Game Theoretic Channel Allocation for the Delay-Sensitive Cognitive Radio Networks

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Abstract— **In this paper, we propose several channel allocation schemes via the Game theoretical approaches for the distributed CR networks. Distinguished from the literature, more important factors are taken into account when designing the potential games for the interweave and underlay CR networks, i.e. the queueing delay, complete inter-system interference and protection of primary users (PUs). Particularly, in the underlay CR networks, a PU can be protected by adaptively adjusting the cost for secondary users (SUs) to share a subchannel with him. Consequently, SUs and PUs can achieve higher end-to-end throughput and maintain the desired signal-to-noise-and-interference ratio, respectively. Moreover, for proving the convergence of the proposed schemes, the associated potential functions are also defined. Via the simulation results, the proposed schemes are proved to be capable of effectively reducing the queuing delay at the cost of the slightly decreased throughput.**

Index Terms— **Cognitive radio, Potential Game, channel allocation, Nash Equilibrium, Game theory.**

I. Introduction

COGNITIVE radio (CR), a new paradigm of wireless communication system, has recently been deemed a potential solution to spectrum inefficiency of the incumbent systems [1]. By taking the advantage of the temporarily unoccupied or partially occupied spectrum, i.e. the so-called spectrum holes, the CR systems can opportunistically access the wireless networks so as to enhance the overall spectrum efficiency. Nevertheless, the nature of the spectrum holes may be sporadic and unstable. Therefore, radio resource management (RRM) then becomes a pivotal technique to the success of the CR systems.

In the CR Ad-hoc or mesh networks, RRM should operate in the distributed fashion. Accordingly, the theory of Game was recently applied to design the dynamic spectrum allocation for the distributed CR networks and characterize the distributed interactions between the CR networks and incumbent systems [2]–[8]. In [2], the authors proposed two game-theoretical dynamic channel allocations by jointly taking the utility and pricing functions into account such that a noncooperative game can possess some cooperative properties. Specifically, the utility functions are in the form of capacity and logarithmic signal-to-noise-and-interference ratio (SINR), while the corresponding pricing functions are the required capacity and SINR in the logarithmic form plus the weighted transmission power. In [3], a cooperative game was designed to distributedly select a channel for each CR terminal so as to have a better capacity than the requirement. Also, the so-called no-regret learning algorithm was applied to adjust the probability distributed function (pdf) of mixed strategy.

With the nice property of guaranteeing the existence of Nash equilibrium, Potential Game has also been utilized to solve the RRM problems in the distributed wireless networks. In [4], the authors defined a utility function for the CR networks by jointly taking the generated and experienced interference into account, i.e. the interference from the desired user to the whole networks and vice versa. In addition to the property of Potential Game, the utility function can achieve higher SINR and preserve fairness. Based on this concept, the authors in [5] incorporate the beamforming technique into the formulation of the utility function so as to enhance the effectiveness of interference elimination. Moreover, the same philosophy of defining the utility function was also utilized to design the distributed subcarrier allocation strategy for the orthogonal frequency-division multiple access (OFDMA) systems [6]. In [7], [8], the utility function in [4] was modified for the underlay and overlay CR networks by including incentives to increase transmission power and relay data packets for primary users (PUs). Nevertheless, the SINR requirement of PUs can not be guaranteed when sharing subchannels with secondary users (SUs).

From the literature, we find that some important factors are neglected in designing the utility functions for the distributed CR networks, i.e. the queuing delay, complete inter-system interference and protection of PUs in the underlay mode. Thus, in this paper, we take these

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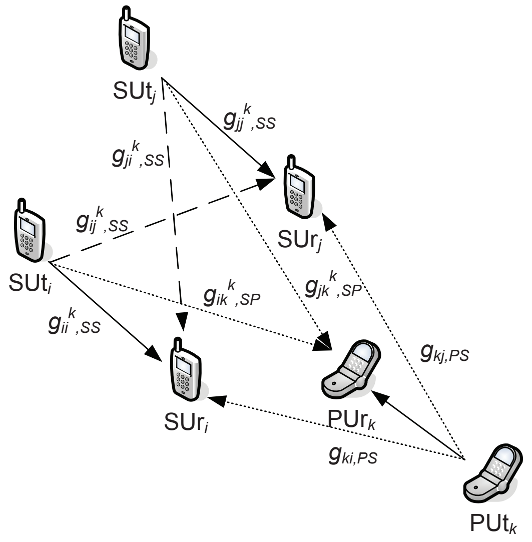


