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DYNAMIC SPECTRUM ALLOCATION ALGORITHM BASED ON NETWORK CONGESTION

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Abstract. *By the research of the present situation of the dynamic spectrum allocation based on graph theory, a dynamic spectrum allocation algorithm based on network congestion is proposed. To take the advantages of classical algorithm color-sensitive graph coloring (CSGC), unoriented network topology graph with minimum interference is constructed. Considering channel congestion, we design a labeling system based on minimum network congestion degree and the color model based on the maximum network gains to allocate the optimal channel for current cognitive users. Simulation results illustrate that the network performance of our algorithm is superior to the traditional CSGC algorithm under rule of collaborative max sum bandwidth (CMSB) and collaborative max proportional fairness (CMPF). The proposed algorithm can ensure smooth communication and maximize revenues of the network.*

Keywords: Network congestion, Network gains, Interference, Dynamic spectrum allocation

1. **Introduction.** Cognitive wireless network is recognized as one of the core architectures to solve the contradiction of spectrum resources supply and demand, whose efficient dynamic spectrum management (DSM) scheme can reduce the pressure on demand, help to solve the problem of low utilization rate of spectrum, and ease the current contradiction between supply and demand fundamentally [1]. Dynamic spectrum allocation will be built into a real-time updated graph, which has become the research hot spot. It is also a useful tool for the optimal spectrum allocation, and experts and scholars at home and abroad have carried out extensive research. The authors of [2-6] improve the traditional CSGC algorithm, respectively from the angle of algorithm complexity, user's requirement and fairness. Although these results are able to enhance the efficiency of spectrum allocation, network congestion degree and the network gains are not ideal. The author in [7] puts forward the dynamic sub-channel allocation algorithm based on graph theory. It divides total channel into a series of continuous sub-channels, using the theory of graph coloring for the spectrum allocation of cognitive users. Although it can effectively solve the problem of the down link interference, the network gains are unsatisfactory.

The above algorithm only focuses on the study of local optimization, but not fully considers the network gains, congestion degrees of communication network and comprehensive performance of the system [8]. To solve this problem, we propose a dynamic spectrum allocation algorithm based on network congestion. This algorithm retains the advantages of CSGC, builds with minimum interference of unoriented network topology for allocating optimal channel to cognitive user and optimizes total revenues of the network.

The organization of the paper is as follows. Section 2 describes the system model. Section 3 introduces network congestion degree and designs utility function and spectrum allocation algorithm. Simulation results and discussion are presented in Section 4, and finally Section 5 concludes the paper.

2. **System Model.** To simplify the model, we define interference radius between cognitive users or between cognitive users and primary users, and select nodes outside interference radius to construct a wireless network (cognitive unoriented graph). Figure 1 demonstrates a simple graph coloring model of cognitive wireless network. Assuming that there exits A, B, C three channels in the area, ①②③④⑤ represent cognitive users. If the two nodes are connected, they cannot share channels at the current area. The idle spectrum is divided into a series of equal bandwidths and mutual orthogonal channels. If two users within its interference distance use the same channel at the same time, they will interfere with each other. Graph coloring model can be abstractly represented by interference matrix, available spectrum matrix, revenue matrix and allocation matrix [9].

