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Dynamic overlapped spectrum allocation based on potential game in cognitive radio networks①

Jia Yanan (贾亚男)②*, Yue Dianwu***

(* College of Information Science & Technology, Dalian Maritime University, Dalian 116026, P. R. China)

(** National Mobile Communications Research Laboratory, Southeast University, Nanjing 210096, P. R. China)

Abstract

In order to make full use of wireless spectrum resources, the behavior of cognitive radio (CR) for dynamic spectrum allocation is analyzed based on the game theoretic framework. The traditional spectrum allocation schemes consider the spectrum allocation among independent frequency bands only, without taking into account mutually overlapped frequency bands. For this reason, an optimal allocation etiquette is defined to promote the cross characteristic of the frequency bands in a dynamic spectrum allocation model. New interference operator and interference temperature constraints are introduced in order to realize calculation of the interference, and the corresponding spectrum allocation scenario can be further formulated as a potential game. Based on the characteristic of dynamic selection using the game theory and the interference avoidance rule of interference temperature, the robustness of CR networks is increased and the scenario is more suitable for the dynamic changing of actual wireless communication and energy saving communication systems. Simulation results show that the signal to interference and noise ratio (SINR) level can be significantly improved through the optimal allocation of any available spectrum. The utilization rate of spectrum and throughput of overall CR networks are increased by fully utilizing the spectrum resources in the dynamic spectrum allocation model.

Key words: cognitive radio (CR), game theory, spectrum allocation, nash equilibrium

0 Introduction

The rapid growth in wireless communications has contributed to a huge demand on the deployment of new wireless services in both licensed and unlicensed frequency spectrums. However, recent studies have shown that the fixed spectrum assignment policy enforced today results in poor spectrum utilization[1]. To address this problem, the cognitive radio (CR) was coined by Mitola, and has emerged as a promising technology to sense the external environment, learn from the history, make intelligent decisions to adjust its transmission parameters according to the current environment, and thereby increase the spectral efficiency[2]. The desired CR users can reuse the spectrum when the degradation intruded on the other communicating users' performance is null or tolerable. As plenty of wireless multi-vision applications for home entertainment are becoming an important trend in consumer electronic domains. And most of the existing applications are operating in the unlicensed free Industrial scientific medical (ISM) band which is becoming overexploited and experiences serious coexistence problems. Using the dynamic spectrum access techniques[3], an unlicensed CR indoor multi-vision system can operate in the UHF TV band for short-range indoor transmission of high definition TV contents. In the actual communication, users randomly leave or enter the same cell to build their links through different information rates. The dynamic situation leads to the interference level between users changing accordingly. So it needs a dynamic spectrum access algorithm to realize an optimized allocation of available spectrum resource, and then the interference level can be reduced. For decreasing greenhouse gas emissions and energy costs, the environment-friendly CR standardization can assist the use of CR to both save energy for wireless communications, and ensure that the energy consumption in CR networks and devices is minimized[4].

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② To whom correspondence should be addressed. E-mail: jiayanan666@163.com

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The potential contributions of CR to spectrum sharing between independent frequency channels and an initial framework for formal radio etiquette have been discussed in Ref. [3]. According to the proposed etiquette, users should listen to the environment, determine the interference from their neighbors on the determinate channel and estimate their interference contributions on their neighbors. In this model, the interference exists only when users communicate with each other in the same independent channel. And the cumulative interference in the chose channel may exceed the tolerable interference by communication equipment when plenty of users signal at the same time in an equilibrium station. Consequently the failing communication will require packet retransmission to ensure the correct packet reception, so it will consume more energy. As an intelligent communication system, the CR users should change their transmission parameters according to the dynamic channel environments adaptively[5]. For some communication systems, the communication bands may be partially overlapped, such as the Multitone CDMA (MT-CDMA), spread spectrum communications, and so on. According to the quality of service (QoS) and communication system constraints cognitive users should adaptively select communication bandwidths and center frequency from all of the available spectrums, and not just a limited number of independent channels. So the cognitive users (CUs) should have a more flexible scenario to choose the communication parameters. For this reason a novel spectrum allocation model is proposed to make the interference not only exist in the independent channels but also can be reflected between the overlapped channels. An improved interference function is introduced in which it contains a new interference operator and interference temperature constrains. So the system will be more energy saving and robust, and the spectrum utilization and system throughput can be effectively improved.

The rest of the paper is organized as follows. In Section 1, it describes a system model of CR networks for the dynamic spectrum allocation. In Section 2, it provides a brief introduction to the Game theory, used to build a dynamic spectrum allocation engine. Simulation results and discussions are presented in Section 3. Finally, the conclusion of this paper is in Section 4.

