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Primary–secondary interaction modelling in cellular cognitive radio networks: a game-theoretic approach

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Abstract: Underutilisation and scarcity of the available bandwidth have led to the idea of spectrum sharing as primary users partially transfer their rights for spectrum access to others in return for rewards. In this study, we introduce a new distributed game-theoretic approach in order to analyse the dynamic spectrum leasing problem in the uplink side of cellular cognitive radio networks. In such scenarios, it is necessary to define utility functions for primary and secondary users according to their incentives in order to model such interaction properly. We prove the existence of the Nash equilibrium point as well as its uniqueness for our model in the framework of standard power control algorithms and demonstrate fast convergence rate of the proposed method through numerical results. Owing to cellular architecture of the problem, the improvement in power consumption and signal-to-interference ratio (SIR) levels as users are given the opportunity to switch between different base stations is then investigated. Furthermore, we propose a simple admission control scheme and show the resulting performance improvement through simulations. In addition, the proposed framework provides the possibility of investigating trade-offs in terms of various system parameters.

1 Introduction

Scarcity of available bandwidth and its underutilisation have led to the idea of implementing secondary networks on top of the original ones [1]. However, for such system to work properly, primary users who have the right to use network resources must be protected from extra interference through proper spectrum-sensing mechanisms [2]. On the contrary, secondary users have to be served with a minimum acceptable level of quality of service (QoS) [3]. Such QoS level may be defined based on the given application scenario. The target signal-to-interference ratio (SIR) level achieved at an acceptable power consumption level is usually a good criterion for service assessment. For example, the model in [4] considers a cost function involving power consumption as well as SIR deviation from a target value. The algorithm in [5] focuses on achieving minimum error probability for a predefined SIR value. Using an adaptive method for modification of cost factors during the game in [6], faster convergence with respect to [4] is achieved, at the expense of slight degradation in SIR levels. In a recent study [7], it has been shown that a proper choice of utility function results in lower power levels and higher throughputs with respect to [4].

Secondary networks may be implemented in three different ways [8]. The first option is open sharing in which there is no difference between primary and secondary users for resource access. Another option is hierarchical access in which secondary users tend to use the spectrum without disturbing the performance of primary ones. The last one, adopted in this study, is dynamic exclusive use in which primaries are willing to partially transfer their rights to others in return for receiving rewards. At the same time, secondary users desire acceptable service levels at minimum power consumption level possible. Consequently, satisfaction of each user's goals disturbs other users in the form of imposed additional interference.

In this study, we focus on a game-theoretic approach [9] to analyse primary–secondary interaction in the uplink side of a cellular network based on the dynamic exclusive use option. This problem was first addressed by [10] where a primary user improves QoS level through cooperating with secondary users, at the expense of leasing a portion of the assigned time slot to the secondary network. However, the aforementioned study does not involve simultaneous transmission of primary and secondary networks which is the main issue in our work. One main contribution to this domain, also known as dynamic spectrum leasing (DSL), which relies on a game-theoretic approach is proposed in [11]. In their approach, primary users also participate in the devised game and the effect of different receiver types, matched filter (MF) and minimum mean squared error (MMSE), on secondary base stations is considered. In [12], for the case of slow-varying fading channels, the trade-off between performance and channel state information update rate is addressed. In [13], new utility functions for both secondary and primary users are introduced and the effect of the new model on system performance is analysed. A general DSL structure considering different variations of channel conditions is also introduced in [14]. In a recent study [15], the algorithm in [11] is generalised to a centralised method with MF and MMSE receivers. Finally [16], investigates interaction of two secondary operators competing for spectrum leasing. It also compares the performance of the non-cooperative method with the case in which operators collaborate, and concludes that in some scenarios anarchy is more beneficial to the end users.

Although the interaction between primary and secondary users has been initially addressed in [11], in this study, we specifically consider such interaction in cellular cognitive radio networks. The effect of permitting users to switch over base stations is then investigated and the resulting reduction in power consumption is demonstrated. We also propose an admission control as a way to improve performance of our algorithm in terms of power consumption, SIR levels and network capacity in serving users. The main point of this work is to introduce different system design trade-offs which may be utilised in order to control network performance in various scenarios.

The outline of this study is as follows. After introducing the system model in Section 2, convergence of the proposed algorithm and uniqueness of the resulting Nash equilibrium (NE) point will be proved in Section 3. The admission control method will be described in Section 4. Numerical results are presented in Section 5 and finally, Section 6 concludes the study.

2 System model

Consider a cellular network with B cells, where a base station is located at the centre of each cell with K available mutually orthogonal channels in the frequency domain. In addition, there are N cognitive users distributed uniformly throughout the network, each of them being active with probability $p_{\rm a}$. The licensed users, known as primaries, are willing to share their rights of spectrum access with others, known as secondaries, in return for receiving rewards. In fact, primary users are the ones who decide to share their channels with the secondary ones, not the primary network operator. So in such scenario, while there may be available channels, only the ones that have been assigned to primary users will be utilised to serve secondary ones. Although letting others use the spectrum is beneficial to primaries, the imposed interference may violate their QoS levels. In other words, there will be a reward-QoS level trade-off that can be properly modelled by utility and cost values. On the other hand, each secondary user selfishly chooses its action in order to maximise its own utility. Naturally, such behaviour affects the performance of other users through multiple access interference.

