Spectrum allocation of cognitive radio based on game theory

Qiang Shu
School of science, Jimei university, Xiamen, China
shuqiangmail@sina.com

Yangfan Cui
School of ocean information engineering, Jimei university, Xiamen, China
202211810003@jmu.edu.cn

Guangsong Yang
School of ocean information engineering, Jimei university, Xiamen, China
gsyang@jmu.edu.cn

Guowei Lei*
School of science, Jimei university, Xiamen, China
gwlei@qq.com

ABSTRACT

With the development of wireless communications, spectrum resource is becoming more and more scarce. To solve the shortage of spectrum resources in the radio system and make better use of the free frequency bands of authorized users, spectrum allocation of multiple authorized users in cognitive radio based on game theory is studied in this paper. Graph theory coloring algorithm can quickly achieve fast Nash equilibrium, which can solve the problem of frequency band allocation of multiple authorized users. Experiments are simulated to validate the analysis.

CCS CONCEPTS

• **Information systems**; • **Information systems applications**; • **Mobile information processing systems**;

KEYWORDS

cognitive radio, game theory, spectrum allocation

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1 INTRODUCTION

With the development of wireless communication technology, spectrum resources are becoming increasingly scarce. Therefore, spectrum sharing technology that can exploit non renewable spectrum resources has received widespread attention. Because the idle spectrum resources are limited, users need to compete to use the idle spectrum. Meanwhile the priorities and requirements of different users are different, so cognitive radio systems need to ensure that users with high priority receive services first, but also ensure that spectrum resources are not monopolized by some users, that is, the system needs to manage the idle spectrum resources fairly and effectively. The main purpose of idle spectrum allocation is to allocate a certain amount of spectrum resources fairly and effectively based on the priority and other requirements of users, so as to improve system performance or approach the optimal state.

In a cognitive radio networks with primary licensed users and unlicensed users, game theory can be used to assess the performance of the spectrum sharing process [1]. In addition to cognitive radio, game theory also can be used in distributed resource allocation between device-to-device (D2D) communication and cellular users [2]. Moreover, a differential game based approach is proposed to solve the bandwidth allocation problems in satellite communication network [4]. A non-cooperative game with statistical strategies is defined, can seek to balance between near and far players (users) belonging to the same base station, in terms of allocated power based on green communications [3]. A game based secure data transmission scheme is investigated in burgeoning unmanned aerial vehicle (UAV) assisted vehicular internet of things (UVIoTs) [5].

In order to solve the shortage of spectrum resources in the radio system and make better use of the free frequency bands of authorized users, spectrum allocation of multiple authorized users in cognitive radio based on game theory is studied in this paper. Moreover, graph coloring is exploited in the proposed algorithm. As graph theory, coloring algorithm can quickly achieve fast *Nash* equilibrium, which can solve the problem of frequency band allocation of multiple authorized users.

2 GAME THEORY IN COGNITIVE RADIO

Game modeling refers to the process of abstracting the actual problems in cognitive radio into game models. This is mainly based on the three elements of the game, participants, strategy space and utility function, to abstract authorized users who interact with each other in cognitive radio into participants, to abstract the range of each user's parameter channel, power, etc. into strategy space, and to abstract the effect function of the target to be achieved according to the user's parameter selection.

2.1 Game model

Game theory is the mathematical method that studies whether the parties struggling in a game have the most reasonable behavior, and how to find this reasonable method. Game theory considers the predicted and actual behavior of individuals in a game and studies

*Corresponding author: Guowei Lei, is with the school of science, Jimei university.

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their optimization strategies. For the purpose and interests, each party must consider the various strategy and try to choose the most beneficial or reasonable solution for itself.

Any game can be represented by $G = N, S, \{u_i\}$., where G represents a specific game. It contains three basic elements:

(1) Participants: $N = \{1, 2, 3, \cdots, n\}$, each one with decision-making power can become a participant in a competition or game.
(2) Optional strategies for participants: Si,. $S = S_1 \times S_2 \times \cdots \times S_n$ is the strategy space. In a game, each participant has a choice of a practical and feasible complete action, meaning that the plan is not a specific stage of action, but a plan that guides the entire action. A feasible and globally plan for each participant is called a strategy for this participant.
(3) The profit: $\{u_i\} = \{u_1, u_2, \cdot\cdot\cdot, u_n\}$. The profits of each participant at the end of a game are not only related to the strategy chosen by the participant themselves, but also to a set of strategies determined by other participants. Hence, at the end of a game, the profit of each participant is a function of a set of strategies determined by all participants, commonly referred to as the average payoff function.