1 System model

As shown in Fig. 1, a new system model is proposed in which the CR network consists of n IEEE 802.11b hotspots, with one access point (AP) and multiple Wi-Fi users per hotspot, and one 802.16a cell, with one base station (BS) and multiple subscribe station (SS). The Wi-Max network can cover a range of 3km and the Wi-Fi hotspots inside the 802.16a cell can cover a shorter range of 150m. Both systems are independent from each other in one geographic area. The SS and Wi-Fi users can be regarded as primary users (PUs). It assumes that the cognitive users randomly distributed in the cognitive network are static or quasi-static (slower than the convergence time for the proposed algorithms) when reusing the ISM (Industrial Scientific Medical) band to communication. In this situation, the CU's data transmission should not damage the PU's communication, so each CU can accurately measure the available spectrum before deciding transmission frequency and the transmission energy must satisfy certain interference temperature constrains.

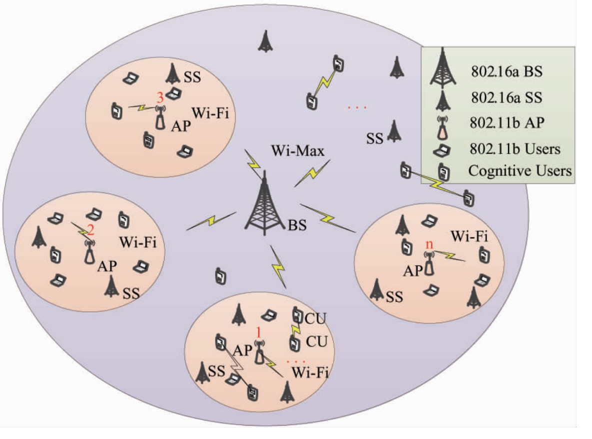

Fig. 1 CR network architecture

Fixed bandwidth allocation is used in the Wi-Fi and Wi-Max systems. The two systems can share the same ISM band. The Wi-Fi radios use direct sequence spread spectrum (DSSS) with a bandwidth of 22MHz per channel and a total of 14 overlapped channels are allocated in the ISM band[6]. The Wi-Max radios use OFDM with 20MHz bandwidth and 4 non-overlapped channels are considered. In the study it assumes alignment of the center frequencies of Wi-Fi channel index a with Wi-Max channel index 1 at 2412MHz, as shown in Fig. 2. Furthermore, there are M Wi-Fi frequency channels available for a set of N transmitting-receiving pairs of CUs to transmission, with $M < N$. By selecting a transmitting frequency in a distributive way, the CU radios construct a channel reused distribution map with reduced co-channel interference effectively.

The transmission link quality of the CR networks can be characterized by a required signal to interference and noise ratio (SINR) target which represents

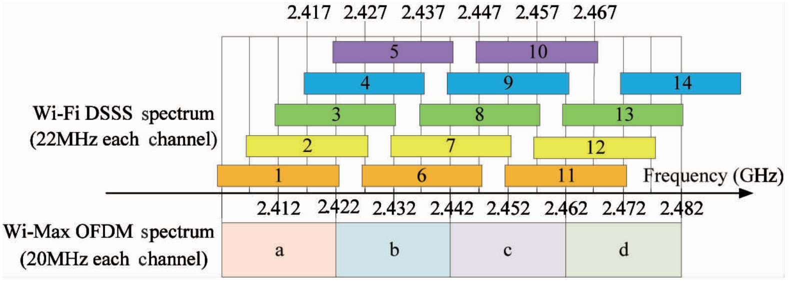

Fig. 2 Wi-Fi and Wi-Max channel allocation

the situation of interference. Such as SINR measured at receiver i can be formulated as

$$SINR_{ii} = \frac{p_i \mid H_{ii} \mid^2}{\sum_{k=1,k\neq i}^{N} p_k \mid H_{ki} \mid^2 \sigma(f_k, f_i) + \rho_i^2} \quad (1)$$

where p_i is the transmission power at transmitter i, H_{ii} is the link gain between the transmitting-receiving pair i, $H_{ki}(k \neq i)$ is the interference gain between transmitter k and receiver i, f_k is the center frequency of the RTS/CTS signal of CR k, ρ_i^2 is the additive white Gaussian nose (AWGN) received by receiver i, and B_i is the bandwidth of the transmitting signal used by user i. Moreover, $\sigma(f_k, f_j)$ is proposed as an interference operator characterizing the overlapped interference created by transmitter k to receiver j, and is exactly defined as

$$\sigma(f_k, f_j) = \begin{cases} \frac{\max\{(B_k + B_j)/2 - \Delta f_{k,j}, 0\}}{(B_k + B_j)/2}, & \Delta f_{k,j} \geqslant \Delta B_{k,j} \\ \frac{B_j}{(B_k + B_j)/2}, & \Delta f_{k,j} < \Delta B_{k,j} \end{cases} \quad (2)$$

with $\Delta f_{k,j} = \mid f_k - f_j \mid$ and $\Delta B_{k,j} = \mid B_k - B_j \mid /2$. From Eq. (2) the interference operator shows different interference degree when CUs choose different communication frequencies and bandwidths.