Fig. 1. Illustration of system topology.

three factors into account when designing the Potential Game for the distributed CR networks. In particular, in the underlay CR networks, a PU can be protected by adaptively adjusting the cost for SUs to share a subchannel with him. Consequently, SUs and PUs can achieve higher end-to-end throughput and maintain the desired SINR, respectively. In order to the prove the convergence of the proposed schemes, the corresponding potential functions are also defined. The simulation results show that in one of the considered case, the proposed schemes can reduce the queuing delay by 81% at the minor cost of 7.4% degradation in throughput. Also, it is found that single channel rather than multiple channels allocation strategy can perform better in the aspects of both throughput and queuing delay.

The rest of this paper is organized as follows. In Section II, we introduce the system model and problem formulation via the Game theoretical approach. In Section III, various utility functions are designed for the interweave and underlay CR networks. The associated potential functions are defined in Section IV. Sections V and VI give the simulation results and the concluding remarks.

II. Problem Formulation and System Model

Fig. 1 shows the snapshot of the system topology, in which two SUs' transmission pairs may share a subchannel with one PU's transmission pair, where SUt_i and SUr_i are the i-th SU's transmitter and receiver; PUt_k and PUr_k are those for the k-th PU; $g_{ji,SS}^{(k)}$ and $g_{ik,SP}^{(k)}$ are the path gains of the k-th subchannel from SUt_j to SUr_i and that from SUt_i to PUr_k, respectively. Analogously, the other path gains can also be defined. In this paper, $\mathcal{N} = \{1, 2, \cdots, N\}$ SU's transmission pairs and $\mathcal{K} = \{1, 2, \cdots, K\}$ subchannels are assumed, where $N > K$ is set to avoid a trivial case.

Two CR operation modes are considered, i.e. spectrum-interweave and spectrum-underlay modes. In the spectrum-interweave mode, a subchannel can only be available for SUs when it is not occupied by any particular PU. On the contrary, in the spectrum-underlay mode, a subchannel occupied by a PU can also be shared among various SUs. In either mode, an SU's transmission pair may transmit over a single or multiple channels. Therefore, one can say that a subchannel is the one occupied by the PU's transmission pair, which also means that the number of subchannel is equal to the number of PU's transmission pairs, i.e $\mathcal{K}$.

The strategic form game can now be defined as $\mathcal{G} = (\mathcal{N}, \{\mathcal{S}_i\}_{i\in\mathcal{N}}, \{\mathcal{U}_i\}_{i\in\mathcal{N}})$, where $\mathcal{S}_i$ and $\mathcal{U}_i$ mean the strategy set and utility function for the i-th SU's transmission pair, respectively. According to the above descriptions, the strategy set $\mathcal{S}_i$ can be expressed as $\mathcal{S}_i = \{a_i^{(k)}[n] | \sum_{k=1}^{K} a_i^{(k)}[n] = K_i, a_i^{(k)}[n] \in \{0,1\}\}$, where $a_i^{(k)}[n] = 1$ when the k-th subchannel is used by i-th SU's transmission pair at the n-th time slot; otherwise $a_i^{(k)}[n] = 0$; K_i is the number of subchannel needed by the i-th SU's transmission pair. To summarize, the strategy space of the game $\mathcal{G}$ can be expressed as $\mathbb{S} = \mathcal{S}_i \times \cdots \times \mathcal{S}_N$; and the utility function for the i-th SU's transmission pair can be defined as $U_i(S_i, S_{-i}) : \mathbb{S} \to \mathbb{R}$, $\forall S_i \in \mathcal{S}_i$. At last, the game $\mathcal{G}$ can be formulated as follows:

$$\begin{aligned} &\text{Max } \; U_i(S_i, S_{-i}),\ \forall i \in \mathcal{N} \\ &\text{s.t. } \; \Sigma_{k=1}^{K} a_i^{(k)}[n] = K_i,\ \forall a_i^{(k)} \in \{0,1\}. \end{aligned} \tag{1}$$

Then, the goal is to find a Nash equilibrium (NE) of (S_i^*, S_{-1}^*) such that $U_i(S_i^*, S_{-i}^*) \geq U_i(S_i', S_{-i}^*)$, $\forall S_i' \in \mathcal{S}_i$, $i \in \mathcal{N}$ [9]. In the following, the system model will be introduced so as to define the utility functions for the spectrum-interweave and spectrum-underlay CR networks.

