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Spectrum Optimization in Cognitive Satellite Networks with Graph Coloring Method

Li Wang[1,2] · **Kwok-Yan Lam**[2] · **Jiangxin Zhang**[1,*] · **Feng Li**[1]

Abstract Cognitive satellite networks can enhance spectrum efficiency by enabling satellite networks to dynamically share idle spectrum with terrestrial networks. However, when taking into consideration the inter-cell or internet interferences in various application circumstances, dynamic spectrum optimization in cognitive satellite networks remains challenging due to the diversified QoS demands of secondary terrestrial users. To address this issue, this paper proposes an efficient spectrum allocation algorithm which is based on graph coloring technique and combined with analytic hierarchy process so as to meet the requirements of dynamic spectrum allocation to secondary terrestrial users with diversified QoS demands and yet without causing severe inference to primary satellite users. In this paper, we combine graph coloring algorithm and analytic hierarchy process so as to assign the heterogeneous spectrum bands to secondary users in an orderly manner. The method of graph coloring is applied to control obvious interference caused by the secondary users. We also provide numerical results to evaluate the impacts of different parameter settings on the performances of the proposed solution.

Keywords Cognitive satellite networks · spectrum optimization · graph coloring

1 Introduction

With the rapid growth of satellite communication services, spectrum shortage has become a critical issue especially when the data storm is ongoing for future

[1] College of Information Engineering, Zhejiang University of Technology, Hangzhou, 310023, China.

[2] School of Computer Science and Engineering, Nanyang Technological University, 639798, Singapore.

Corresponding author: Jiangxin Zhang, zjx@zjut.edu.cn

satellite networks [1]-[4]. In some frequency bands, the demand for bandwidth has been increasing rapidly, while many high-quality satellite spectrum is still under utilized. The emergence of cognitive satellite networks is widely accepted to be a solution to alleviate the spectrum shortage problem. The key objective of cognitive radio technique is to enable wireless communication device to find "spectrum holes" and use them efficiently.

In cognitive satellite networks, the task of designing adaptive resource allocation schemes is challenging especially when taking into consideration admission control, Quality of Service (QoS) requirements of satellite users, efficiency of spectrum sensing, resource marketing and interference controlling [5]-[7]. Many mathematical techniques have been applied, including convex optimization, game theory, graph theory and intelligent algorithms [8]-[11]. In this paper, in order to control the interference, we adopt a graph theoretic approach which is a classical optimization method to directly describe and specify the interference conditions between different networks [12][13]. Besides, graph theory has been well investigated for addressing many critical problems in cognitive radio networks. Specifically, [14] presented a channel optimization algorithm on the basis of graph coloring theory, including benefit-based distributed greedy algorithm and fairness-based distributed fairness algorithm. In [15], the authors designed a spectrum optimization method according to the maximum independent set, wherein the idle spectrum can be assigned to multiple users at the same time without obvious interference. Based on this, [16] devised another coloring-based spectrum allocation algorithm, combined with the use of power control technology to enhance spectrum utilization. [17] introduced the improved binary firefly algorithm into the graph coloring model to increase the spectrum efficiency and the fairness of cognitive users. [18] put forward an idea of hierarchical spectrum sharing, which includes three aspects: network classification, Spectrum Classification and user classification.

In this paper, we apply a multi-objective decision method of analytic hierarchy process (AHP) to improve the spectrum allocation obtained by graph coloring, thus providing a reasonable spectrum access strategy to respond to the heterogeneous spectrum and users' demand. The proposed scheme aims at solving the problem that traditional graph coloring algorithms tend to excessively emphasis on distribution while ignoring the spectrum heterogeneity. This improved model takes into account the spectral characteristics, whose intention is to approach to the actual circumstance of the dynamic spectrum allocation in cognitive satellite networks. We adopt the method of graph coloring to ensure no severe interference on primary systems. Combining the advantages of the two optimization methods, our proposal not only enhances the spectrum efficiency for general secondary users, but also meets the requirements of the overall network benefits. Numerical results are supplied to evaluate the performance of our proposal and the effects of various parameters on network capacity.