2.2 Nash equilibrium

For game $G = \{S_1 \cdots S_n; u_1 \cdots u_n\}$,$\{S_1 \cdots S_n\}$ is the strategy set of game participants, for each participant i=1,2, . . .n, the condition must be meet *Nash* equilibrium as follows

$$U_i\left(S_1^*, \cdot\cdot\cdot, S_n^*\right) \geq U_i\left(S_1, \cdot\cdot\cdot, S_n\right) \tag{1}$$

In the game process, if the game participants are aware of the information situation of other participants and also know that they have used a strategy to achieve *Nash* equilibrium, then the participants also use this strategy, which is beneficial to their own interests. If the participant maximizes their own interests, they will easily choose their own strategy because they know the strategy adopted by other game participants to achieve *Nash* equilibrium, To maximize one's own interests, *Nash* equilibrium is an important standard form that can measure the stability of non cooperative games, analyze the strategies of game participants, and the results after playing the game.

2.3 Pareto Optimal

*Pareto*optimal is an important concept in game theory, which is involved in social science, economics and engineering. Pareto optimality is an ideal state of resource allocation, in which a game participant randomly modifies their strategy in order to increase their own game profits. However, this behavior is not allowed in the game, as it will harm the interests of other participants. It is impossible for participants to increase their own profits without harming the interests of other participants.

Unfortunately, this concept always provides a set of solutions called *Pareto* optimality, rather than a single solution. The vector in the solution set that satisfies *Pareto* optimality is called non dominated. The image of the *Pareto* optimal solution set under the objective function is called the *Pareto* frontier.

We assume $S^* \in S$ is a Pareto optimal strategy. If thereis no other strategy $S \in \mathcal{S}$, such that $u_i(S) \leq u_i(S^*)$, (i=1,2,. . .,n), and at least we can find j such that $u_i(S) < u_i(S^*)$, (j=1,2,. . .,n).

2.4 Spectrum Allocation of Graph Theory Coloring

In cognitive radio systems, when cognitive users access the free spectrum resources of authorized users, they are bound to be affected by the conditions such as the location and whether the spectrum of authorized users is free. In cognitive radio systems, when graph coloring is used to analyze the allocation of free spectrum for authorized users, some constraints of authorized users on cognitive users should also be considered.

In general, graph theory coloring models include idle matrix, interference matrix, benefit matrix, and allocation matrix. Idle spectrum refers to the spectrum resources that are not used by authorized users at a certain time in a certain space. The idle spectrum is allocated into orthogonal sub-bands, and there is no interference between these sub-bands. In the cognitive radio system, whether the spectrum resources of the authorized user are free for the cognitive user is expressed by the idle matrix. If two cognitive users utilize an idle spectrum resource at the same time, they will interfere with each other, and the interference between cognitive users is represented by a thousand disturbance matrix. Due to the different communication environments or technologies adopted by each cognitive user, the benefits obtained by different cognitive users on the same effective idle frequency band may also be different. Therefore, the benefits obtained by cognitive users are represented by a benefit matrix

Use $L = \{l_{n,m} | l_{n,m} \in \{0, 1\}\}_{N \times M}$, where the total number of free spectrum is denoted as M, the number of users in cognitive radio system is denoted as N, then $l_{n,m} = 1$represents that the free spectrum resource is available; $l_{n,m} = 0$represents that there are no free users in the authorized users.

$C = \{c_{n,k,m} | c_{n,k,m} \in \{0, 1\}\}_{N \times K \times M}$represents the set of interference matrix. As both user n and user k occupy the spectrum m, the interference will exist.

$B = \{b_{n,m}\}_{N \times M}$represents the benefit matrix, then, $b_{n,m}$is expressed when user n occupies the spectrum m. Thus, $B = \{l_{n,m} \cdot b_{n,m}\}_{N \times M}$denotes the effect function of effective spectrum.