A. Signal to Interference and Noise Ratio (SINR)

Based on the system topology shown in Fig. 1, the SINR at the receiving ends of SUr_i and PUr_k via the k-th subchannel can generally be expressed as (here the time index $[n]$ is ignored for brevity)

$$\gamma_{i,S}^{(k)} = p_{i,S}^{(k)} g_{ii,SS}^{(k)} \times \left[\sum_{j=1, j\neq i}^{N} p_{j,S}^{(k)} g_{ji,SS}^{(k)} \delta_{ji,SS}^{(k)} + \sum_{k=1}^{K} p_{k,P}^{(k)} g_{ki,PS}^{(k)} \delta_{ki,PS}^{(k)} + \sigma_N^2 \right]^{-1} \tag{2}$$

and

$$\gamma_{k,P}^{(k)} = \frac{p_{k,P}^{(k)} g_{kk,PP}^{(k)}}{\sum_{i=1}^{N} p_{i,S}^{(k)} g_{ik,SP}^{(k)} \delta_{ik,SP}^{(k)} + \sigma_N^2}\ , \tag{3}$$

respectively, where $p_{i,S}^{(k)}$ and $p_{k,P}^{(k)}$ represent the transmission power of SUt_i and PUt_k over the k-th subchannel; σ_N is the power of the additive white Gaussian noise (AWGN). Note that when multiple subchannels are used by the i-th SU's transmission pair, $p_{i,S}^{(k)} = P_{Max}/K_i$, where P_{Max} is the maximum transmission power for an SU. Furthermore, $\delta_{ji,SS}^{(k)} = 1$ when the j-th and i-th SU's transmission pairs share the k-th subchannel. Similarly $\delta_{ki,PS}^{(k)} = 1$ when the k-th PU's transmission pair shares the k-th subchannel with the i-th SU's transmission pair. By analogy, $\delta_{ik,SP}^{(k)} = \delta_{ki,PS}^{(k)}$. In addition, $\delta_{ik,SP}^{(k)} = \delta_{ki,PS}^{(k)} = 0 \ \forall i \in \mathcal{N}$ and $\forall k \in \mathcal{K}$ when the CR network operates in the spectrum-interweave mode.

Now, with the SINR expressions of (2) and (3), it gives the link capacity (in other words, the end-to-end throughput) of the i-th SU's transmission pair at the n-th time slot as

$$r_{iS}[n] = B \sum_{k=1}^{K} a_i^{(k)}[n] \log_2(1 + \gamma_{i,S}^{(k)}[n]) \ , \tag{4}$$

where B denotes the bandwidth of a subchannel; $\gamma_{i,S}^{(k)}[n]$ is the receiving SINR of SUr_i via the k-th subchannel at the n-th time slot.

B. Queuing Delay

Assume that each terminal has a queue of infinite length. Then, the queuing delay of a particular data packet is defined as the time duration counted from the instant of its arrival to the departure. Let $Q_i[n]$ be the amount of bits stored in the SUt_i's queue at the n-th time slot. Then, we can have

$$Q_i[n+1] = \max(Q_i[n] - r_{iS}[n]T_s + a_i[n], 0), \tag{5}$$

where T_s is the duration of a time slot; $a_i[n]$ represents the amount of newly arrived data bits at the n-th time slot. The average queuing length can now be calculated by

$$\overline{Q}_i[n] = (1 - \rho_w)\overline{Q}_i[n-1] + \rho_w Q_i[n], \tag{6}$$

where $\rho_w = T_s/T_w$ and T_w is the length of averaging window. Finally, based on the Little's Law [10], the average queuing delay of SUt_i can be expressed as

$$W_i[n] = \frac{\overline{Q}_i[n]}{\lambda_i}, \tag{7}$$

where λ_i is the average arrival bit rate of SUt_i.