The main advantage of this hybrid method compared with other traditional solutions such as single graph coloring or convex optimization lies in that we

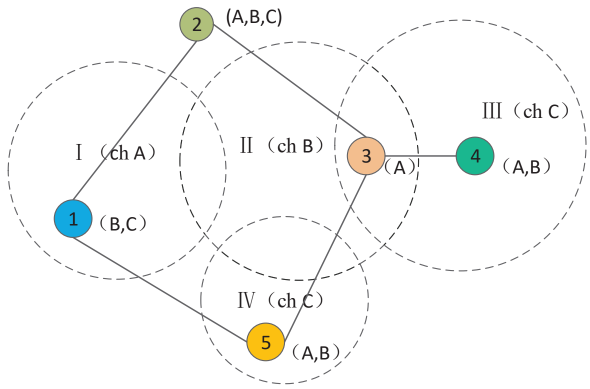

Fig. 1 Graph coloring model

introduce satellite user's demand index to satisfy the personalized requirement, not only avoiding internet interferences or enhancing system capacity.

Furthermore, most of graph theory-based cognitive spectrum optimization is subject to the terrestrial cellular networks. Yet, in this paper, we take into account the effects of satellite communications, such as oblique projection and multibeam interference. Besides, the main advantage of using AHP method in satellite networks is to distinguish various satellite users' demands from the perspectives of service types.

The rest of this paper is organized as follows. We give the system model of network interference based on graph theory in Section II. Then, the method of AHP in Section III to address the diversity of users' demand. In Section IV, numerical results show the performance of our proposed solution in various perspectives. We summarize this paper in Section V.

2 Spectrum Optimization Based on Graph Coloring Model

In the interference model of spectrum allocation by using graph theory, the user distribution topology is first formulated as an un-directional graph, as shown in Fig. 1, in which vertexes represent cognitive terrestrial users, and edges represent interference. Two cognitive terrestrial users will conflict when using the same channel at the same time. Each vertex in the graph (cognitive terrestrial user) has its own set of available spectrum, which indicates that the cognitive user can use all the available spectrum resources in the current area. Because of the dispersed locations of different cognitive users, the available spectrum set is random.

Fig. 1 presents a graph coloring model in cognitive satellite networks. Five vertices in the graph represent five different secondary users, each of which has the opportunity to access three channels of A, B, C. I-IV represent four

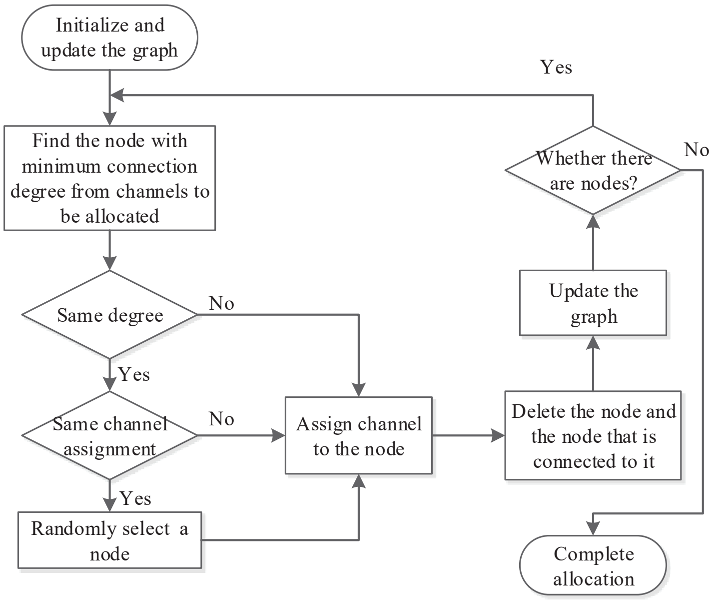

Fig. 2 Diagram of graph coloring method

primary users, using the channel A, B, C, C respectively. According to the regulation, when a primary user uses one band, adjacent cognitive users can not interfere with it. Therefore, the secondary users in the primary user's interference area can only use the same spectrum when other primary users do not use it.

The dotted line in the graph represents the interference range of primary users. As transmit powers of different primary users are different, the radius of the circles are diverse.

In practice, the channel state is real-time, the power of primary users and secondary user's location and other factors are also changing. Therefore, the network structure is not fixed, but in order to facilitate the research, it is assumed that the network structure is invariant in a detection time.