In such networks, several questions arise regarding the interaction between secondary users and the trade-off introduced for primary ones. First of all, what is the proper way to define utility functions for different users in order to model their incentives properly? Secondly, what are the strategy set and the action that maximises utility of each user? Is there any point at which some kind of equilibrium occurs such that no one can unilaterally achieve more benefits and if such point exists, what are its properties?

Since secondary and primary users interactively adjust their actions and are rational decision makers who thrive to maximise their own utilities, game-theory can be a suitable tool to analyse such environment. In order to do so, we need to define a normal game which is based on three elements: the set of players, the utility functions and the corresponding actions.

The set of players which is defined as $\Gamma = \{1, 2, \ldots, S+P\}$, comprises all active users in the network, where S and P, respectively, denote the number of secondary and primary ones.

As stated earlier, primary users want to gain reward by letting secondary ones access the network while maintaining their own QoS levels. Therefore, they should set a proper bound on imposed interference value, in order to ensure their QoS levels. The larger the bound, the more reward they achieve. Consequently, in the simplest form, we can model their utility with a linear function of admissible interference level. However, we should take into account the following two issues when addressing the cost assignment problem. If the imposed interference is larger than the given bound, acceptable QoS levels are violated and they should be penalised. On the contrary, even if the imposed interference is lower than the bound, they should still be penalised, since they are consuming unnecessary additional power to achieve their QoS levels. It is clear that primary transmission at higher power levels in presence of secondary ones is inevitable, but such increase should be made in a controlled manner. In other words, the goal is to attain the condition where primary users do not consume more power than is required while keeping their interference under control. However, for an equal deviation from optimal interference level, the penalty incurred in the case of violating QoS levels should be much larger than consuming higher power levels. Therefore, we consider the following form for the utility function of primary users

$$u_p(Q_p, I_p) = Q_p - \frac{a_p Q_p^2 + b_p}{c_p Q_p + d_p}; \quad \forall p = 1, 2, \ldots, P \qquad (1)$$

in which a_p, b_p, c_p, d_p denote the cost parameters, Q_p as the admissible interference level adjusted by primary user p and I_p is the instantaneous value of imposed interference value on primary user's uplink signal, because of the secondary users. Although the right-hand side of (1) does not seem to depend on I_p, as will be discussed later, the cost parameters, b_p and d_p, actually depend on the interference value. The imposed interference value on primary user p is given by

$$I_p = \sum_{s=1}^{S} \psi_s^p \rho_{s,p}^2 p_s^k + \sum_{q=1, q\neq p}^{P} \Phi_q^p \rho_{q,p}^2 p_q^k \qquad (2)$$

where ψ_s^p and Φ_q^p denote the uplink channel gains from secondary user s and primary user q to the base station serving primary user p, respectively. Parameters $\rho_{s,p}$ and $\rho_{q,p}$ respetively denote the cross-correlation coefficients between signalling waveforms of secondary user s and primary user q with that of the specified primary user. Finally, p_s^k and p_q^k denote the power levels of secondary user s and primary user q on the typical channel k assigned to that primary. It is clear that users who are not served on the channel assigned to the primary user p, do not contribute to the value of I_p.

It should also be noted that each primary user has to adjust its uplink transmission power level on the assigned channel according to its own admissible interference value in order to control its QoS level, based on the following

$$p_p^k = \frac{\gamma_p^{\text{tar}}(Q_p + \sigma_p^2)}{\Phi_p^p} \tag{3}$$

where σ_p^2 and γ_p^{tar} denote background noise power level within user bandwidth at the corresponding receiver on the base station and target SIR level, respectively, for primary user p.

Fig. 1 shows graph of the utility function against admissible interference value for $I_p = 10^{-10}w$ and typical values of cost parameters where b and d are calculated based on the values of a and c, as will be discussed later. As aforementioned, the utility function has sharper descent on its left side where imposed interference becomes larger than the bound, than the right side which computes the cost value because of extraneous power consumption level. Another point to be noted is that the utility function is concave and continuous in primary user's strategy set. Consequently, a compact and convex strategy set guarantees existence of at least one NE point [9].

The last issue to be taken into account in the definition of utility function is the effect of parameters a_p, b_p, c_p and d_p on its shape. For simplicity, we drop the subscript p for primary users. It can be easily verified that the ratio a/c controls the rate of decrease in the utility function for extraneous power consumption level. It is obvious that for a comparable decrease in utility with respect to the left branch which declines asymptotically, a/c should be chosen much larger than unity. Besides, if the instantaneous value of interference is equal to the admissible interference level, the value of the cost function, $(aQ^2 + b)/(cQ + d)$, should be kept at a minimum level. As a result, by adapting b the minimum of that function occurs at I

$$b = aI^2 + \frac{2ad}{c}I \tag{4}$$

Finally, parameter d is used to set the vertical asymptote at a value such that the deviation of the imposed interference value from admissible level becomes significant when QoS level is violated.