III. Joint Interference-Aware and Queue-Aware Channel Allocation Scheme

The prototype of utility function, named the interference-aware utility (IU), for the potential game in [4] was defined as

$$U_i(S_i, S_{-i}) \triangleq -\sum_{k=1}^{K'} \sum_{j=1, j\neq i}^{N} \Big(\delta_{ji,SS}^{(k)} p_{j,S}^{(k)} g_{ji,SS}^{(k)} + \delta_{ij,SS}^{(k)} p_{i,S}^{(k)} g_{ij,SS}^{(k)}\Big), \forall i \in \mathcal{N}, \tag{8}$$

where K' is the number of subchannels unoccupied by PUs; Similar to (2) and (3), the time index $[n]$ is ignored for brevity. (Also, $[n]$ is ignored in the expressions of other utility and Potential functions, i.e., (9), (10), (11), (13), (14) and (15), which will be introduced in the following sections.) Then, an incentive factor for SUs to increase transmission power, i.e. $\beta \log(1 + p_{i,S}^{(k)} g_{ii,SS}^{(k)})$, was added into the utility function in [7], [8], where the factor β represents the self-interested coefficient. Here, we further incorporate the queuing delay, complete inter-system interference and protection of PUs into the utility functions. Note that the weight of queuing delay can be adjusted according to the system requirement. Moreover, the key of protecting a PU is to adaptively adjust the cost for SUs to share a subchannel with him such that his SINR requirement can be maintained.

A. Joint Interference-Aware and Queue-Aware Utility Function

The joint interference-aware and queue-aware utility (IQU) function for the spectrum-interweave CR networks is now defined as:

$$U_i(S_i, S_{-i}) \triangleq -\sum_{k=1}^{K'} \sum_{j=1, j\neq i}^{N} \Big(\delta_{ji,SS}^{(k)} p_{j,S}^{(k)} g_{ji,SS}^{(k)} W_j^{-\alpha} + \delta_{ij,SS}^{(k)} p_{i,S}^{(k)} g_{ij,SS}^{(k)} W_i^{-\alpha}\Big), \forall i \in \mathcal{N}, \tag{9}$$

where W_i and W_j are the queuing delay defined in (7); Also, the factor α can be adjusted for different sensitivity of queuing delay.

It should be highly emphasized that the philosophy behind the weighting factor W_i lies in the privilege to produce interference. For example, when the i-th user suffers from longer delay, i.e. a larger value of W_i, he can have a privilege to produce a larger amount of interference by weakening the product $\delta_{ij,SS}^{(k)} p_{i,S}^{(k)} g_{ij,SS}^{(k)}$ via the weighting factor $W_i^{-\alpha}$. That is given the weighting factor $W_i^{-\alpha}$ and $\delta_{ij,SS}^{(k)}$ $\forall j \neq i \in \mathcal{N}$, and $k \in \mathcal{K}$, he can maximize his utility function $U_i(S_i, S_{-1})$ by using larger transmission power $p_{i,S}^{(k)}$. Moreover, in this situation, it is allowed for him to selected a subchannel with higher $g_{ij,SS}^{(k)}$. Thus, one can also say that the effects of interfering other users are weaken by using a smaller weight of $W_i^{-\alpha}$. As a result, larger transmission power and more flexibility of choosing a subchannel render the i-th user a better opportunity to increase the transmission rate such that the delay W_i can be consequently reduced.

B. Modification for the Spectrum-Interweave CR Networks

The modified utility function for the spectrum-interweave CR networks is named spectrum-interweave utility (SIU) function. Similar to the IQU function, the SIU function can now be defined as

$$U_i(S_i, S_{-i}) \triangleq -\sum_{k=1}^{K'} \left[\sum_{j=1,j\neq i}^{N} \left(\delta_{ji,SS}^{(k)} p_{j,S}^{(k)} g_{ji,SS}^{(k)} W_j^{-\alpha} + \delta_{ij,SS}^{(k)} p_{i,S}^{(k)} g_{ij,SS}^{(k)} W_i^{-\alpha} \right) - \beta \log(1 + p_{i,S}^{(k)} g_{ii,SS}^{(k)}) \right], \forall i \in \mathcal{N}. \quad (10)$$

Note that as aforementioned, $\beta \log(1 + p_{i,S}^{(k)} g_{ii,SS}^{(k)})$ is regarded as an incentive factor for SUs to increase transmission power.