The general objective function of the graph coloring model can be expressed as

$$U_{su} = \sum_{n=1}^{N} \sum_{m=1}^{M} a_{n,m} \cdot b_{n,m} \tag{1}$$

Define $A = \{a_{n,m} | a_{n,m} \in \{0, 1\}\}_{N \times M}$ as a $N \times M$ matrix, which represents a feasible spectrum allocation scheme. If $a_{n,m} = 1$, it means the frequency band m is allocated to the cognitive user. Otherwise, $a_{n,m} = 0$ means the channel is idle. No interference distribution matrix must meet no interference constraints: $a_{n,m} + a_{k,m} \leq 1$, where $c_{n,k,m} = 1$, $\forall n, k < N, m < M$. $B = \{b_{n,m}\}_{N \times M}$ is a $N \times M$ matrix, on behalf of the secondary user n's benefits by occupying the spectrum m (such as, throughput, bandwidth, transmission rate, etc.). $b_{n,m} = \alpha$ indicates that secondary user n uses frequency band m to get the benefit of α. The basic coloring flow chart of the interference pattern is only considered as shown in Fig. 2.

3 Spectrum selection strategy based on AHP

AHP is an optimization method of multi-objective decision, which was proposed by Saaty [19]. This method decomposes the elements involved in the final decision into target, criterion programs, etc. Qualitative and quantitative analysis are carried out during the course. The corresponding weight of each program relative to each criterion is gained by experience or other methods. Finally, the optimal scheme is selected from all the programs to provide a simple decision method for the complex decision problems with multiple criteria, multiple targets or non structural characteristics.

In cognitive networks, owning to the spectrum heterogeneity, the characteristics of spectrum resources are diverse, such as the time of primary users to use the spectrum, delay and bandwidth, etc. Secondary users in wireless networks do not have their own licensed spectrum to be used, just opportunistically access to other licensed "spectrum holes". These licensed spectrum is various due to geographical location and management strategy, thus there is a huge difference in spectrum characteristics. In the use List-Coloring algorithm, randomly select a channel and assign it to secondary users according to the steps of the algorithm. To improve the overall performances of cognitive satellite networks, the proposed algorithm can utilize a better decision method to choose an optimal spectrum for the next step. At present, most of the spectrum selections are based on single attribute decision making [20]. However, it is known that multiple factors need to be considered when choosing the target spectrum. Therefore, this paper proposes a multi-attribute decision making mechanism.

3.1 Application of AHP in spectrum decision

AHP has been applied recently in heterogeneous wireless networks, mainly for the evaluation of network characteristics and the selection of the best network[21-23]. Using AHP algorithm to analyze some sensitive characteristics, such as bandwidth, jitter, delay, price and other characteristics, then carry out a comprehensive assessment to identify the best network.

When using AHP to make multi-objective decision, there are four main steps.

1) Establish hierarchical structure

According to the relationship between various elements in decision-making system, they are decomposed into different parts, each part is called an element, then group the elements into complementary related hierarchies based

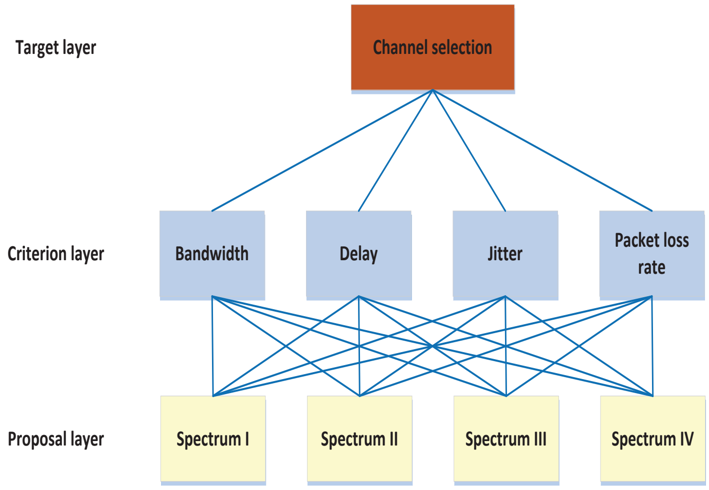

Fig. 3 Hierarchical graph of spectrum optimization decision on basis of AHP algorithm

on attributes. The upper layer has a dominant effect on the part or all of the elements of next layer, so that the dominance relation is formed, which can be divided into the following three levels.

a. Target level (highest level): Intended target of the problem;

b. Standard layer (middle layer): Guidelines for the implementation;

c. Decision level (lowest layer): Measures to achieve the ultimate goal;

Amidst selecting spectrum bands, secondary users tend to choose the spectrum with more bandwidth, lower delay, lower jitter as well as ideal packet loss rate. In this case, we choose the above key parameters including spectrum bandwidth, transmission delay, packet loss rate and jitter as the criteria for spectrum selection. The model for this structure is as shown in Fig. 3. Besides, the QoS preferences of the secondary users should also be taken into consideration in the selection process. As the number of considering factors increases, it will be very difficult for the secondary users to rationally choose based on qualitative analyses. In this circumstance, we adopt the AHP method to analyze the problem in detail by decomposing it into three levels as shown in Fig. 3.