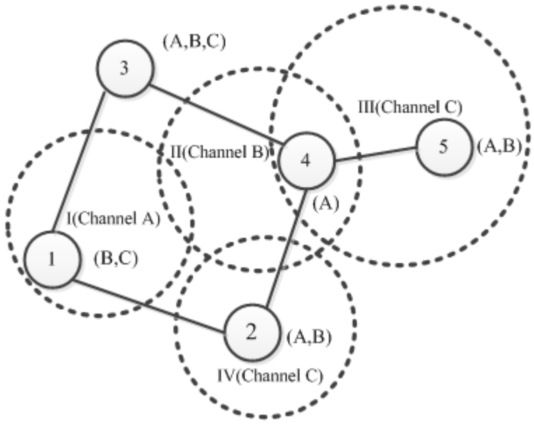

FIGURE 1. Graph coloring model of cognitive radio networks

(1) N is the number of cognitive users.
(2) M is the number of channels.
(3) $B = \{b_{n,m}\}_{N\times M}$ is on behalf of revenue matrix. $b_{n,m}$ is the maximum throughput if user n can transmit data in the channel m.
(4) $L = \{l_{n,m}\,|l_{n,m} \in \{0,1\}\}_{N\times M}$ is available spectrum matrix, which is a binary matrix. $l_{n,m} = 1$ only if channel m is available at user n. In general, $l_{n,m} = 0$ when channel m is occupied by a primary user who conflicts with user n, so that the transmissions of user n on this channel will interfere with the primary's activity if they use channel m concurrently.
(5) $C = \{\mathrm{c}_{n,k,m}|c_{n,k,m} \in \{0,1\}\}_{N\times N\times M}$ is interference matrix. If $c_{n,k,m} = 1$, users n and k would interfere with each other if they use the same channel m. The interfere constraint depends on the signal strength of transmission and the distance between users.
(6) $A = \{a_{n,m}|a_{n,m} \in \{0,1\}\}_{N\times M}$ is allocation matrix, where $a_{n,m} = 1$ denotes that channel m is assigned to user n; 0, otherwise. A satisfies all the constraints defined by C, that is, $a_{n,m} + a_{k,m} \leq 1$; if $C_{n,k,m} = 1$, $\forall n$, $k < N$, $m < M$.

3. **Spectrum Allocation Based on the Network Congestion.**

3.1. **Network congestion degree $\boldsymbol{\beta_m}$.** Network congestion is closely linked to network throughput, which directly affects the communication smooth characteristic and stability of the system. In CSGC algorithm, utility function cannot satisfy the requirement of network congestion. For allocating spectrum to cognitive users optimally and maximizing channel utilization, a new utility function based on the network congestion is defined. Assuming that data transfer rate of cognitive user n is ω_n, after spectrum allocation, congestion degree of channel m can be formulated as:

$$U_m = \begin{cases} 1 & \beta_m > 1 \\ 1 - \beta_m & 0 \leq \beta_m \leq 1 \end{cases} \tag{1}$$

$\beta_m = \omega_n / \sigma_n \cdot M \cdot b$ is congestion degree of channel m. $\sigma_n = \sum_{m=1}^{M} a_{n,m} \cdot b_{n,m} \Big/ \sum_{n=1}^{N} \sum_{m=1}^{M} a_{n,m} \cdot b_{n,m}$ represents resource allocation coefficient, which is the ratio of cognitive user n and the total allocated channel resources. If $\omega_n > \sigma_n \cdot M \cdot b$, the channel throughput reaches saturation. In other words, other users cannot access the channel.

In the study of the current spectrum allocation, most did not consider the priority of the cognitive users, so it is easy to cause the problem that spectrum allocation cannot achieve the optimal effect. The priority of the cognitive users is strongly linked to the needs of users [10]. According to the requirements of the cognitive users, this paper builds cognitive user priority function, and makes the system secondarily allocate spectrum in accordance with the users' priority. Assuming that request time of cognition user n is r_n, and that assigned time is t_n, we can get the priority of the cognitive user n, $\varphi_n = t_n/r_n$. The greater the ratio of request time of cognitive users and assigned time of the channel are, the greater the demand of cognitive users for spectrum is. It makes priority of cognitive users more greater.

3.2. **Utility function design.** According to the above definition, in a certain range of time domain, total congestion degree is denoted as

$$U_1 = \sum_{m=1}^{M} U_{1,m} \tag{2}$$

The utility function of the system can be expressed as

$$\min U_1 = \min \sum_{m=1}^{M} U_{1,m} \tag{3}$$

This utility function only considers the current network congestion degree, but in real communication situation, the needs of users' communication may not be satisfied within a time period T. In other words, before completing their communication services, they must be in the shortest time to switch to the rest of the available spectrum. To prevent this kind of situation, we introduce ON-OFF model to predict the future availability of channel. ON indicates that current channel is occupied by primary users, namely the channel being busy. OFF denotes that the channel is idle, and that cognitive users can use this channel. The duration of the two states is depicted by random variables Y_m, and obeys exponential distribution with parameter $\lambda_{Y_m}(t)$.