In case of secondary users, it is obvious that higher SIR levels result in lower bit error rates and more reliable

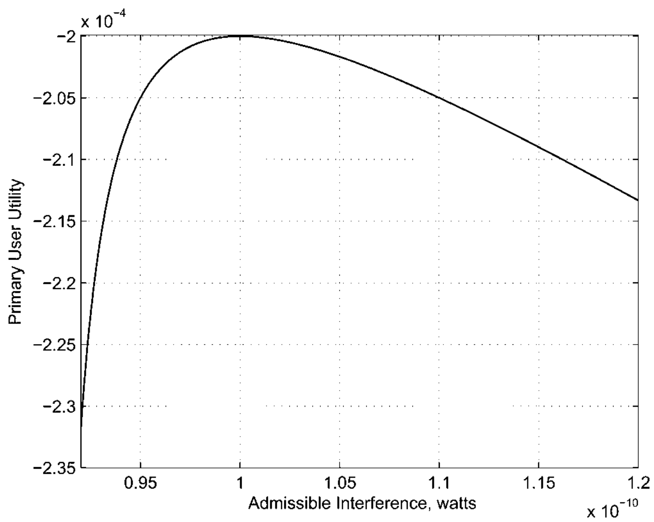

Fig. 1 *Primary user's utility as a function of admissible interference for $I_p = 10^{-10}$w, $a = 10^6$ and $c = 1$*

service quality. However, in order to achieve this goal, the user should transmit at higher power levels. Therefore the two issues that must be taken into account in definition of secondary users' utility functions are service-level assessment as well as user's lifetime. A proper choice for this purpose is the cost function proposed in our last work [17] that for each user is given by the weighted sum of power consumption and SIR level deviation as follows

$$J_s(p_s, \gamma_s) = e_s p_s + f_s \cosh(\gamma_s - \gamma_s^{\text{tar}}); \quad \forall s = 1, 2, \ldots, S \tag{5}$$

where γ_s and γ_s^{tar} denote the instantaneous and target SIR levels, respectively, for secondary user s. It should be noted that secondary users' cost function is dependent on their uplink power levels as well as the channel of the primary user that they choose to transmit on. As a result, The instantaneous SIR value for secondary user s who is served on typical channel k is formulated as

$$\gamma_s^k = \frac{p_s^k \Psi_s^s}{I_s + \sigma_s^2} = \frac{p_s^k \Psi_s^s}{\sum_{m=1, m \neq s}^{S} \Psi_m^s \rho_{m,s}^2 p_m^k + \sum_{p=1}^{P} \phi_p^s \rho_{p,s}^2 p_p^k + \sigma_s^2} \tag{6}$$

where Ψ_m^s and ϕ_p^s, respectively, denote the uplink channel gains from secondary user m and primary user p to the base station serving secondary user s. In addition, the target SIR value is defined based on the type of modulation and coding as well as desirable error probability of each user. The first term on the right-hand side of (5) accounts for power consumption level or equivalently user's lifetime, whereas the second term addresses deviation from the desired service level. As a result, each user can adjust parameters e_s and f_s in order to put more emphasis on power consumption or SIR deviation. If the value of f_s is increased, achieving target SIR is more emphasised, otherwise power consumption level is prioritised. Furthermore, the cost function is non-negative and convex in the user's strategy set, and therefore existence of at least one non-negative NE point will be guaranteed by a compact and convex strategy set assumption [9].

Based on the aforementioned issues, the devised game is defined as $G = \{\Gamma, \{A_k\}, \{u_k\}\}$, where $\Gamma = \{1, 2, \ldots, S + P\}$ denotes the set of players, and $A_p = [0, \bar{Q}_p]$ is the strategy set for a typical primary user where $\bar{Q}_p$ denotes the maximum admissible interference on the primary user's uplink signal. The strategy set for each secondary user is the Cartesian multiplication of the set of available power levels and the two channels of the primary users who are in the same cell as the secondary user, denoted by $A_s = [0, P_s^{\max}] \times [k_{\text{pu}_1}, k_{\text{pu}_2}]$. Here k_{pu_1} and k_{pu_2} denote the channels of the primary users who are present in the same cell as of the aforementioned secondary one. In addition, $\{u_k\}$ denotes the set of utility/cost functions as defined earlier. It should be noted that $\bar{Q}$ is calculated for each primary user as the maximum interference level that he/she can tolerate while still being capable of approaching his/her target SIR level considering the corresponding power budget, noise power level and uplink channel gain as given by (3).

3 Algorithm convergence

In the following subsections, we first formulate the algorithm for strategy update of primary as well as secondary users, and then prove algorithm convergence to the unique NE point.