2) Construct comparison matrix

After establishing the hierarchical structure, the relationship between the elements of both upper and lower levels is determined. Compare various elements of the same level on the importance of one of the criteria on upper level and quantify it, thus construct the comparison matrix.

To compare the impact of factors $C_1, C_2, \cdots, C_n$ on its upper layer's factors O, take C_i and C_j at same time and compare their importance to the target

Table 1 1-9 scale method

Importance scale	Implication
1	Indicate the two factors are of equal importance
3	Indicate the one factors is slightly more important than another
5	Indicate the one factors is significantly more important than another
7	Indicate the one factors is strongly more important than another
9	Indicate the one factors is extremely more important than another
2,4,6,8	The intermediate value of the two adjacent judgments
Reciprocal	Comparing factors i and j to get a_{ii}, j and l to get $a_{ij} = 1/a_{ii}$

factor O, calculate the corresponding weights $W_1, W_2, \cdots, W_n$. The weights are assigned by $1-9$ scale methods, defined as a_{ij} whose meanings have been given in Table 1. All comparison results are expressed in comparison matrix A which can be denoted as

$$A = (a_{ij})_{n\times n}. \tag{2}$$

The comparison matrix has the following properties

$$\begin{cases} a_{ij} > 0 \\ a_{ji} = 1/a_{ij} \\ a_{ii} = 1 \end{cases} \tag{3}$$

When all the elements of the comparison matrix are satisfied with the formula above, the matrix is called consistency matrix.

The comparison matrix of the target layer A to the standard level layer B_1, B_2, B_3, B_4 is

$$A = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix} = \begin{pmatrix} 1 & 3 & 5 & 3 \\ 1/3 & 1 & 2 & 1 \\ 1/5 & 1/2 & 1 & 1/2 \\ 1/3 & 1 & 2 & 1 \end{pmatrix} \tag{4}$$

When wireless terminals dynamically monitor available frequency bands, they can obtain the corresponding weights according to current network status, which depends on four main network attributes namely bandwidth, delay, jitter, and packet loss rate. Then, assign values to the elements in comparison matrix. Finally, obtain the comparison matrix of the standard layer B_1, B_2, B_3, B_4 with respect to $P_1, P_2, \cdots, P_n$. A comparison matrix for the effect of B_1 can be given as

$$A = \begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \cdots & \cdots & b_{ij} & \cdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{pmatrix} \tag{5}$$

3) Single hierarchical arrangement and consistency check

Single hierarchical arrangement, which denotes the same level of the corresponding factors with relative importance, can be achieved by normalizing

Table 2 Random index RI

Matrix order	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.40

the eigenvector (weighted vector) W. Thus, the key point is to calculate the weight vector.

The calculation of the weight vector can be performed by characteristic root method, method of summation, power method and so on. In this paper, we use the method of summation.

The details of the summation method can be listed as:

1. Normalize the column vectors of matrix $A : \tilde{W}_{ij} = a_{ij} / \sum\limits_{i=1}^{n} a_{ij}$.
2. Make summation for each row of $A : \tilde{W}_{ij} = a_i / \sum\limits_{j=1}^{n} \tilde{W}_{i,j}$.
3. Normalize above matrix vector $W = \tilde{W}_i / \tilde{W}_{ij} = a_i / \sum\limits_{i=1}^{n} \tilde{W}_i$, then obtain $W = (W_1, W_2, \cdots, W_n)^T$ as weight vector.
4. Calculate AW.
5. Set $\lambda_{max} = \frac{1}{n} \sum\limits_{i=1}^{n} \frac{(AW)_i}{W_i}$, which denotes the approximate value of the largest eigenvalue.