For a channel, there are two states, ON and OFF depicted by 0 and 1. So continuous state of the channel is a binary time series, which has Markov properties. $p^m_{d_1 d_2}(t)$ is the probability of state of channel m changing from d_1 to d_2. States of the channel are $(0,0)$, $(0,1)$, $(1,0)$, $(1,1)$, respectively. According to the theory of Markov chain and update, we can get equations below.

$$p^m_{00}(t) = \frac{\lambda_{Y_m}}{\lambda_{Y_m} + \lambda_{X_m}} + \frac{\lambda_{X_m}}{\lambda_{Y_m} + \lambda_{X_m}} e^{-(\lambda_{Y_m} + \lambda_{X_m})t} \tag{4}$$

$$p^m_{11}(t) = \frac{\lambda_{X_m}}{\lambda_{Y_m} + \lambda_{X_m}} + \frac{\lambda_{Y_m}}{\lambda_{Y_m} + \lambda_{X_m}} e^{-(\lambda_{Y_m} + \lambda_{X_m})t} \tag{5}$$

$$p^m_{10}(t) = 1 - p^m_{11}(t), \quad p^m_{01}(t) = 1 - p^m_{00}(t) \tag{6}$$

Based on Equations (4)-(6), utilization rate of channel m is as follows

$$u^m = \frac{\lambda_{X_m}}{\lambda_{Y_m} + \lambda_{X_m}} = \frac{p_{01}^m(t)}{p_{01}^m(t) + p_{10}^m(t)} \tag{7}$$

Therefore, network benefits of user n in channel m are descripted as:

$$R_{n,m} = u^m \cdot B \cdot \log_2 \left(1 + K\frac{p_{n,m} \cdot g_{n,m}}{N_0}\right) \tag{8}$$

where B is the bandwidth of the subcarrier, N_0 is white bilateral power spectral density of Gaussian noise. $p_{n,m}$ is transmission power of cognitive user n on the channel m, and $g_{n,m}$ is channel gain. K represents the relationship of M-ary quadrature amplitude modulation (M-QAM) and signal-to-noise ratio of Shannon capacity. If it is Rayleigh channel, K can be shown as

$$K = -\frac{1.5}{\ln(5 \cdot BER)} \tag{9}$$

where BER is bit error rate. Taking into consideration channel congestion degree and the income of the user on channel m, we need to not only ensure that the entire network communication is smooth, but satisfy requirement of users' QoS. So the system utility is converted to

$$\max U_2 = \max \sum_{m=1}^{M} R_{n,m}/\sigma_n \cdot M \cdot b \tag{10}$$

Various service qualities of each channel lead to the difference of congestion degree of each channel. In order to more fully use every available channel, coordinate network congestion, and formulate allocation principle, we label each of available channels. According to the utility function, the system selects the best user to access to the current channel. Label mechanism and coloring model are as follows:

$$label_{n,m} = \min U_{1,m} \tag{11}$$

$$color_{n,m} = \arg\max U_{2,m} \tag{12}$$

3.3. **Description of spectrum allocation algorithm.** The proposed algorithm can be divided into two steps. The first step is to allocate spectrum based on maximizing the total bandwidth. The second step is to allocate spectrum based on priority of users for the users whose requirement t_n cannot be satisfied in the first step. In the first phase of the frequency spectrum allocation, the system calculates the congestion degree of all current channels, according to Equation (1). It will label each available channel, and there is a one-to-one correspondence between label and color. The algorithm gives priority to selecting vertex whose congestion degree is low to coloring. Then according to Equation (10), the system allocates the channel to cognitive users that have the greatest networks gains. During each assignment, the channel will be labeled, and there is a one-to-one correspondence between label and cognitive users.

At the start of the iteration, label value of each vertex will be calculated, and it will find the minimum value $\min U_{1,m}$ of vertex and assigns the color. Then the system updates the topological structure, and deletes the edge whose vertex has been assigned the same color. If color list of the vertex is empty, the vertex will be deleted. If the color list of vertex has colors, it will be into the second step. The system calculates the priority of vertexes whose color list is not empty, and according to the order of priority from high to low, allocates spectrum for cognitive users in turn. When color lists of all vertexes are empty, the algorithm ends.