C. Modification for the Spectrum-Underlay CR Networks

Based on SIU function in (10), the following spectrum-underlay utility (SUU) function is designed to include the effects of complete inter-system interference and protection mechanism for PUs.

$$U_i(S_i, S_{-i}) \triangleq -\sum_{k=1}^{K} \Bigg[\sum_{j=1,j\neq i}^{N} \left(\delta_{ji,SS}^{(k)} p_{j,S}^{(k)} g_{ji,SS}^{(k)} W_j^{-\alpha} + \delta_{ij,SS}^{(k)} p_{i,S}^{(k)} g_{ij,SS}^{(k)} W_i^{-\alpha} \right) - \beta \log(1 + p_{i,S}^{(k)} g_{ii,SS}^{(k)}) + \underbrace{\delta_{ik,SP}^{(k)} p_{i,S}^{(k)} g_{ik,SP}^{(k)} + \delta_{ki,PS}^{(k)} p_{k,P}^{(k)} g_{ki,PS}^{(k)}}_{\text{Complete inter-system interference}} + \underbrace{\delta_{ki,PS}^{(k)} \varphi^{(k)}}_{\text{Cost of sharing the } k\text{-th subchannel with the } k\text{-th PU}} \Bigg], \quad (11)$$

$\forall i \in \mathcal{N}$, where $\varphi^{(k)}$ can be adjusted by the k-th PU's transmission pair according to the following rule.

$$\varphi^{(k)}[n+1] = \begin{cases} \varphi^{(k)}[n] + \triangle, & \text{if } \gamma_{k,P}^{(k)}[n] < \gamma_{k,target} \\ \varphi^{(k)}[n], & \text{if } \gamma_{k,P}^{(k)}[n] \geq \gamma_{k,target} \end{cases}, \quad (12)$$

where $\gamma_{k,target}$ and $\gamma_{k,P}^{(k)}[n]$ are the k-th PU's target and receiving SINRs at the n-th time slot; $\triangle$ is the step size for adjusting the cost. Note that, the NEs of (S_i^*, S_{-1}^*) associated with (9), (10) and (11) should be updated whenever $\varphi^{(k)}$ is adjusted.

It should be noticed that the operations of the proposed schemes require some necessary information exchanges via a common communication channel. An applicable protocol for exchanging information as well as the method of measuring channels can be referred to [4]. However, how to design a more efficient one may go beyond the scope of this paper.

IV. Potential Functions

According to the theory of Potential Game, a well-defined potential function can preserve the convergence of the associated game [11], [12]. Thus, in addition to the definition of Potential Game, the potential functions for the above IQU, SIU and SUU functions will also be provided in this section.

Definition 1: Exact Potential Game (EPG)
A strategic form game $\mathcal{G} = (\mathcal{N}, \{\mathcal{S}_i\}_{i\in\mathcal{N}}, \{U_i\}_{i\in\mathcal{N}})$ *is called an exact potential game if there exists a function* F *such that* $U_i(S_i, S_{-i}) - U_i(S_i', S_{-i}) = F(S_i, S_{-i}) - F(S_i', S_{-i})$ *can be satisfied. Then, the function* F *is called exact potential function of the game* $\mathcal{G}$ [13]. ■

Then, based on the following corollaries, we know that every finite exact Potential Game can have a finite improvement path (FIP), which can confirm the convergence to the Nash equilibrium.

Corollary 1: FIP and Nash equilibrium
All games with FIP have at least one Nash equilibrium. [13] ■

Corollary 2: Exact Potential Game and FIP
Every finite exact potential game has FIP. [13] ■

To make it clear, the definition of FIP is provided in the following.

Definition 2: Finite Improvement Path
A ***path*** *in the strategy set* $\mathbb{S}$ *is a sequence* $\Omega = (\mathbf{S}[0], \mathbf{S}[1], \cdots)$, *where* $\mathbf{S}[k] = (S_i[k], S_{-i}[k]) \ \forall \ S_i[k] \in \mathcal{S}_i$*; and the index in the bracket indicates the* k*-th deviation step. An* ***improvement path*** *is a path which preserves* $U_i(\mathbf{S}[k]) > U_i(\mathbf{S}[k-1]) \ \forall k \geq 1$, *where the* i*-th player is the unique deviator at the* k*-th step. A game* $\mathcal{G}$ *is said to have the* ***finite improvement property*** *if all improvement paths in* $\mathcal{G}$ *are finite, where the finite means that the path consists of finite deviation steps* [13]. ■