According to the above method, taking matrix A, we obtain the weight vector $W = (0.488, 0.190, 0.089, 0.233)^T$. Its corresponding maximum eigenvalue is $\lambda_{max} = 4.025$. Similarly, the largest eigenvalue of B_1, B_2, B_3, B_4 and its weight vector can be calculated.

The importance ranking of a correct judgment matrix is logical. For example, if A is more important than B, B is more important than C, logically speaking, A should be more important than C. Otherwise, the judgment matrix violates the consistency criterion and is logically unreasonable. Therefore, in practice, the judgment matrix should satisfy the general consistency and the a consistency test is needed. Only through, the test considers the judgment matrix to be logically reasonable and the results can be analyzed.

The procedure for the consistency check is as follows:

Step 1: Calculate the consistency index (CI).

$$CI = \frac{\lambda_{max} - n}{n - 1}. \tag{6}$$

Step 2: Form a table to identify the random index (RI), as shown in Table 2. According to the order of judgment matrix, we can obtain the average the index.

Step 3: Calculate the consistency ratio as follows and make judgments.

$$C_r = \frac{CI}{RI}. \tag{7}$$

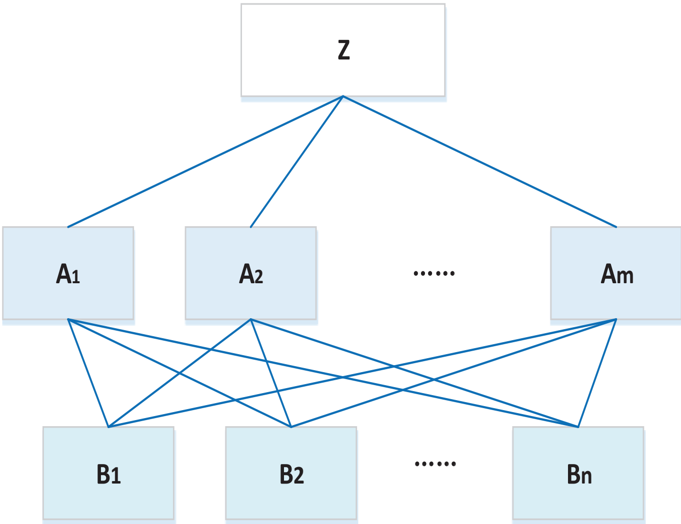

Fig. 4 Hierarchical structure model

When $C_r < 0.1$, the consistency is proper. Besides, when $C_r > 0.1$, we take into account that the judgment matrix cannot satisfy the consistency requirement, the judgment matrix needs to be revised again.

To assess the consistency, we set matrix A as an example and use (3) to calculate the consistency index $CI = 0.0083$, and then obtain $RI = 0.9$ via Table 1. Finally, according to $C_r = 0.0092 < 0.1$, it can be concluded that A is verified to pass consistency check.

4) Total arrangement of hierarchy and consistency check

Total arrangement of hierarchy refers to the calculation of the relative importance of each layer' weight of all factors to the highest level (total goal). It can obtain the bottom of each program on the target's weight so as to select the program. Wherein, the process also needs consistency check.

As shown in Fig. 4, all the factors of layer $A_1, A_2, \cdots, A_m$ on target Z are $a_1, a_2, \cdots, a_m$. The single hierarchical arrangement of n factors of the layer on the upper level A's factor A_j is $b_{1j}, b_{2j}, \cdots, b_{nj} (j = 1, 2, \cdots, m)$. Besides, ith factor of B layer on the total target weight is $\sum_{j=1}^{m} a_j b_{ij}$. The total arrangement of B layer is shown in Table 3.

Table 3 Hierarchical aggregate sort table of B layer

A/B	$A_1, A_2, \cdots, A_m$ $a_1, a_2, \cdots, a_m$	Total arrangement of hierarchy of B layer
B_1	b_{11} b_{12} b_{1m}	$\sum_{j=1}^{m} a_j b_{1j} = b_1$
B_2	b_{21} b_{22} b_{2m}	$\sum_{j=1}^{m} a_j b_{2j} = b_2$
.	. . .	…
.	. . .	…
.	. . .	…
B_n	b_{n1} b_{n2} b_{nm}	$\sum_{j=1}^{m} a_j b_{nj} = b_n$

Set the single hierarchical arrangement consistency index of n factors of B layer $B_1, B_2, \cdots, B_n$ on the upper level(A layer) factor $A_j (j = 1, 2, \cdots, m)$ as CI_j. Since random index is RI_j, so the consistency ratio of the total arrangement is as follows

$$CR = \frac{\sum_{j=1}^{m} a_j CI_j}{\sum_{j=1}^{m} a_j RI_j}. \tag{8}$$

4 Improved spectrum allocation algorithm model

We now identify the optimal spectrum by using the List-Coloring algorithm. Through the proposed method, we are capable of making full use of the available spectrum and improve the overall capacity of cognitive satellite networks.