$A = \{a_{n,m} | a_{n,m} \in \{0, 1\}\}_{N \times M}$represents the matrix of allocated spectrums without interference. For instance, $a_{n,m}$=1 denotes that spectrum m is allocated to user n.

If the target is under interference constraints and obtains the maximum number of spectrum allocation, that is, a radio system with open spectrum access, where a mathematical formula can be given as

$$\max \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} a_{i,j} \tag{2}$$

where $a_{\mathrm{i,j}}$ is denoted as the matric entry showing that the conditions can be fulfilled and the spectrums are allocated.

When using coloring algorithms to allocate spectrum resources, there are four specific steps. Firstly, according to the allocation rules of this algorithm, calculate the label and corresponding color of each node, that is, calculate the label. Secondly, select the node

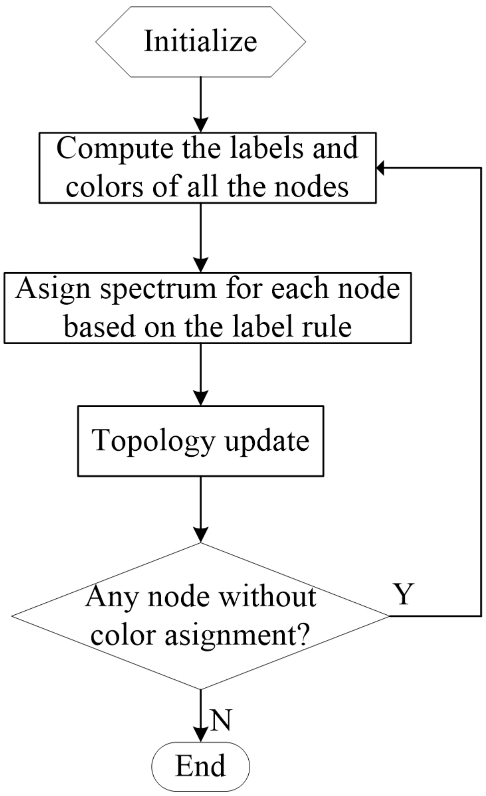

Figure 1: coloring algorithm of color sensitive graph theory

with the largest label and assign the corresponding color to it, i.e., the label. Thirdly, update various information in the entire radio system, namely topology updates. Fourthly, check whether the color allocation in the radio system is complete, that is, whether graph G is empty. If graph G is empty, then the allocation is completed and the first step needs to be returned for another spectrum allocation. The entire allocation flowchart of the color sensitive graph theory coloring algorithm is shown in the figure 1

The economic benefits of authorized users renting their idle spectrum to cognitive users are based on the premise that authorized users have lost communication service quality QoS, which is the cost consumption brought by authorized users renting idle spectrum. We evaluate the system in terms of the total economic benefits E_i and cost consumption $F_i$by establishing communication links between authorized users and cognitive users. Hence, they can be expressed as [6]

$$E_i = a_1 D_i \tag{3}$$

$$F_i\left(c_i\right) = a_2 D_i \left(C_i^{req} - v_i^q \frac{W_i - c_i}{D_i}\right) \tag{4}$$

In the formula, C_i^{req} is the communication bandwidth requirement of authorized users, W_i is the total spectrum resources for authorized user i, both a_1 and a_2 are constant, representing the weight of the cost against benefits of authorized users. The number of links established between authorized users and cognitive users is D_i, v_i^q is the transmission efficiency of authorized user. As the authorized users rent idle spectrum, the net economic benefit can be expressed as follow

$$Q_i\left(q\right) = c_i q_i + E_i - F_i\left(c_i\right) \tag{5}$$

$$q_i^{t+1} = q_i^t + \alpha \frac{\partial \left(\sum_{i=1}^{N} Q_i^t\left(q\right)\right)}{\partial q_i^t} \tag{6}$$

3 EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Experimental design

As shown in figure 2, we give the flowchart of spectrum allocation algorithm.