Now, the potential functions for the IQU, SIU and SUU functions can be respectively defined as follows:

$$F(\mathbf{S}) \triangleq -\frac{1}{2} \sum_{i=1}^{N} \sum_{k=1}^{K'} \sum_{j=1,j\neq i}^{N} \left(\delta_{ji,SS}^{(k)} p_{j,S}^{(k)} g_{ji,SS}^{(k)} W_j^{-\alpha} + \delta_{ij,SS}^{(k)} p_{i,S}^{(k)} g_{ij,SS}^{(k)} W_i^{-\alpha} \right), \quad (13)$$

$$F(\mathbf{S}) \triangleq -\frac{1}{2} \sum_{i=1}^{N} \sum_{k=1}^{K'} \left[\sum_{j=1,j\neq i}^{N} \left(\delta_{ji,SS}^{(k)} p_{j,S}^{(k)} g_{ji,SS}^{(k)} W_j^{-\alpha} + \delta_{ij,SS}^{(k)} p_{i,S}^{(k)} g_{ij,SS}^{(k)} W_i^{-\alpha} \right) - 2\beta \log(1 + p_{i,S}^{(k)} g_{ii,SS}^{(k)}) \right] \quad (14)$$

and

$$F(\mathbf{S}) \triangleq -\frac{1}{2}\sum_{i=1}^{N}\sum_{k=1}^{K}\Bigg[\sum_{j=1,j\neq i}^{N}\Big(\delta_{ji,SS}^{(k)}p_{j,S}^{(k)}g_{ji,SS}^{(k)}W_j^{-\alpha} + \delta_{ij,SS}^{(k)}p_{i,S}^{(k)}g_{ij,SS}^{(k)}W_i^{-\alpha}\Big) - 2\beta\log(1+p_{i,S}^{(k)}g_{ii,SS}^{(k)}) + 2\delta_{ik,SP}^{(k)}p_{i,S}^{(k)}g_{ik,SP}^{(k)} + 2\delta_{ki,PS}^{(k)}p_{k,P}^{(k)}g_{ki,PS}^{(k)} + 2\delta_{ki,PS}^{(k)}\varphi^{(k)}\Bigg]\ . \quad (15)$$

With these potential functions, one can prove the property of Potential Game by calculating $U_i(S_i, S_{-i}) - U_i(S_i', S_{-i}) = F(S_i, S_{-i}) - F(S_i', S_{-i}),\ \forall i \in \mathcal{N}$.

V. Simulation Results

In the simulation, a CR ad-hoc network is deployed within a 500×500 (m^2) square area, in which $N = 20$ SUs' transmission pairs are uniformly distributed. Also, the distance between the transmitting and receiving ends of any particular SU's pair is uniformly distributed over the range of [50 150] (m). The same data arrival rate is assumed for each SU's transmission pair. There are $K = 5$ PUs' transmitters positioned at the boundary of the square, which means that the number of available subchannels for the CR network is five. Also, the distance between a PU's transmitter and receiver is uniformly distributed over the range of [100 200] (m). All the players in the Potential Game take turns to bid according to the Round Robin scheduling rule. The flat Rayleigh fading and empirical log-distance path loss model with path loss exponent of four is considered for generating the path gains. The path gains are fixed within the duration of a time slot, i.e. $T_s = 4$ (msec.). The maximum transmission power P_{Max} is 40 (mW). The bandwidth of a subchannel is 100 (kHz), while the power spectrum density of AWGN is -174 (dBm/Hz).

A. Convergence of the Proposed Schemes

To prove the convergence of the proposed schemes, Fig. 2 shows the evolution of the IQU potential function, i.e. FIP of Potential Game, with $\alpha = 0, 1, 2, 3$ and $K_i = 1\ \forall i \in \mathcal{N}$. It is obviously that the FIP presents the positively unilateral deviation in each iteration until the steady state is reached.