The diagrams of the improved spectrum allocation algorithm combining graph coloring and analytic hierarchy process are shown in Fig. 5.

The spectrum optimization algorithm implemented in Fig. 5 can be depicted as below: Firstly initializing the cognitive systems and updating the node information, then based on the measured values, including bandwidth, delay, etc, the hierarchical structure can be established by using analytic hierarchy process. Then, ascertain the corresponding comparison matrix, and obtain the sort of spectrum efficiency. At last, the selected optimal spectrum is allocated based on the coloring algorithm. This will not only improve the transmission capacity, but also satisfy the cognitive networks' requirements on capacity, thus forming a complete mechanism from spectrum decision to distribution.

5 Numerical Results

In simulated tests, we assume there exist six licensed users in 10×10km region, and the number of channels is 10. In this circumstance, different parameter settings of the network utilities are analyzed and compared. Use U_{su} to detect

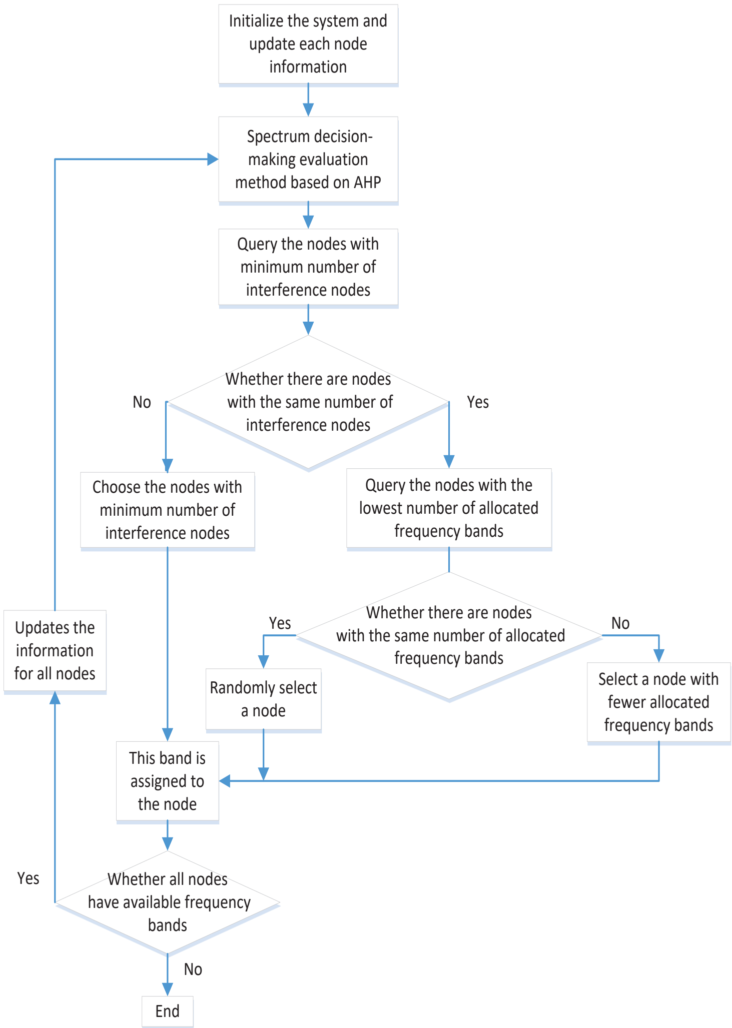

Fig. 5 Diagram of greedy-based spectrum allocation algorithm combined graph theory and AHP

network efficiency while the variance is applied to denote the user fairness. In the following tests, network topology is formed randomly and various parameters are shown in Table 4.

Table 4 Parameter setting of the proposed method

Parameter	Values
Number of secondary users N	Random setting between $[40, 120]$
Number of bands M	10
Available spectral matrix L	0-1 random matrix
Interference matrix C	0-1 random symmetric matrix
Benefit matrix B	Random numbers in $[0, 1]$
Simulation cycle times	100

Four attributes of spectrum matrix, including bandwidth, delay, jitter, packet loss rate, are as shown in Table 5.