Algorithm 1 Dynamic spectrum allocation algorithm based on network congestion

Require:
N, M;
G(E,L,V);
Ensure:
The spectrum allocation matrix A and the transmit power of cognitive user;
while $t_n \geq \sum_{m=1}^{M} l_{n,m}$ **do**
  $label_{n,m} = \min U_{1,m}$;
  $color_{n,m} = \arg\max U_{2,m}$;
  Node(m*) = min($label_{n,m}$);
  Color(m*) = $\arg\max U_{2,m}$;
  Updating network topology
  Update G(E,L,V);
  Delete Node(m*);
  Delete Color(m*);
end while
while $G = \text{NULL}$ **do**
  Find the largest φ;
  Let $\varphi = \varphi_k$;
  $label_{n,m} = \varphi_k$;
  $color_{n,m} = \arg\max \varphi_k$;
  Node(m*) = min($label_{n,m}$);
  Color(m*) = $\arg\max \varphi_k$;
  Updating network topology
  Update G(E,L,V);
  Delete Node(m*);
  Delete Color(m*);
end while

4. **Simulation Results.** We use Matlab 2012b software platform for experiment. Cognitive users are randomly distributed in the range of 400m by 400m. To verify the validity of the proposed algorithm in this paper, it is compared with algorithm CSGC based on rule of CMSB (CSGC-CMSB) and CSGC based on rule of CMPF (CSGC-CMPF). Transmission power values of cognitive users range from 0.01w to 0.1w. BER of receiver of cognitive user is equal to 10^{-5}, namely $BER = 10^{-5}$. Bandwidth $B = 30$kHz, and the channel gain $g = \omega/d^4$dB ($\omega = 0.097$, d is the distance between two nodes). In order to have objective results, we do experiments for 1000 times, and get average results.

Figure 2 shows that the fairness of system based on CSGC-CMPF, CSGC-CMSB and our algorithm varies with the number of cognitive users, when the channel number is 9. The fairness of system is expressed as:

$$f = \left(\prod_{n=0}^{N-1} \sum_{m=0}^{M-1} a_{n,m} b_{n,m}\right)^{\frac{1}{N}} \tag{13}$$

With the number of cognitive users increased, the fairness of system decreases sharply. The fairness of system based on CSGC-CMPF is the best, but our algorithm is greater than CSGC-CMSB.

Figure 3 demonstrates that communication overhead of time based on CSGC-CMPF, CSGC-CMSB and our algorithm varies with the number of cognitive users, when the channel number is 9. Communication overhead of time of our algorithm is approximated

