p = 10$ kbps, $\lambda_s = 1$ kbps, and different μ ranging from 100 to 160 kbps for the Stackelberg games in Section 3.2 and cost function defined with Eq. 11

Figures 7 and 8 demonstrate the impact of different cost functions on the utility function and the saturation of the cognitive network. In the following cost functions, we include μ and n_p as additional inputs to determine the cost of spectrum access. First, the cost is monotonically increasing with the number of primary users in the cognitive network and with the available spectrum, i.e.,

$$C_2(n_s, n_p, \mu) = \ln(1 + n_s) + \ln(n_p \times \mu). \quad (22)$$

In the second cost function, we assume that an increase in μ reduces the cost of sharing the available spectrum, i.e.,

$$C_3(n_s, n_p, \mu) = \ln(1 + n_s) + (n_p \, \mu). \quad (23)$$

Figure 7 shows the relationship between the cost function and varying normalized utility of both players versus the number of primary users. Here, the parameters for our game are $n_s = 3$, $\lambda_p = 10$ kbps, $\lambda_s = 1$ kbps, and $\mu = 100$ kbps. It can be concluded that via a Vickrey auction, we can have different saturation points for the number of secondary users. For Eqs. 11, 22, and 23, we have a saturated network for $n_p = 5, 6$, and 6, respectively.

Figure 8 provides a comparison of the utility functions of both players versus the number of secondary users, where $n_p = 2$, $\lambda_p = 10$ kbps, $\lambda_s = 1$ kbps, and $\mu = 100$ kbps. Here, for Eqs. 11, 22, and 23, we have saturation for $n_s = 8, 9$, and 9, respectively. As can be seen in Fig. 8, there will be a cutoff point for the number of secondary users. This means that, no matter what cost function we use, there is a point beyond which the queue will be saturated. By choosing an appropriate cost function, one can modify the maximum number of secondary users admitted in to the network.

In a queue with $n_s = 2$, $n_p = 2$, $\lambda_p = 10$ kbps, $\lambda_s = 1$ kbps, and $\mu = 100$ kbps, we assume that one of the secondary users is a greedy player defined in Section 3.1 with $e_g = 1.05$. As mentioned before, the other secondary users will sense the extensive spectrum usage and turn into a vigilante player with $e_v = 1.2$. The cyclic behavior of the greedy player in each cell can be seen in Fig. 9. This cyclic behavior has been predicted by the analysis presented in Section 2.1. A normal player turned to a vigilante player will force a greedy player to act normal in our queue.

5 Conclusions

Traditional game strategy for cognitive radio networks generally only includes static non-cooperative players. More efficient cognitive radio networks can be constructed by modeling more realistic dynamic players with various goals that lead to different strategies. In this paper, an altruistic cognitive player is introduced to monitor and police the network. A dynamic greedy player and vigilante player in each cell are used to study the cyclic behavior of a game to maximize the throughput of greedy and cooperative (non-vigilante) players, respectively. In our simulations, without loss of generality, we assumed that the network is divided into cells containing the same number of nodes. We assumed a static vigilante player because any cooperative player can sense its throughput and follow an altruistic strategy. We studied the correlation between the number of players in a cell and the aggression factor of a vigilante player with the greedy player's throughput.

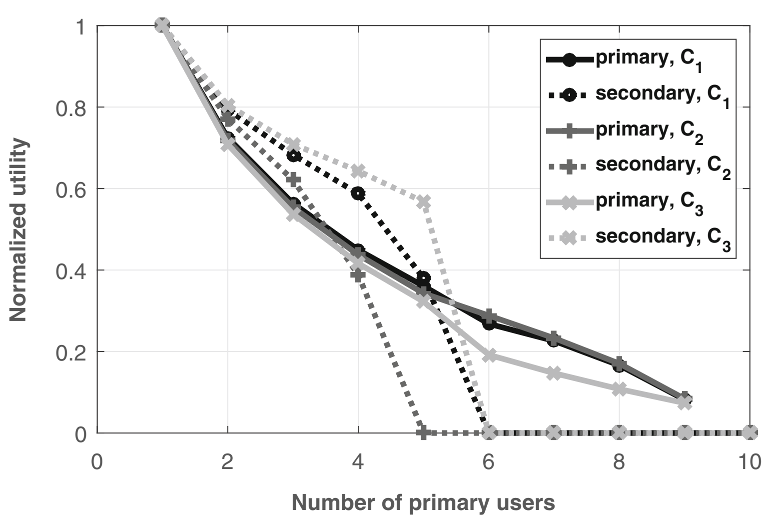

Fig. 7 The two players' normalized utilities versus the number of primary users with $n_s = 3$, $\lambda_p = 10$ kbps, $\lambda_s = 1$ kbps, and $\mu = 100$ kbps and three cost functions with C_1, C_2, and C_3 defined by Eqs. 11, 22, and 23, respectively