Table 5 Comparison of spectrum attributes

	Bandwidth	Delay	Jitter	Packet loss rate
Bandwidth	1	3	5	2
Delay	1/3	1	2	1
Jitter	1/5	1/2	1	1/3
Packet loss rate	1/2	1	3	1

Properly set parameter values including bandwidth, delay, jitter and packet loss rate of each available frequency band in current cognitive satellite networks (the parameters satisfy the data transmission standard raised by ITU-T [24]). According to above parameters, use matlab platform to test the spectrum allocation algorithm, and the numerical results are averaged by 100 cycles.

In order to make the simulation results more comparable and convincing, we introduce the algorithm in [25] for comparative analysis. Authors in [26] considered the factors of node degree (ie, the number of neighbors of secondary users) and channel weight (ie $b_{n,m}$), and proposed a weighted distributed greedy algorithm (WDGA) based on list coloring.

From Fig. 6 and Fig. 7, we can observe that compared with the original distributed greedy algorithm (DGA), both the WDGA and the greedy algorithm combined with AHP method (AHP-DGA) proposed in this paper can improve the network efficiency. The network utility in Fig. 6 and Fig. 8 means the overall channels allocated to the secondary users. In this case, more channels equal to higher network utility as the users can enhance their transmission capacities by broad bands. We can obtain from Fig. 6 that improved graph-based method receives high network utility than traditional method since users' demands have been taken into account which enables a full usage of the channels.

Besides, we can observe from Fig. 6 and Fig. 8 that the utility is lowered when the algorithm is performed in fairness mode. Also, from Fig. 7 and Fig. 9, we can achieve more fairness between the secondary users which means the channel number obtained by different users gets closer. Thus, the proposed method allocates spectrum to secondary users more balanced. For some specific circumstances, it will be more proper to apply fairness mode to manage the resource allocation. It is should be noted that the proposed method in this paper can realize relatively ideal fairness. Comparing the above simulation graphs, we can find that the network efficiency obtained by the greedy

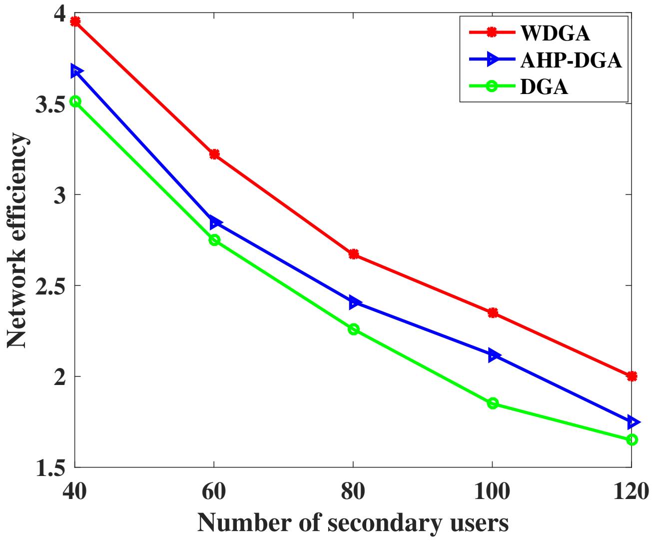

Fig. 6 Network utility of the three algorithms with different numbers of cognitive users in greed mode

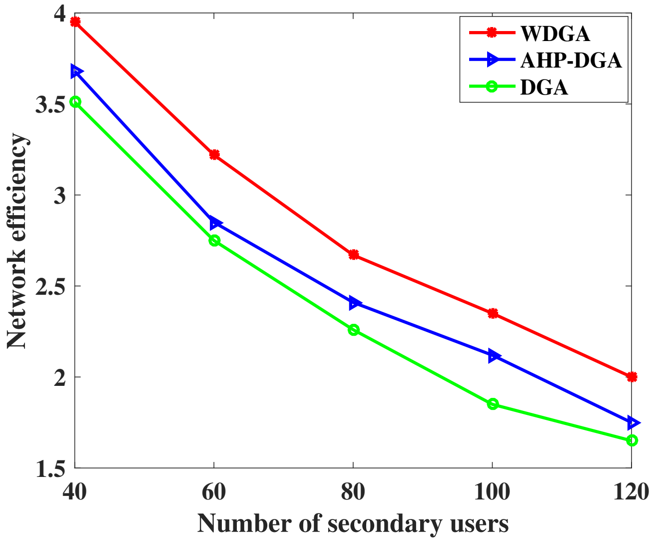

Fig. 7 Fairness variance of the three algorithms with different numbers of cognitive users in greed mode