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3.1 Algorithm for strategy updates

In order to obtain the strategies update formulas, we should derive best-response functions of primary and secondary users. For this purpose, we have to differentiate primary utility and secondary cost functions with respect to admissible interference and power levels, respectively, and equate them with zero. For primary users, we have

$$\frac{\partial u_p(Q_p, I_p)}{\partial Q_p} = 0 = 1 - \frac{2a_pQ_p(c_pQ_p + d_p) - c_p(a_pQ_p^2 + b_p)}{(c_pQ_p + d_p)^2} \tag{7}$$

Without loss of generality we set $c = 1$. After some manipulations, the best-response function for primary user p will be in the simple form of

$$Q_p^{(l+1)} = (I_p^{(l)} + d_p)\sqrt{\frac{a_p}{a_p - 1}} - d_p \tag{8}$$

If the resulting value of (8) becomes larger than the maximum admissible interference level, because of the concavity of utility function, the best response will be $\bar{Q}_p$.

In case of secondary users, they choose the uplink power level as well as the channel of a primary user present in their cells. For each channel, the best response for the power level and also the cost function should be computed. It is clear that the set of channel and power level which results in lower cost value will be chosen by the secondary user.

$$\frac{\partial J_s(p_s, \gamma_s)}{\partial p_s} = 0 = e_s + f_s\frac{\partial \gamma_s}{\partial p_s}\sinh(\gamma_s - \gamma_s^{\text{tar}}) \tag{9}$$

It is clear that at NE point, SIR level will be lower than or equal to the target value for each user. Denoting the interference imposed on user s by I_s and after some manipulations we have

$$p_s^{(l+1)} = \begin{cases} \dfrac{I_s^{(l)}}{\Psi_s^s}\left(\gamma_s^{\text{tar}} - \sinh^{-1}\left(\dfrac{e_sI_s^{(l)}}{f_s\Psi_s^s}\right)\right) & \text{if positive} \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

Owing to convexity of the cost function, the best response for secondary user s on a channel will be $P_s^{\max}$ if the resulting value becomes larger than the maximum available power. It should also be noted that if the power level becomes negative, the user should be silent during that stage.

According to (8) and (10), the main advantage of the proposed algorithm is that each user can update his/her strategy only with the knowledge of his/her own uplink interference level and as a result, the method can be implemented in a distributed manner. It should be noted that this process can be implemented with the help of the base stations through computation of the uplink interference levels and informing the corresponding users.

3.2 Convergence

In [18], Yates shows that if a fixed point of the algorithm $p_i^{(k+1)} = g_i(\boldsymbol{p}^{(k)})$ exists – where $\boldsymbol{p}^{(k)} = \{p_1^{(k)}, p_2^{(k)}, \ldots, p_i^{(k)}, \ldots\}$ denotes the vector including all users' power levels – and g satisfies the following three conditions for all values of i

1. positivity $g_i(\boldsymbol{p}) \geq 0$,
2. monotonicity $\boldsymbol{p} \geq \boldsymbol{p}' \Rightarrow g_i(\boldsymbol{p}) \geq g_i(\boldsymbol{p}')$ and
3. scalability $\forall\alpha \geq 1;\ \alpha g_i(\boldsymbol{p}) \geq g_i(\alpha\boldsymbol{p})$.

Then function g will be standard and it will converge to the unique fixed point. Earlier, we proved existence of at least one NE point for the proposed algorithm. Since NE is a fixed point of the best-response functions, if we can demonstrate satisfaction of these conditions for our method, the algorithm convergence to the unique NE point will be guaranteed.

The three conditions for primary users' best-response functions to be standard are met as follows. From (8), it can be observed that since a_p is larger than unity and also the absolute value of d_p is smaller than I_p, the positivity condition is easily met.

For monotonicity, if $\boldsymbol{p} \geq \boldsymbol{p}'$ element-wise, then $I_p \geq I_p'$, and therefore $g(\boldsymbol{p}) \geq g(\boldsymbol{p}')$. It can also be verified easily that $\alpha g(\boldsymbol{p}) \geq g(\alpha\boldsymbol{p})$. As a result, primary users' best-response functions are standard.

For secondary users, from (10) we see that positivity requires

$$I_s \leq \frac{\Psi_s^s f_s}{e_s}\sinh(\gamma_s^{\text{tar}}) \tag{11}$$

Since $\sinh(\gamma_s^{\text{tar}})$ is usually large, if we choose a proper value for f_s/e_s, the positivity condition can be easily met.

For monotonicity, it is sufficient to have an increasing best-response function with respect to I. If we differentiate (10) with respect to I, we will have

$$\Psi_s^s\frac{\partial g(\boldsymbol{p})}{\partial I_s} = \gamma_s^{\text{tar}} - \sinh^{-1}\left(\frac{e_sI_s}{f_s\Psi_s^s}\right) - \frac{e_sI_s}{f_s\Psi_s^s}\frac{\partial \sinh^{-1}((e_sI_s)/(f_s\Psi_s^s))}{\partial((e_sI_s)/(f_s\Psi_s^s))} \tag{12}$$

Using inequalities $\sinh^{-1}(x) \leq x$ and $\{(\partial \sinh^{-1}(x))/\partial x\} \leq 1$, for monotonicity, we should have

$$\gamma_s^{\text{tar}} \geq \frac{2e_sI_s}{f_s\Psi_s^s} \Rightarrow I_s \leq \frac{f_s\Psi_s^s}{2e_s}\gamma_s^{\text{tar}} \tag{13}$$

which is tighter than (11).