To minimize the SINR of whole network, namely, to minimize SINR of each user, while the interference of users on the frequency channel is interactive to each other. This multi-objective optimization problem is consistent with the application background of the game theory. So game theory is used to represent CU's mutual interference in the communication system.

2 Potential game for dynamic spectrum allocation

2.1 Game theory

Game theory is a field of applied mathematics that describes and analyzes interactive decision processes[7]. It provides analytical tools to predict the outcome of these interactions and to identify optimal strategies for each player. The main areas of application of the game theory are economics, political science, biology, sociology, and so on. Since the early 1990s, the game theory has been used in engineering and computer science.

In a cognitive network, CR users who are intelligent and rational have the ability to learn their environment and to optimize their own performance. Since users generally belong to different authorities and pursue different goals, fully cooperative behaviors cannot be taken for granted. Instead, users will cooperate with others only when cooperation can improve their own performance[8-10]. Therefore, a key problem in cognitive networks is how to stimulate cooperation among selfish users. To address the interactions of the dynamics among conditions, resources, environments, and players, game theory has naturally become an important emerging tool that is ideal and essential in studying, modeling, and analyzing the cognitive interaction processes[11]. The interactions between CR users can be modeled as a game theoretic formulation by modifying their transmission parameters.

In particular, a game theoretic formulation of dynamic spectrum allocation problem is proposed for CR networks[12]. In this model, the players are the CR users and their actions (strategies) are the transmitting frequencies which not only influence their own performance, but also neighboring users. And their payoffs are associated with the quality of chosen frequencies which is determined through measurement on different radio frequencies by CR users.

The channel allocation problem can be modeled as a normal or strategic form game, that can be mathematically defined as $\Gamma = \langle N, F, \{U_i\} \rangle$, where $N = \{1, 2, \cdots, n\}$ represents the set of n CR users (decision makers), F is the frequency space formed as the Cartesian product of the sets of actions available to each user, $F = F_1 \times \cdots \times F_n$ where F_i and $i \in N$ specifies the frequencies available to CR user, and $\{U_i\}$ satisfies the following expression: $F \rightarrow R$, is the set of utility functions that denote the CR users' decision processes. For every user i in game Γ, the utility function U_i is a function of f_i which is the action chosen by user i, and the current strategy profile of its opponents: $\boldsymbol{f}_{-i}$. Together, f_i and $\boldsymbol{f}_{-i}$ make up the action tuple $\boldsymbol{f}_i$. An action tuple is a unique choice of actions by each user. From this model, steady state conditions can be identified as Nash equilibrium. The aim of user i, given the other users' actions $\boldsymbol{f}_{-i}$, is to choose an $f_i \in F_i$ that maximizes its utility function $U_i(f_i, \boldsymbol{f}_{-i})$ and satisfies the interference temperature constraints $g(f_i, \boldsymbol{f}_{-i}) \leqslant P_{\max}$. Function $g(f_i, \boldsymbol{f}_{-i})$ represents the interference to the channel whose frequency is f_i and the maximum interference value $P_{\max}$ is chosen by cognitive network according to the QoS requirements. Mathematically, i. e.

$$\begin{aligned} &\underset{f_i}{\text{maximize}} \quad U_i(f_i, \boldsymbol{f}_{-i}) \\ &\text{subject to} \quad f_i \in F_i,\ g(f_i, \boldsymbol{f}_{-i}) \leqslant P_{\max} \end{aligned} \tag{3}$$

Roughly speaking, a Nash Equilibrium (NE) problem is a set of coupled optimization problems[13]. In analyzing the outcome of the game, as the users make decisions independently and are influenced by its opponents' decisions, it is important to determine if there is a convergence point for this adaptive channel allocation algorithm.