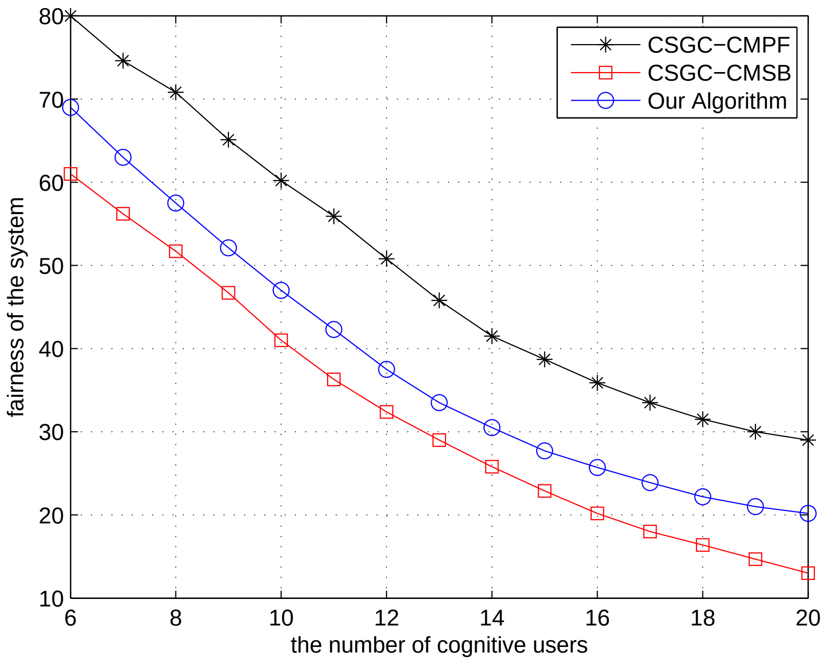

FIGURE 2. Fairness of the system

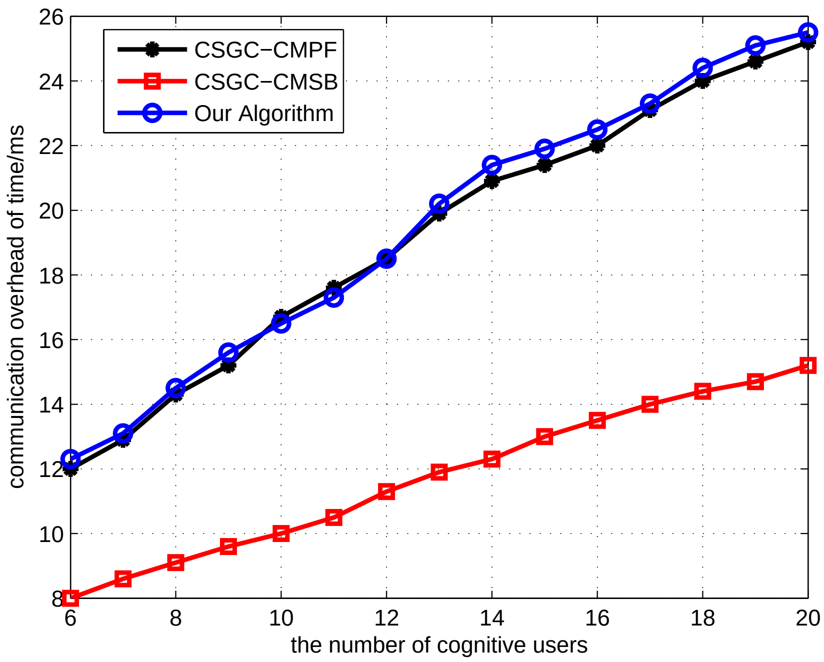

FIGURE 3. Communication overhead of time

by CSGC-CMPF, but exceeds that of CSGC-CMSB, which is caused by our algorithm maximizing system revenue.

Figure 4 shows the curve of total revenue of the system based on CSGC-CMPF, CSGC-CMSB and our algorithm. If the channel number does not change, with cognitive users increased and users' requirement augmenting, total revenue of the system declines visibly. However, total revenue of the system based on our algorithm is significantly higher

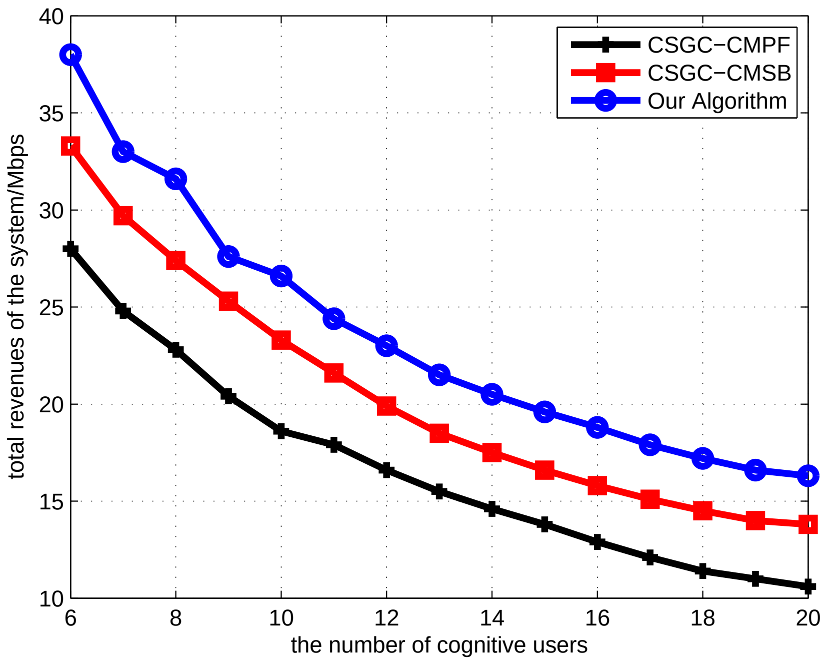

Figure 4. Total revenues of the system

than CSGC-CMPF and CSGC-CMSB. In other words, under the condition of the same bandwidth, our algorithm can support more cognitive users to access to the system.

5. **Conclusions.** Taking channel congestion degree into consideration, a dynamic spectrum allocation algorithm based on network congestion is proposed, which combines the advantages of CSGC algorithm and builds an unoriented network topology with minimum interference. Simulation results show that although communication overhead of time of our algorithm is higher than CSGC-CMSB, fairness of the system is based on our algorithm overtop CSGC-CMSB. Total revenue of the system based on our algorithm is significantly higher than CSGC-CMPF and CSGC-CMSB. To sum up, under the premise of ensuring smooth communication and communication needs of cognitive users, the algorithm of this article can markedly maximize revenues of the system. Further research work is to use smart algorithms to solve this problem quickly and accurately.

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