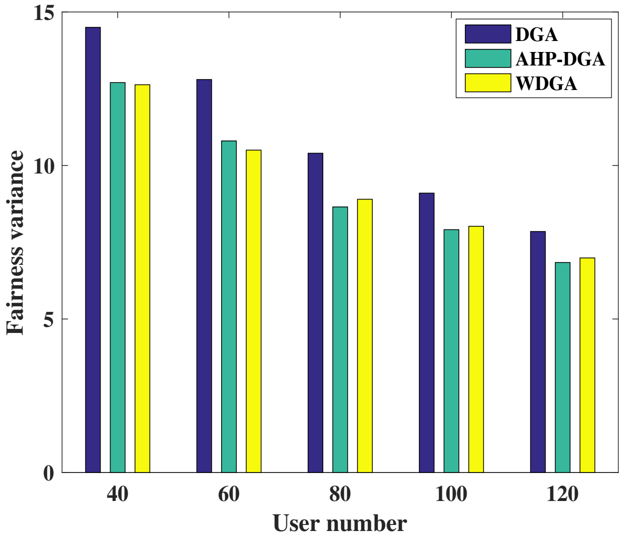

Fig. 8 Network utility of the three algorithms with different numbers of cognitive users in fair mode

algorithm is larger than that of the fairness algorithm, but is not as fair as the fairness algorithm.

6 Conclusions

In this paper, we adopted a hybrid method, which combines analytic hierarchy process and graph coloring, for spectrum allocation in cognitive satellite networks. The main contribution of this paper lies in that we we introduced a novel improved graph theory-based method to solve the spectrum optimization problem in satellite networks. Unlike traditional graph-based method, we used analytic hierarchy process to take into account heterogeneity in users' QoS requirement by analyzing different spectrum diversity. We applied a multi-objective decision method of analytic hierarchy process to improve the spectrum allocation obtained by graph coloring, thus providing a reasonable spectrum access strategy. We adopt the method of graph coloring to ensure no severe interference on primary systems. Combining the advantages of the two algorithms, it not only improves the efficiency of cognitive users, but also meets the requirements of the overall benefits of cognitive satellite networks. Due to secondary users' heterogeneous preferences on various spectrum, a more detailed spectrum allocation scheme should be designed to address users' demands. By assigning diverse weigh parameters to users, we described the model, an improved graph-based spectrum allocation algorithm was raised in this paper. Numerical results were also given to testify the performances of

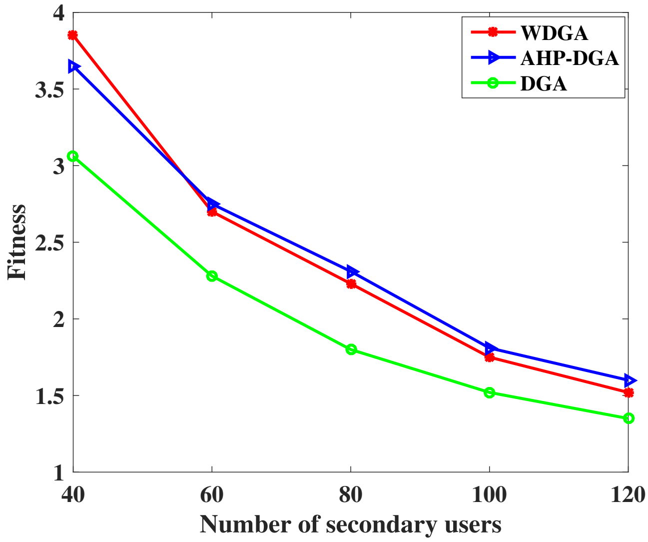

Fig. 9 Fairness variance of the three algorithms with different numbers of cognitive users in fair mode

our proposal. In the following research work, we plan to investigate the resource management strategy in more complex circumstances where secondary users' diverse demands have an apparent impacts on the resource allocation. Numerical results are provided to evaluate the performance of our proposal and the effects of various parameters on network capacity.

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