Finally, we should prove scalability of our method. Since α is larger than unity, we have $\sinh^{-1}((e_sI_{s(\alpha\boldsymbol{p})})/(f_s\Psi_s^s)) \geq \sinh^{-1}((e_sI_{s(\boldsymbol{p})})/(f_s\Psi_s^s))$. As a result, the condition for scalability can be written as

$$\alpha g(\boldsymbol{p}) - g(\alpha\boldsymbol{p}) \geq (\alpha - 1)\sigma_s^2\left(\gamma_s^{\text{tar}} - \sinh^{-1}\left(\frac{e_sI_s}{f_s\Psi_s^s}\right)\right) \tag{14}$$

Therefore for scalability it is enough that positivity of the best-response functions be met. Consequently, our method meets the conditions of the standard power control framework and its convergence to a unique NE point is guaranteed.

4 Admission control description

We also propose a simple admission control in order to improve performance of the proposed algorithm. Naturally, if a network has the capacity to serve users with their desired service levels, then the SIR levels increase monotonically to the target point during the convergence period [18]. As a result, a decline in a user's instantaneous SIR level during the convergence period can be interpreted as a sign that the offered load is too heavy to be feasible. Thus, adopting a proper admission control algorithm to decrease network load is a way to improve the algorithm performance. Since users whose levels are declining cannot approach their target SIR levels, it is rational to reduce their target values in order to mitigate network load. The scheme works as follows.

At each step that the strategies are updated, we decrease target SIR value by a factor of β, for at most n users in each cell who observe a decline in their instantaneous SIR levels. This reduction can be repeated until the target value reaches a level equal to η% of $\gamma_{\text{SU}}^{\text{tar}}$. Although this method may appear unfair at the first glance, we can improve fairness using linear proportional pricing to penalise users based on their locations in the network. In this approach, all secondary users have the same SIR deviation factor, but the power factor is proportional to their distance to base stations. Based on this method, users become more cautious with their power consumption as they become closer to the base. In addition, if there are more than n users whose SIR levels have decreased, we randomly select n of them in order to avoid repeated target SIR levels reduction for same users.

5 Numerical results

In this section, we investigate performance of our proposed algorithm in a cellular network through different simulation scenarios. For simplicity, we consider four square cells of 2-km length each, having $K = 4$ mutually orthogonal channels in the frequency domain. The four frequency channels are identically repeated across all cells leading to a frequency reuse ratio of unity. Base stations are placed at the centre of each cell and secondary users are located randomly based on uniform distribution throughout the network. In addition, two primary users are uniformly placed in each cell as shown in Fig. 2. The receiver background noise power level within users bandwidth is $\sigma^2 = 5 \times 10^{-15} w$ and all uplink channel gains are inversely proportional to the fourth order of the distance between users and the corresponding base stations.

The maximum available power is $P^{\max} = 20w$ and target SIR of all users is considered to be $\gamma_{\text{PU}}^{\text{tar}} = \gamma_{\text{SU}}^{\text{tar}} = 10\,\text{dB}$. For primary users' utility function, we consider $a = 10^6$, b calculated as (4), $c = 1$ and d is set such that the asymptotic level be placed on the point where QoS level violation exceeds 10% of the target SIR value. In addition, for secondary users' cost parameters we choose $f/e = 100$. Furthermore, the cross correlation coefficients between secondary users' signalling waveforms and between secondary–primary waveforms are considered to all have the same value of 0.1. We also update users' strategies synchronously.

5.1 Algorithm convergence

Fig. 3 shows the convergence rate of the proposed algorithm to the NE point in a typically loaded network for 200 secondary users with activity probability of 0.2. Owing to brevity, we only presented the convergence period for SIR levels. As can be verified, the method succeeds in acquiring target SIR levels for primary and secondary users in a few iterations. Another point to be mentioned is the possibility of users to switch between base stations. If the nearest base for a secondary user becomes overloaded, it will be beneficial especially for boundary users to switch to other base stations. Such situation can be easily identified by tracking the assigned base station to each user during the convergence period. In cases where switching to another base is not admitted, degradation in algorithm performance is inevitable, especially when number of active secondary users increases. We simulate both conditions for 100 different locations for the users in the network and present the average result. As the results show, 42 and 40% increase in secondary and primary users power consumption level, respectively, will be observed if no switching between bases is allowed. Such difference is even more severe if we consider more heavily loaded scenarios.