Definition 1: An action tuple for users, $\boldsymbol{f} = [f_1, f_2, \cdots, f_N]$ is a NE if and only if

$$U_i(\boldsymbol{f}) \geqslant U_i(f_i^{'}, \boldsymbol{f}_{-i}), \quad \forall i \in N, f_i^{'} \in F_i \tag{4}$$

If the equilibrium strategy profile in Eq. (4) is deterministic, a pure strategy NE exists. For finite games, even if a pure strategy NE does not exist, a mixed strategy NE can be found (equilibrium is characterized by a set of probabilities assigned to the pure strategies).

2.2 Potential game

From the above discussion, it shows that the performance of the adaptation algorithm depends significantly on the expression of the utility function which characterizes a user's preference in one particular frequency channel. Also the utility function must be selected to have physical meaning and appealing mathematical properties for some particular application. So the game will be guaranteed an NE for the adaptation algorithm.

In particular, this paper has worked over and proposed a utility function that captures the channel quality, as well as the level of cooperation and fairness in sharing the frequency resources. Mathematically, i. e.

$$\begin{aligned} U_i(f_i, \boldsymbol{f}_{-i}) = &- \sum_{i \neq j,\, j=1}^{N} p_j \mid H_{ji} \mid^2 \sigma(f_j, f_i) \\ &- \sum_{i \neq j,\, j=1}^{N} p_i \mid H_{ij} \mid^2 \sigma(f_i, f_j) \end{aligned}$$

$$\forall i = 1,2,\cdots,N \tag{5}$$

$$U_i(f_i, \boldsymbol{f}_{-i}) = -I_{di} - I_{oi}, \quad \forall i = 1,2,\cdots,N \tag{6}$$

$$I_{di} = \sum_{i \neq j,\, j=1}^{N} p_j \mid H_{ji} \mid^2 \sigma(f_j, f_i) \quad \forall i = 1,2,\cdots,N \tag{7}$$

$$g(f_i, \boldsymbol{f}_{-i}) = I_{di} \leqslant P_{\max}, \quad \forall i = 1,2,\cdots,N \tag{8}$$

$$I_{oi} = \sum_{i \neq j,\, j=1}^{N} p_i \mid H_{ij} \mid^2 \sigma(f_i, f_j) \quad \forall i = 1,2,\cdots,N \tag{9}$$

where $\sigma(f_i, f_j)$ is the interference function, f_i is the frequency of RTS/CTS signal of CR user i and its bandwidth is B_i, p_i is the transmission power of user i's waveform, and H_{ij} is the interference gain from transmitter i to receiver j. In Eq. (7), I_{di} denotes the interference to receiver i caused by the other transmitters on a particular channel and it's consistent with the interference temperature function $g(f_i, \boldsymbol{f}_{-i})$. And in Eq. (9), I_{oi} stands for the interference to neighboring receivers caused by transmitter i.

In the previous section the utility function is given based on the physical meaning. And NE gives the best strategy given that all the other users stick to their equilibrium strategy too. However, the question is how to find the NE, especially when the system model is implemented in a distributed manner. One approach is to let users adjust their strategies iteratively on the basis of accumulated observations as the game unfolding, and hope that the process could converge to some equilibrium point. Although this is not true in general, the iteration does converge and lead to an NE when the game has certain special structures. In what follows, an exact potential game is formulated for the proposed utility function Eq. (5). Then NE is guaranteed.

Definition 2:[7] A game $\Gamma = \langle N, F, \{U_i\} \rangle$ is an exact potential game if there is an exact potential function: $P: F \rightarrow R$, $\forall i \in N, f_i^{'} \in F_i$, with the property that

$$P(f_i, \boldsymbol{f}_{-i}) - P(f_i^{'}, \boldsymbol{f}_{-i}) = U_i(f_i, \boldsymbol{f}_{-i}) - U_i(f_i^{'}, \boldsymbol{f}_{-i}) \tag{10}$$

From the definition, it is easy to see that any single user's individual interest is aligned with the group's interest, and any user choosing a better action given all other users' current actions will necessarily lead to improvement in the value of potential function. A potential game will terminate in finite steps to an NE that maximizes the potential function when all users adopt their better strategies sequentially[14].

According to the dynamic spectrum allocation game whose utility function is $U_i(f_i, \boldsymbol{f}_{-i})$ formulated previously, an exact potential function can be defined to be:

$$Po(F) = Po(f_i, \boldsymbol{f}_{-i}) = \sum_{i=1}^{N}\Big(-\frac{1}{2}\sum_{i\neq j, j=1}^{N} p_j \mid H_{ji} \mid^2 \sigma(f_j, f_i) - \frac{1}{2}\sum_{i\neq j, j=1}^{N} p_i \mid H_{ij} \mid^2 \sigma(f_i, f_j)\Big) \quad \forall i = 1, 2, \cdots, N \qquad (11)$$

The factor 1/2 appears here due to the half-duplex operation of the transmitting-receiving pairs of CUs. If users take actions following a best response strategy sequentially, from Eq. (11), it shows that the increase of an individual user's utility contributes to the increase of the overall network utility. So Eq. (11) essentially reflects the performance of the whole network.