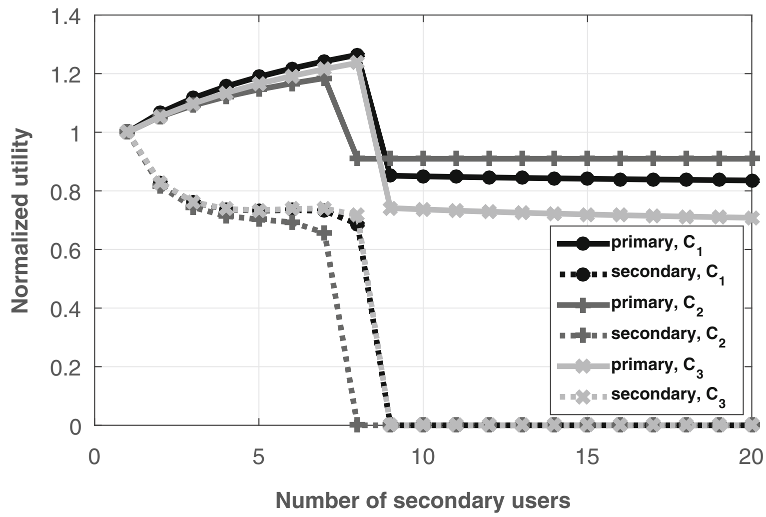

Fig. 8 The two players' normalized utilities versus the number of secondary users with $n_p = 2$, $\lambda_p = 10$ kbps, $\lambda_s = 1$ kbps, and $\mu = 100$ kbps and three cost functions with C_1, C_2, and C_3 defined by Eqs. 11, 22, and 23, respectively

The result is used in the study of a Stackelberg game and assessed in an M/D/1 queue.

We studied the spectrum sharing cooperation by modeling the spectrum and users as an M/D/1 queue, with the goal of encouraging the cognitive players to cooperate. We have focused on the system model that, despite the desire to maximize their individual utilities, the cognitive players find it beneficial to cooperate. We have formulated a Stackelberg game in which the primary license holder and secondary user are leader and follower, respectively, and studied how the leader can influence the follower's decision of participating in the game by varying the cost function. Additionally, we observed that a pricing scheme can be employed to improve all utilities to the social optimality of an M/D/1 queue. In this scenario, cognitive users can employ the cost function to decide how much of the spectrum is used by primary users and secondary users.

A future direction is to study the impact on performance of full and partial knowledge of the game strategies for all players. The partial knowledge is a more realistic study of cognitive radio to be used for wireless transmission. The throughput used by a vigilante player to make the greedy player migrate or cooperate needs to be studied to assess the performance accurately. The complexity of our network can be investigated by modeling it with an embedded Markov chain using an approach similar to

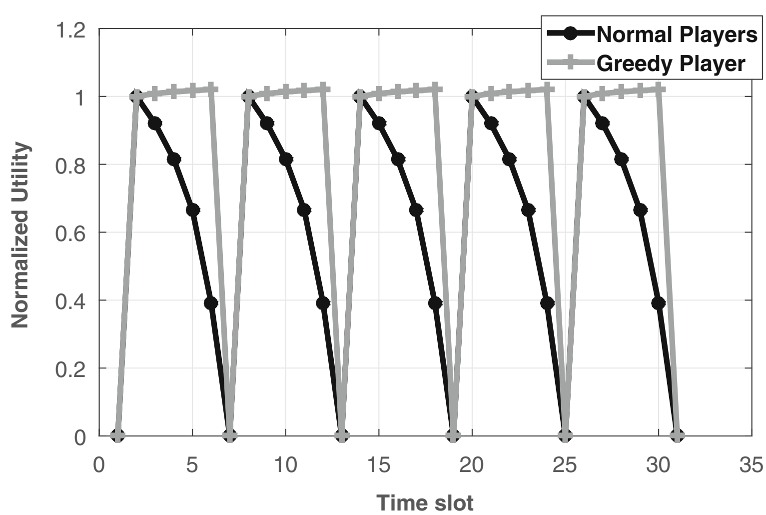

Fig. 9 Greedy player in a queue with $n_s = 2$, $n_p = 2$, $\lambda_p = 10$ kbps, $\lambda_s = 1$ kbps, $\mu = 100$ kbps, $e_g = 1.05$, and $e_v = 1.2$ for the Stackelberg games in Section 3.2 and cost function defined in Eq. 11

that in [29], which investigated consecutive loss in a simple queue. By introducing cells into their scheme, one can use an approach similar to the one presented in that work to study large networks. Naturally, computational complexity will increase significantly if cognitive radios act in a strategy that is between greedy and hybrid. Investigating these tradeoffs is left as future work.

Authors' contributions
KK and SGB conceived and designed the study. Both authors read and approved the manuscript.

Competing interests
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