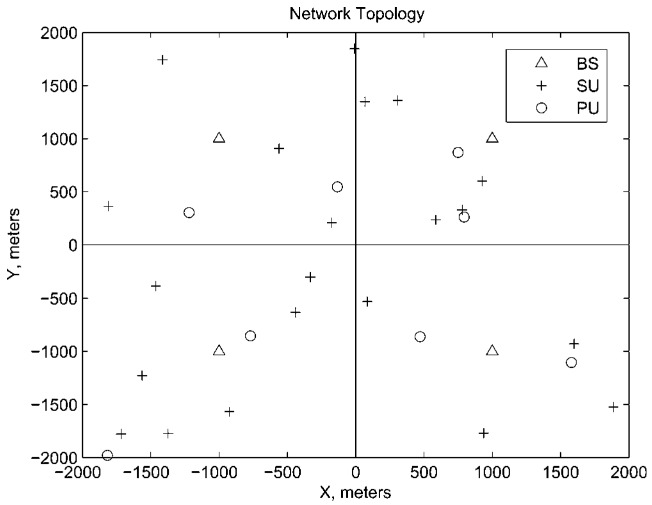

Fig. 2 *Typical location of active mobiles for 200 secondary users with $p_a = 0.1$ and 2 primary users in each cell*

5.2 Effect of the secondary users cost parameters

Another issue to be considered, is dependency of the algorithm's performance on secondary users' cost parameters. As discussed earlier, the cost value depends on the power level and SIR deviation. In order to demonstrate effect of the cost parameters, we have shown the average results for 100 different network topologies. Figs. 4 and 5 show the power consumption level and the average achieved SIR levels as a function of f/e. As expected, the higher the priority given to the power consumption level, the more cautious a user will be about its transmission power level. Consequently, there is higher probability that such user will switch between base stations in order to find less interfering situations. On the contrary, if SIR deviation is more emphasised, the user will not put much emphasis on its power consumption level and consumes more power in order to get closer to the target SIR level. However, such situation leads to more interference imposed on primary users and their performance degrades. Therefore, a trade-off between power consumption level and SIR deviation exists which is adjusted by setting the value of secondary users' cost parameters. It should be noted that in order to better

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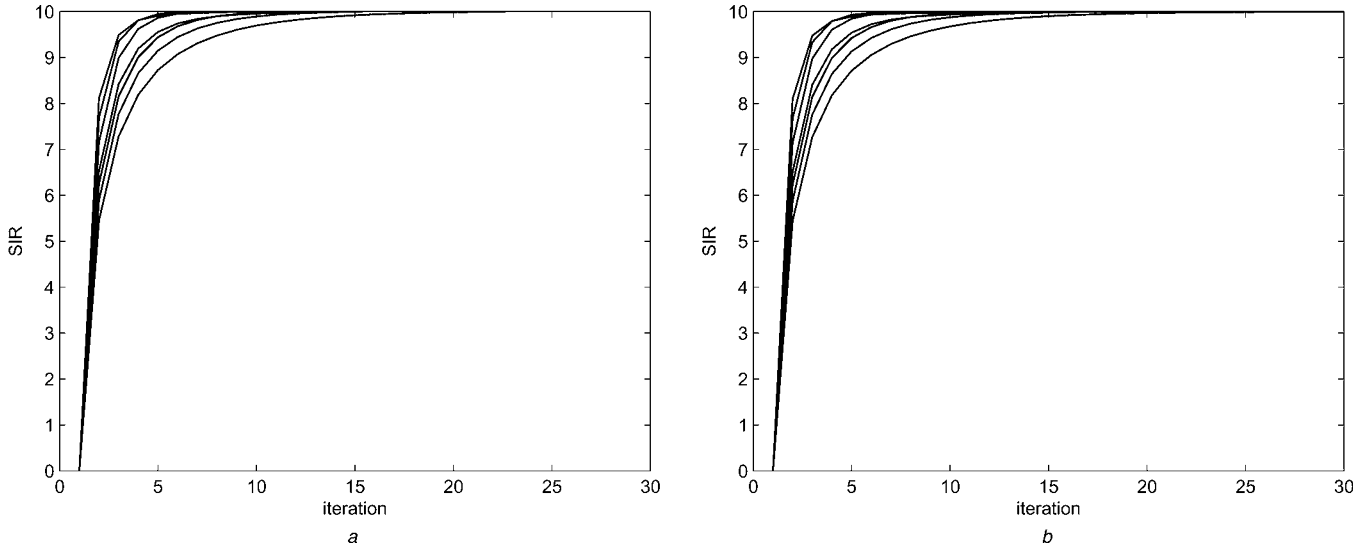

Fig. 3 *Performance of the proposed algorithm for 200 secondary users at $p_a = 0.2$ and 8 primary ones with $\gamma_{PU}^{tar} = \gamma_{SU}^{tar} = 10$*