3 Simulation results

3.1 Simulation steps and environment

The dynamic spectrum allocation is a distributed model, so it needs a distributed scheduler in which the random access based on Bernoulli trail is used for decision making. The CU who wins the game in a trial would choose a new decision based on the current values for the utility function of each frequency, otherwise, he does not change his frequency and keeps listening to the channel station information. Although the random access makes sure that on average exactly one CU makes decision at each trail, of course has a nonzero probability that two or more CUs take actions simultaneously. When two or more CUs choose frequency simultaneously, the overall system performance may decrease temporarily but then the upward monotonic trend will be re-established immediately.

The potential game formulation requires that CUs should be able to evaluate the candidate frequency's utility Eq. (5). This paper uses a three way handshake signaling protocol which is similar to the RTS-CTS packet exchange for the IEEE 802.11 protocol. After a CU is successful in the Bernoulli trial, the handshaking protocol is initiated to choose the best transmission frequency. The signaling packets, START, START _ CH and ACK _ START _ CH (END, ACK _ END) are used to measure the interference components of the utility functions for different frequencies and to assist in computing the utility function. And the signaling packets play a double role, one is to announce the station of current CU to select a particular frequency to transmit information, the other is to serve as probing packets to measure the interference on frequency to be chosen.

For this network, it assumes that the signaling packets transmitted on a common control channel use a fixed transmission power and no collisions occur on common channel. From the utility Eq. (5), it can be known that the measure of interference is divided in two parts: the interference created by other CUs I_{di} and the interference created to its neighbors I_{oi}. Therefore, the protocol requires that both transmitter and receiver should listen to the common channel and maintain a Channel Status Table (CST). In the follows, the steps of the protocol will be outlined as shown in Fig. 3.

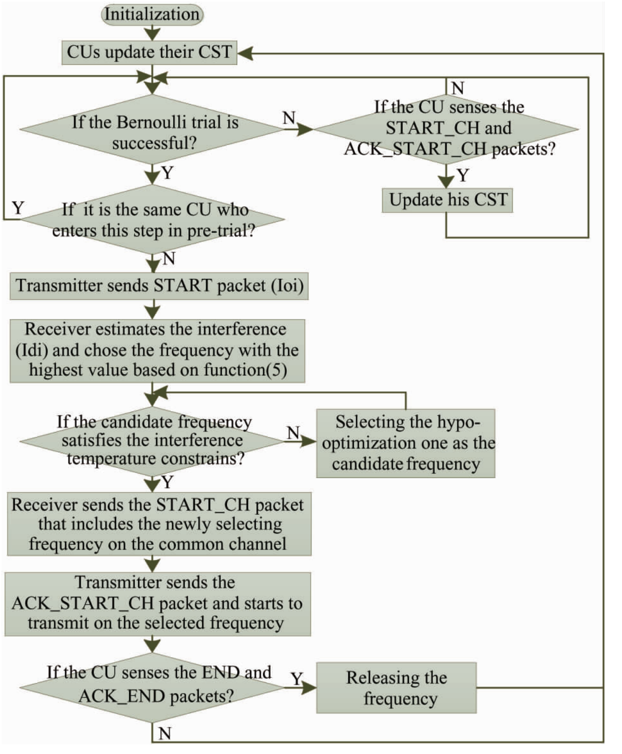

Fig. 3 Flow chart of arithmetic

It can be known that the transmitters and receivers should maintain different copies of the CST-t and CST-r respectively. The list of each table contains neighboring users who have requested a frequency, the center frequency, the bandwidth, and the estimated link gain between the CUs.

In this paper, the dynamic overlapped spectrum allocation technique is simulated with MATLAB programs on the underlying cognitive radio system. In particular, in the proposed simulation a Gaussian frequency-selective multiuser interference channel is employed, composed of $N = 40$ transmitting-receiving pairs of CR users whose signals have the same transmission power, and they are randomly distributed in the Wi-Fi network index 1 whose radius D is 150 meters long, as shown in Fig. 1. It assumes that the Wi-

Max network will always operate and the Wi-Fi network is unused at the same time. From Fig. 2, based on the purpose of improving the frequency band utilization rate and decreasing the interference energy, it assumes that the channel index 1, 5, 9, 13, 14 will be the available channel for CUs' selection. For convenient simulation the five available channels are numbered from 1 to 5 according to the channel index. It will make full use of the frequency resource rather than just choosing the non-overlapping channel index 1, 9, 14 in the method[3]. At the beginning, the initial frequencies are selected in a random way.