B. Effects of the Number of Allocated Channels

Figs. 3(a) and 3(b) show the effects of the number of allocated channels, i.e. K_i, on the (a) average queuing delay with respect to various data arrival rates and; (b) end-to-end throughput with the data arrival rate fixed at 180 kbps for the game using IQU function with $\alpha = 0, 1, 2, 3$. Apparently, one can see that when $K_i = 2$ channels are allocated to each SU's transmission pair, the average queuing delay becomes significantly longer

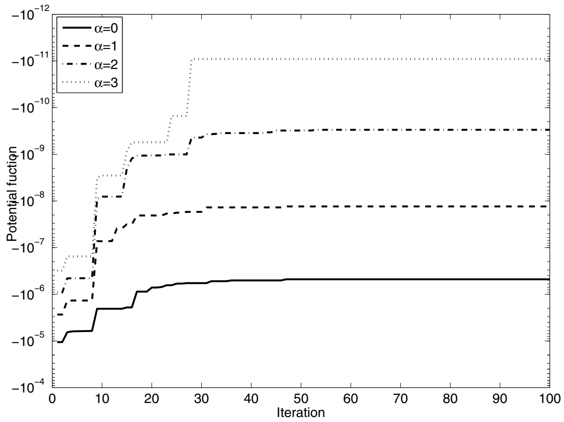


Fig. 2. Evolution of the IQU potential function, i.e. FIP of Potential Game, with $\alpha = 0, 1, 2, 3$ and $K_i = 1\ \forall i \in \mathcal{N}$.

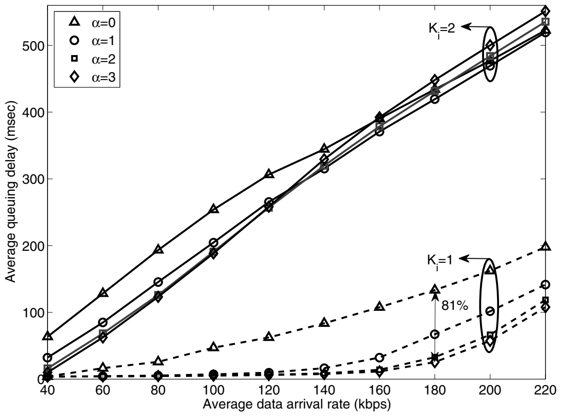
than that of $K_i = 1$. This is because when $K_i = 2$, the transmission power of each transmission pair equally distributes over two subchannels, which may lead to lower power efficiency. On the contrary, when $K_i = 1$, all the transmission power can be efficiently pour into one less-interfered subchannel. The same reason also explains the lower end-to-end throughput of $K_i = 2$ in Fig. 3(b).

As shown in Fig. 3(a), with $K_i = 1$, the queuing delay can largely decrease as the value of α increases from 0 to 3. For example, with $K_i = 1$ and the data arrival rate fixed at 180 kbps, the average queuing delay can reduce by 81%. Moreover, this improvement comes only with a minor 7.4% degradation in end-to-end throughput of Fig. 3(b).

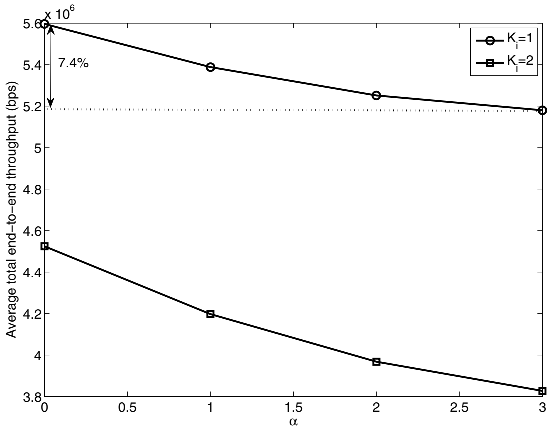
C. Performance Comparison between the Games using the IQU, SIU and SUU Functions

Figs. 4(a) and 4(b) compare the (a) queuing delay with respective to various data arrival rates; and (b) end-to-end throughput with the data arrival rate fixed at 150 kbps between the games using IQU, SIU and SUU functions with $\alpha = 0, 3$ and $K_i = 1$. In the simulation, the self-interest coefficient $\beta = 0.1$ is set for the cases of using the SIU and SUU functions. For the case of using SUU function, the step size $\triangle$ and SINR $\gamma_{k,target}$ in (12) are set to be 0.0001 and 10 dBs, respectively.

Observing these figures, one can find that the best performance in terms of both queuing delay and end-to-end throughput can be obtained by using the SUU function. For example, with $\alpha = 0$ and data arrival rate of 150 kbps, SUU can outperform IQU and SIU by 47% and 30% in queuing delay, while the improvement in end-to-end throughput can be 28% and 12%, respectively. Most importantly, when the CR network operates in the underlay mode using the SUU function, the PU can be protected by adjusting the cost $\varphi^{(k)}$ in (12), which is proved in Fig. 5.