a Primary users' SIR update
b Secondary users' SIR update

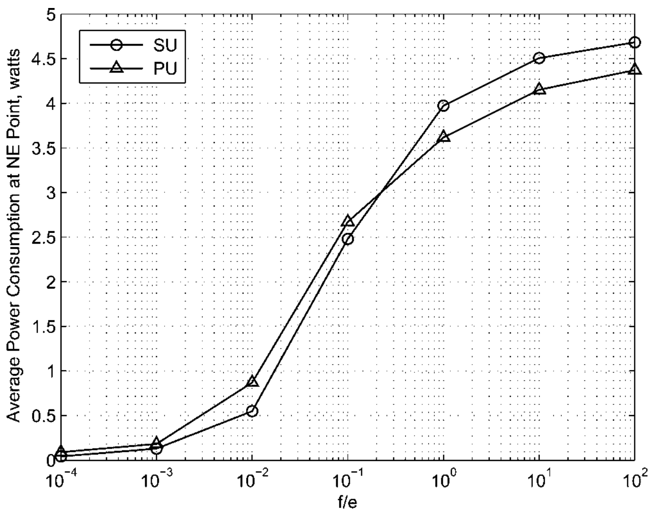

Fig. 4 *Dependency of average power consumption at NE point on secondary cost parameters for 200 secondary users at $p_a = 0.4$ and 8 primary ones*

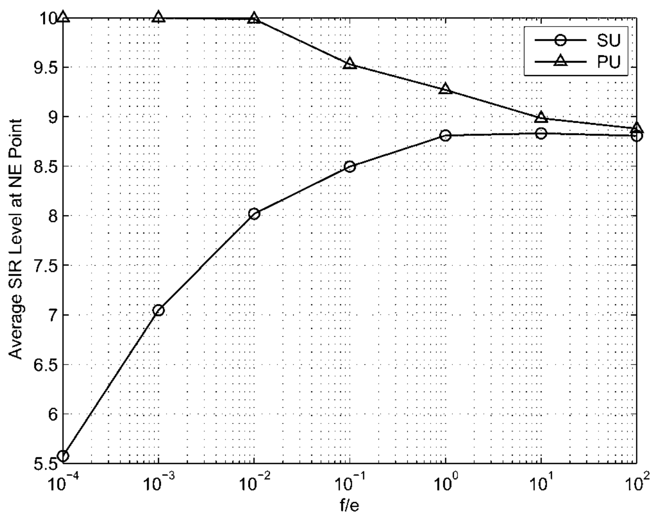

Fig. 5 *Dependency of average SIR levels at NE point on secondary cost parameters for 200 secondary users at $p_a = 0.4$ and 8 primary ones with $\gamma_{PU}^{tar} = \gamma_{SU}^{tar} = 10$*

observe such situation, the network was loaded twice as much as the first case; in other words the activity probability for secondary users was set to 0.4.

5.3 Effect of the admission control

In this section, we investigate the algorithm performance utilising the admission control method proposed in Section 4. Figs. 6 and 7 show users average power consumption and average SIR levels, respectively, at NE point with respect to n for 200 secondary users with activity probability of 0.4, $\eta = 70\%$, $\beta = 0.05$ and SIR deviation cost factor of 10^3. These values are set through simulations such that the best performance is achieved. As can be observed, the larger the value of n, the lower the power consumption level will be. In addition, the SIR levels for primary users increase because of the reduction in

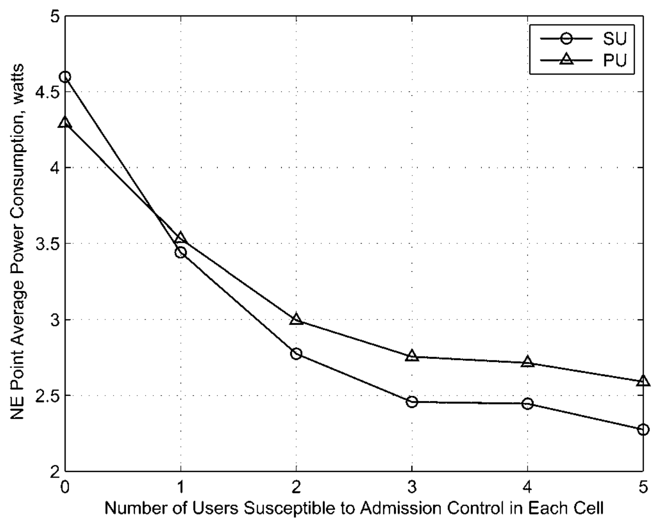

Fig. 6 *Effect of adding the admission control algorithm on average power consumption at NE point for 200 secondary users at $p_a = 0.4$ and 8 primary ones with $\eta = 70\%$, SIR cost factor of 10^3 and $\beta = 0.05$*

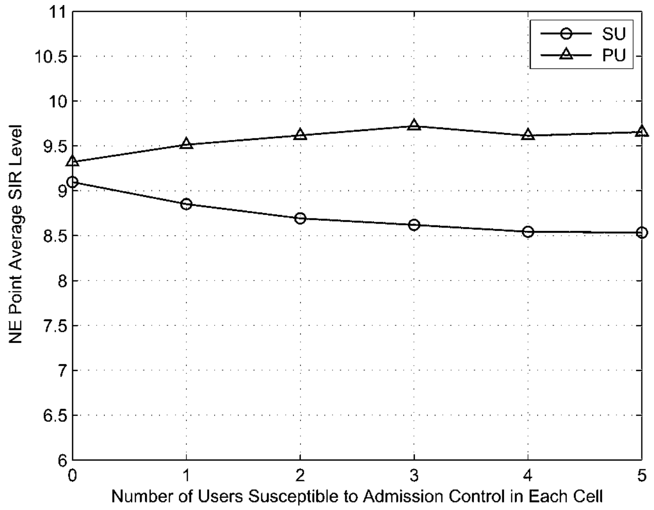

Fig. 7 *Effect of adding the admission control algorithm on average SIR levels at NE point for 200 secondary users at* $p_a = 0.4$ *and 8 primary ones with* $\eta = 70\%$*, SIR cost factor of* 10^3, $\beta = 0.05$ *and* $\gamma_{PU}^{tar} = \gamma_{SU}^{tar} = 10$