- Firstly, to establish an acyclic directed graph, the number of available spectrum resources on a node is defined as "frequency band degrees", and the number of node connections is defined as "connection degrees". Therefore, the spectrum degrees and connection degrees of different nodes may be different. The principle for establishing an acyclic directed graph is that the direction of the edges is that nodes with high-frequency degrees point towards nodes with low-frequency degrees. If the spectral degree is the same, then the edge points from the node with high connection degree to the node with low connection degree. If the connection degree is also the same, then the edge will point from the node with high random number to the node with low random number. So this will generate a non cyclic directed graph. If the node has no edges, it is called a sink node. If the node has no edges, it is called a source node. In a non cyclic directed graph, there will be one or more sink nodes and source nodes.
- Secondly, it is to allocate spectrum to nodes. In order to ensure fairness in spectrum allocation for nodes, the least available frequency bands in the list are allocated to the sink node on all adjacent nodes of the sink node. Each node can only use one segment of spectrum resources each time it is allocated. After the sink node is allocated, it will exit spectrum allocation and issue a set color flag to adjacent nodes. If a non sink node receives the set color flag from all adjacent nodes, that is, the source node receives it, then the node will have no edges and become a new sink node. Afterwards, it will continue to cyclically allocate spectrum resources to sink nodes until there are no sink nodes in the acyclic directed graph.
- Finally, there is a detection issue, which involves checking the availability of spectrum resources for all nodes in the directed graph. If in the wireless system, if the sink node in the non cyclic directed graph is no longer present, but there are still other nodes with available spectrum resources, then the node can be combined with available spectrum resources and a new non cyclic directed graph can be created to allocate spectrum resources, Until all nodes in the radio system have no available spectrum resources. If all nodes in the radio system have no available spectrum resources, then the spectrum allocation of the radio system has been completed.