(a) Queuing delay



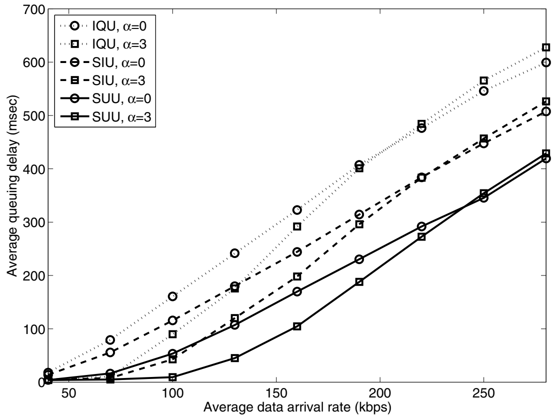
(b) End-to-end throughput

Fig. 3. The effects of the number of allocated channels, i.e. K_i, on the (a) average queuing delay with respective to various data arrival rates and; (b) end-to-end throughput with the data arrival rate fixed at 180 kbps for the game using IQU function with $\alpha = 0, 1, 2, 3$.

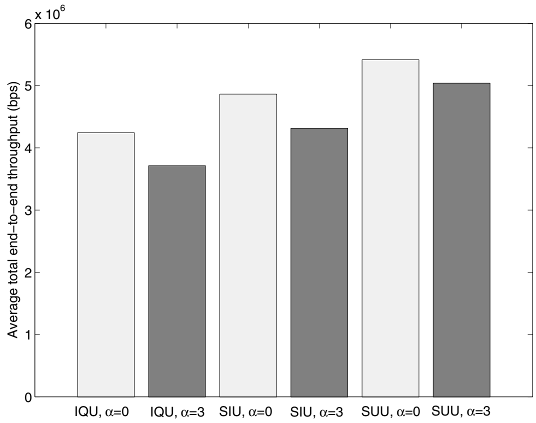
Besides, one may carefully find that as the data arrival rate increases, the queuing delay of $\alpha = 3$ becomes slightly longer than that of $\alpha = 0$. This is because when the queue in each SU's transmitting end becomes overcrowded, selecting the less-interfered channel can be helpful to increase data transmission rate so as to reduce the queuing delay.

VI. Conclusions

In this paper, we have proposed several utility functions by taking the queuing delay, complete inter-system interference and protection of PUs into account for the channel allocation game in the spectrum-interweave and spectrum-underlay CR networks. In the proposed schemes, the sensitivity of queuing delay can be adjusted for different system requirements. Also, a PU can be protected by adaptively adjusting the cost of sharing his subchannel. For the purpose of proving the convergence of the proposed



(a) Queuing delay



(b) End-to-end throughput

Fig. 4. Comparison of (a) queuing delay with respective to various data arrival rates; and (b) end-to-end throughput with the data arrival rate fixed at 150 kbps between the games using IQU, SIU and SUU functions with $\alpha = 0, 3$ and $K_i = 1$.

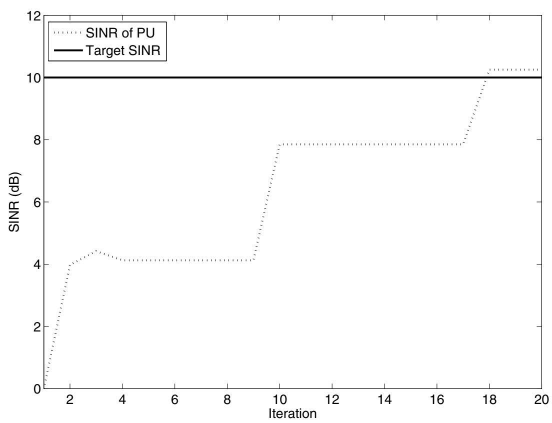


Fig. 5. The evolution of PU's SINR under the protection of adjusting the cost $\varphi^{(k)}$ in (12).

utility functions, the associated potential functions were also defined. With the aids of these potential functions, the convergence of the proposed utility functions was proved based on the theory of Potential Game. The simulation results have also proved that the queuing delay can be significantly reduced, and meantime the throughput can be slightly degraded. Most importantly, the PU's SINR can be maintained at the target value in the underlay CR network.

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