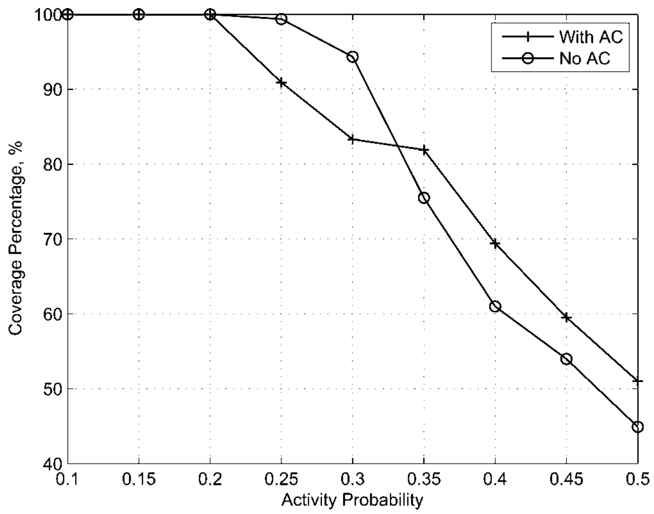

Fig. 8 *Percentage of secondary users meeting their target SIR levels for the case of 200 secondary users with* $\gamma_{SU}^{tar} = 10$, $n = 2$, $\eta = 70\%$*, SIR cost factor of* 10^3 *and* $\beta = 0.05$

interference level caused by secondaries. However, there is a slight decrease in average SIR level of secondary users which is too small to be considered. For example for $n = 5$ there are 51 and 40% decrease in secondary and primary power consumption levels, respectively. In addition, slight improvement in primary users' average SIR level is achieved, at the expense of only 6% degradation in average SIR level of secondary ones.

It should be noted that as we choose smaller values for η or higher number of users under admission control, more power saving at the cost of more reduction in secondary SIR levels occurs, leading to a design trade-off criteria. In order to obtain a better judgement about performance of the admission control method, comparisons on individual SIR levels for the case of $n = 5$ users are presented. By averaging over a number of scenarios, it can be verified that admission control is beneficial for more than 59% of secondary users in terms of improved SIR levels. In addition, the maximum level of improvement is at 87% while maximum degradation is at 23% level. Furthermore, the minimum achieved SIR level at NE point for secondary and primary users is increased by 43 and 41%, respectively. As it can be verified, use of admission control and proportional pricing is beneficial in saving power and improving performance of the proposed algorithm.

The final issue to be considered is the capability of the proposed algorithm in serving secondary users. Fig. 8 shows the percentage of secondary users that approach their target SIR levels with respect to their activity probability with and without applying the admission control algorithm. As it was also observed in Fig. 3, the algorithm demonstrates good performance in typically loaded networks. But as the network load increases, fewer number of users succeed in achieving their incentives tightly. The important point in Fig. 8 is that application of admission control is not recommended in typically loaded scenarios. This is because of the fact that network still has the capacity to tolerate interaction of users and reduction of their target SIR values subjugates their incentives. However, as the load is gradually increases, capacity declines and applying the admission control becomes of higher importance. The effect of admission control on capacity improvement in heavily loaded networks is another evidence for improved performance of the proposed method.

6 Conclusions

We proposed new utility and cost functions for primary and secondary users, respectively, in order to model their interaction as a non-cooperative game in the uplink side of a cellular cognitive radio network. Through simulation results, we demonstrated that when network load is not too heavy, the proposed method succeeds in serving users at their desired objective levels after a few iterations. An important point to be noted is that allowing secondary users to switch between base stations leads to approximately the same SIR levels but with significant power saving levels. In addition, our scheme introduces a trade-off between power consumption and SIR levels at NE point to be properly utilised in the design process by changing secondary users' cost parameters.

Furthermore, we applied a simple admission control to our algorithm and have shown adopting such scheme leads to considerable power saving at the cost of slight reduction in SIR levels. In addition, admission control leads to higher capacity for serving users in heavily loaded networks.

An interesting topic for future research is developing a game-theoretic method for the downlink side of cellular cognitive radio networks considering the channel assignment issue. Adopting a game-theoretic approach in the downlink side leads to a quite different framework in comparison with the one addressed in this study. Such difference is because of the fact that the target SIR levels must be satisfied at all primary and secondary nodes. Furthermore, the available channels should be assigned such that the best utilisation is achieved.

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