3.2 Simulation results and analysis

First, the convergence property of the spectrum sharing algorithm is illustrated based on the potential game. From Figs 4 and 5, the convergence of users' strategies is achieved when using the arithmetic of potential game. In Fig. 5, at the beginning of simulation

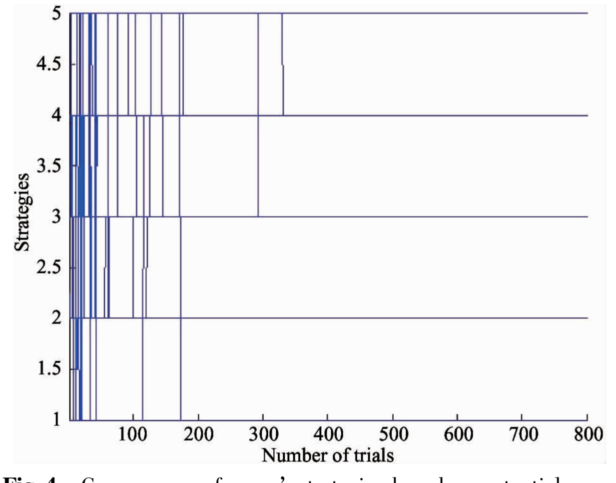

Fig. 4 Convergence of users' strategies based on potential game

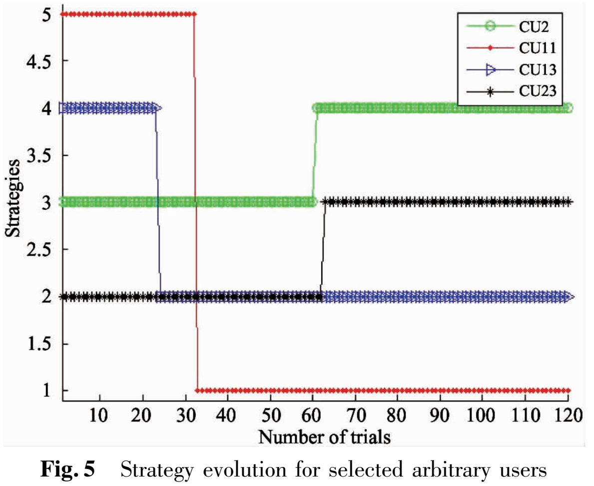

Fig. 5 Strategy evolution for selected arbitrary users based on potential game

users CU2, CU11, CU13 and CU23 randomly choose strategies 3, 5, 4 and 2, respectively, and then they try to update their strategies according to their own utilities, until they converge to the stable situation finally, which is a pure strategy of Nash equilibrium after numbers of trials, e. g., CU11 changes its strategy from 5 to 1 after No. 33 trial to minimize the system interference.

In Fig. 6, the system interference is described by using potential function and it reduces to static along with the trail evolving. It illustrates the changes in the potential function when the potential game evolves, and the result shows that the users can affect the overall utility of the network by respectively improving their utility. All of these results are consistent with the theoretic analysis with potential game.

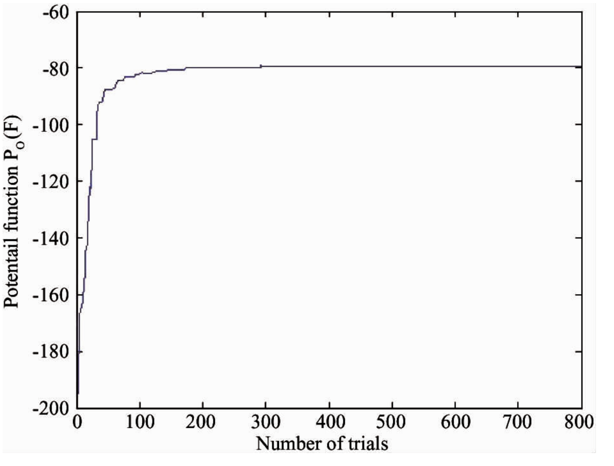

Fig. 6 Evolution of potential function

Figs 7 and 8 illustrate the SINRs observed by CR users on each of 5 different frequencies for initial and final assignments, respectively. At the initial assignment, the distribution of CR users in different frequencies is non-uniform, and the SINRs values of CR users are not rational. In contrast to all CR users' distribution and SINRs value at the initial assignment, when the Nash Equilibrium statement is achieved in the potential game, the final assignment shows that the CR users would be distributed more uniformly and the SINRs values would be significantly improved. From the histogram of SINRs values in Fig. 9, it can be seen that the number of CR users having an SINR below 0dB has been reduced and the SINRs of most of CR users are relatively high, although it comes at the expense of a slight penalty in performance to the CR users who have an initially high SINRs.