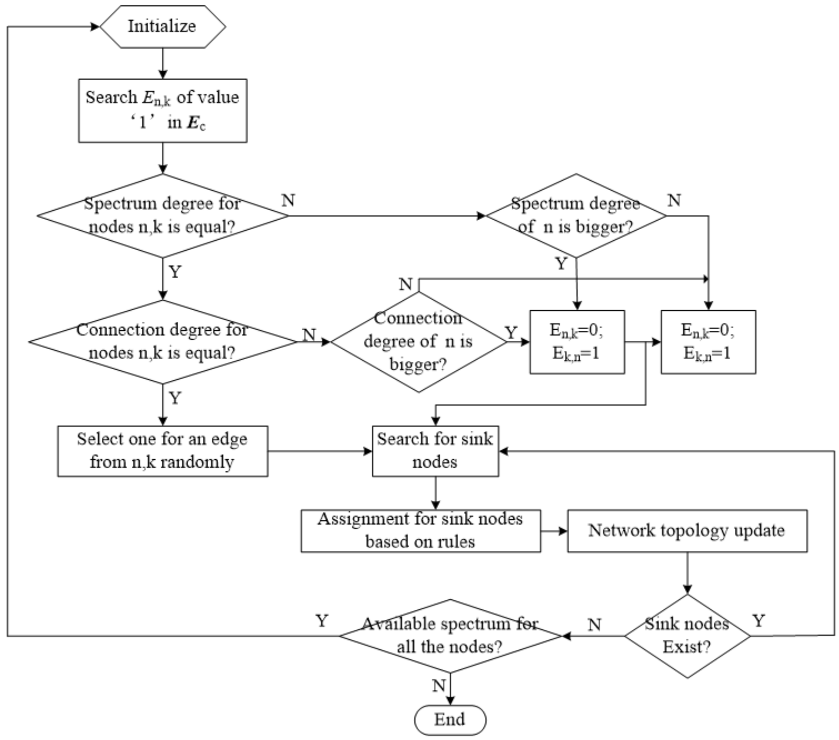

Figure 2: Spectrum allocation algorithm

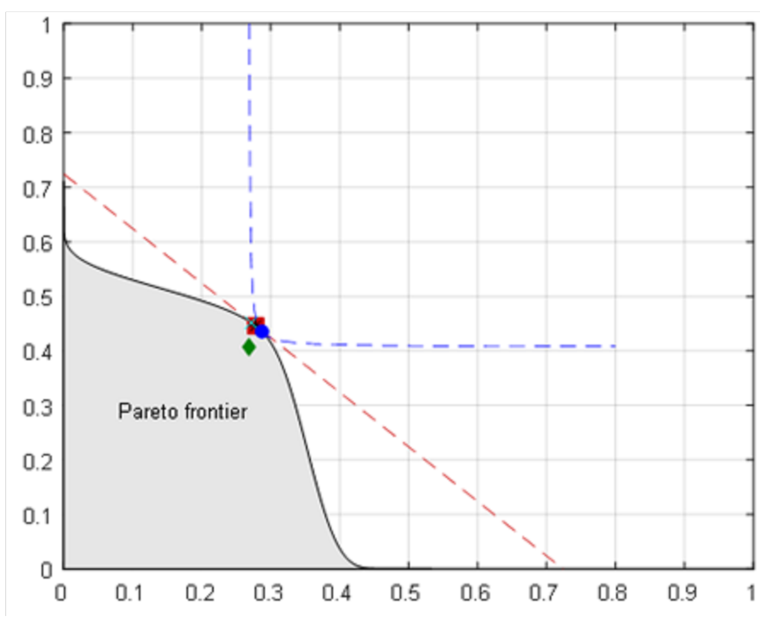

Figure 3: Utility Plan of interference channel game

3.2 Experimental results

In the experiment of CR system, we allocate two authorized users with idle spectrum. The communication bandwidth of authorized users is 2*MHz*, and the error rate of cognitive users reaches 10^{-4}. The replaceable factor of the spectrum is 0.4, and the weights of the cost function against benefits are a_1=a_2=1.5. The signal-to-noise ratio (SNR) is 9dB. The initial price of authorized users is 0 in the iterative algorithm for allocating spectrum prices.

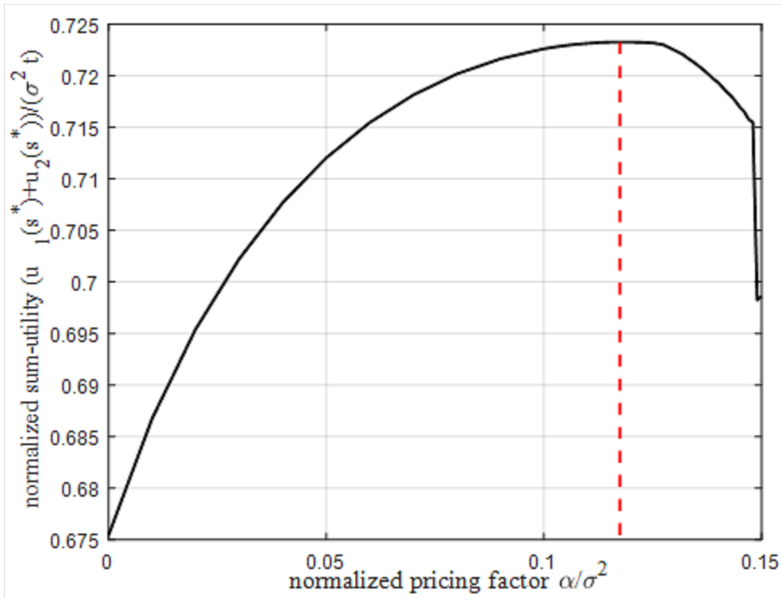

Figure 4: Continuous dynamical game diagram with pricing

As shown in figure 3, the red, green, and blue dots in the figure represent social welfare, *Nash* equilibrium pricing, and *Nash* equilibrium bargaining solutions, all of which have the best advantages near the *Pareto* boundary. Since the calculation method of *Parento* frontier (PF)is by numerical search based on the best response (BR) two-dimensional set, we discretize it on a finite number for convenience.

A continuous dynamic game diagram with pricing is shown in figure 4, with standardized utility on the vertical axis and standardized price factors on the horizontal axis. As shown in the figure, when the standardized price factor is about 0.12 and the maximum utility is about 0.723, and when the standardized price factor is between 0 and 0.12, the curve gradually increases but the slope gradually decreases. When it exceeds about 0.148, the utility will suddenly decrease. The peak point is the optimal pricing factor that maximizes the social efficiency of *Nash* equilibrium.

4 CONCLUSIONS

This paper investigates game based spectrum allocation in cognitive radio system. To analyze the allocation of free spectrum for authorized users, graph coloring is exploited in cognitive radio communication. Finally, the utility plan of interference channel game is plotted, and the social efficiency of interference channel game is simulated and analyzed.

In this paper, each user can only select one channel. However, when the network load is light or the user's traffic demand is high, it may be necessary to allocate multiple channels to a user. So, in future, further research is needed on the situation where a user occupies multiple channels.

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