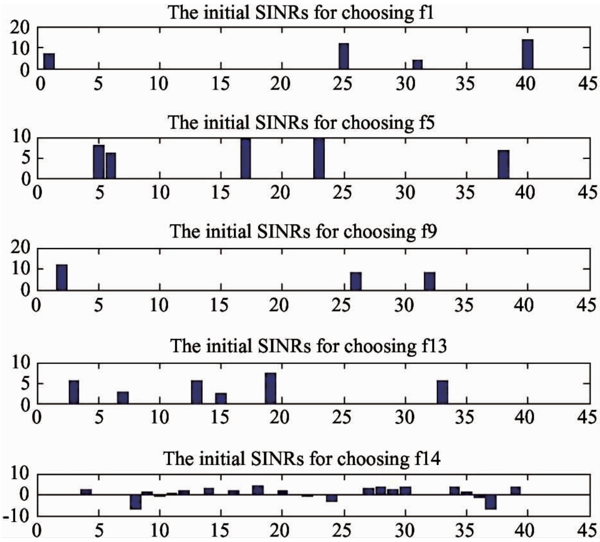

Fig. 7 SINRs for initial frequency assignment

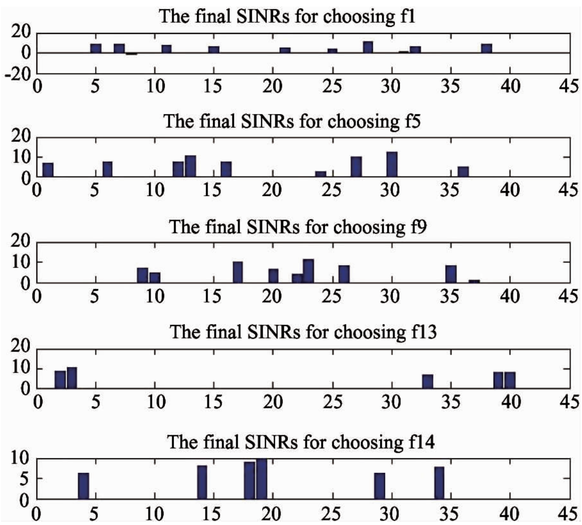

Fig. 8 SINRs for final frequency assignment based on potential game

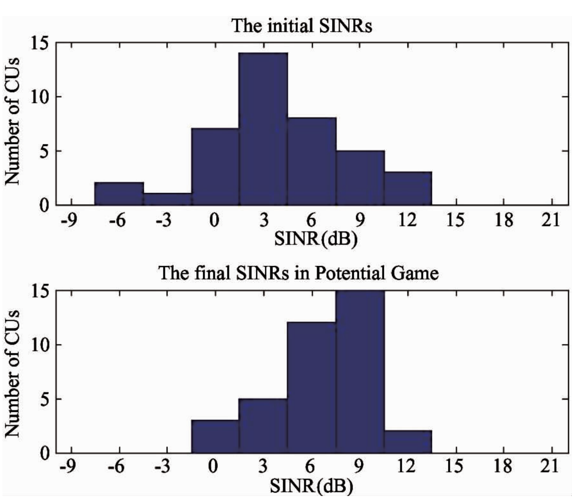

Fig. 9 The SINRs: Initial assignment vs. Final assignment

The expression $R = \log(1 + SINR)$ implies that the spectral efficiency R has the same monotonicity as SINR. So they are essentially identical with each other in the Gaussian frequency-selective multiuser interference channel. In the simulation, only CDF (Cumulative Distribution Function) of SINR is chosen to demonstrate the proposed algorithm. Fig. 10 shows that the percentage of CR users with SINR value less than 5 dB decreases from about 64% to 21%, at the expense of a slight decrease of the SINR value for user with initial SINR value greater than 10dB. Fig. 11 plots the CDF of achieved throughputs for the initial and final spectrum allocation schemes. And it shows that the percentage of CR users with throughputs less than 0.7 decreases from almost 72% to 25%, most of the CR users' throughputs are greater than 0.7 in final assignment. So it gets a significant improvement to the throughputs of the whole CR networks when using the potential game scheme.

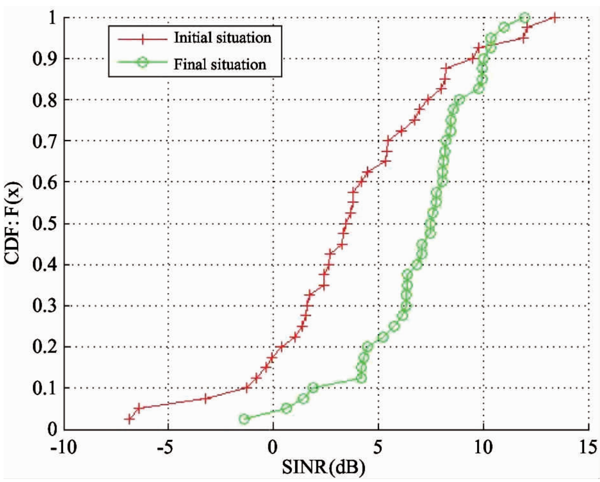

Fig. 10 CDF for the achieved SINRs: Initial assignment vs. Final assignment

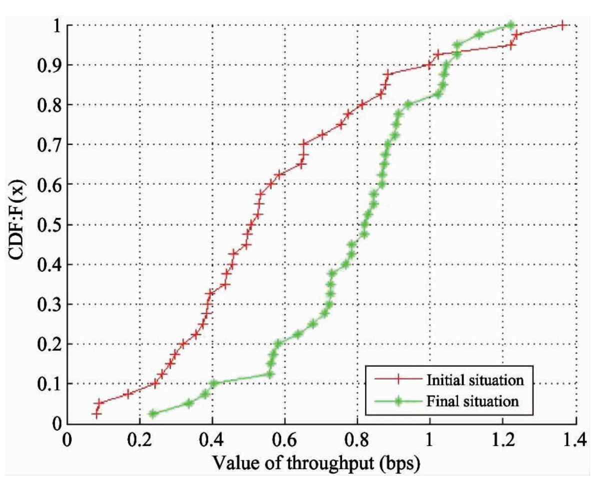

Fig. 11 CDF for the achieved throughputs: Initial assignment vs. Final assignment

Fig. 12 shows that the throughput of the system will be gradually increased with CUs increasing in the cognitive network, and gradually stabilize. The system throughput obtained by our method is larger than the method used in Ref. [3], and the amount of the increasing system throughput becomes larger with the increasing CUs. So, this algorithm is more rational to use the spectrum resources when there are overlapped spectrum resources available.

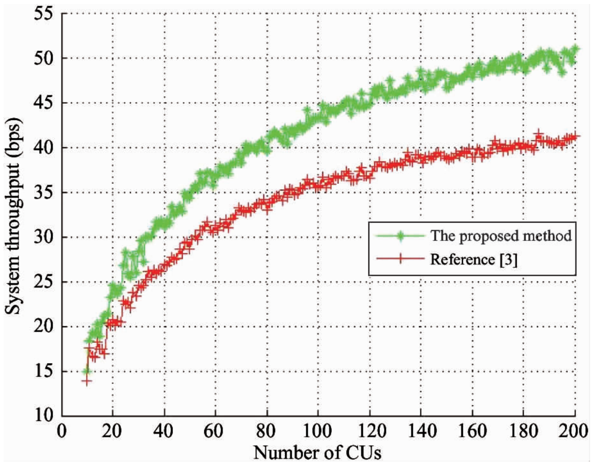

Fig. 12 System Throughputs: The proposed method vs. Ref. [3]

4 Conclusions

A novel dynamic overlapped spectrum allocation model based on game theory is proposed to study CR network, and the dynamic spectrum allocation is analyzed from the perspective of optimization. For the lack of investigation in the overlapped spectrum allocation, there is an improvement to the spectrum utilization by introducing a new interference operator. This makes the interference not only exist in the independent frequencies but also be reflected between the cross frequencies. In particular, the potential utility function has been generalized with the interference temperature which can avoid some unnecessarily failing communication and save more energy for the mobile devices, so the QoS of the PUs and CUs can be guaranteed. This scenario can also be used in some other communication systems which can dynamically change the communication parameters, be more energy efficient for reducing the carbon footprint of wireless networks, e. g. the small cell networks.

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Jia Yanan, born in 1986. He received his B. E. in Electrical and Information Engineering from the PLA Information Engineering University, Zhengzhou, China, in 2010, and the M. E. degree in Information and Communication Engineering from Dalian Maritime University, Dalian, China, in 2012. He is currently pursuing Ph. D degree in Communication and Information System from Dalian Maritime University. His research interests include cognitive radio, game theory and small cell networks