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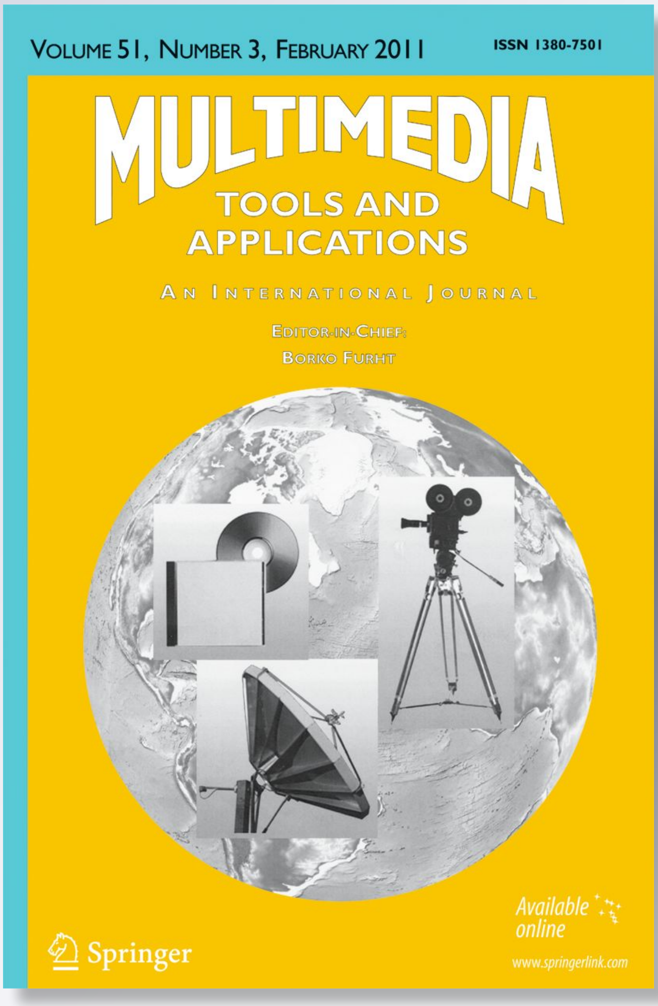

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QoS provisioning wireless multimedia transmission over cognitive radio networks

**Yuming Ge · Min Chen · Yi Sun · Zhongcheng Li ·
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Abstract The rapid growing of wireless multimedia applications increases the needs of spectrum resources, but today's spectrum resources have become more and more scarce and large part of the assigned spectrum is in an inefficiency usage. Cognitive Radio (CR) technologies are proposed to solve current spectrum inefficiency problems and offer users a

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ubiquitous wireless accessing environment, relying on dynamic spectrum allocation. However, there are two unsolved problems in previous work: 1) based on the simplified Quality of Service (QoS) uniform assumption, specific requirements of different wireless multimedia applications cannot be satisfied; 2) aiming at single-objective optimization of spectrum utilization or handoff rate, the co-optimization of these two necessary objectives in CR networks has not been achieved. In this paper, we propose a Two-tier Cooperative Spectrum Allocation method (TCSA) to solve these two problems. TCSA consists of two functional parts: one is a Spectrum Adjacency Ranking algorithm implemented at the secondary users' terminals to satisfy the QoS requirements for different wireless multimedia applications; and the other is a Max Hyper-weight Matching algorithm implemented at the cognitive engines of CR networks to co-optimize spectrum utilization and secondary users' spectrum handoff rate. Simulation results show that, compared with the other Random matching algorithm and Cost minimized algorithm, TCSA can significantly improve the performance of CR networks in terms of secondary users' throughput and spectrum handoff rate.

Keywords Wireless multimedia transmission · Cognitive radio networks · Dynamic spectrum allocation · Quality of service · Spectrum handoff rate

1 Introduction

In recent years, with the fast development of wireless communication technologies and the rapid growing of multimedia applications, wireless multimedia is increasingly ubiquitous [14]. This takes an increasing demand on the usage of spectrum resources [20]. However, the limited spectrum resources have become more and more scarce and they are in an inefficiency usage by a fixed spectrum assignment policy. According to the Federal Communication Commission [9], temporal and geographical variations in the utilization of the assigned spectrum range from 15% to 85%. The limited available spectrum resources and the inefficiency in the spectrum usage become the development bottlenecks for wireless multimedia applications [16].

Cognitive Radio (CR) technologies are regarded as the most promising technologies to solve the current spectrum inefficiency [1, 7] and energy consumption [27] problems. CR is defined as an intelligent radio that can change its transmitter parameters based on interactions with the environment in which it operates [1]. In addition, CR is a technology that can offer users a ubiquitous wireless accessing environment [17, 18], allowing them to enjoy a seamless wireless connection. In CR networks, a Secondary User (SU), also referred to as a cognitive radio user or opportunistic user, is capable of periodically sensing, and identifying available channels in the frequency spectrum to occupy them while they are not being used by a Primary User (PU). Once a PU is detected, the SU occupying the PUs' channels needs to vacate them. CR technologies represent a great potential for wireless multimedia applications [11].

A critical problem in CR networks is how to construct an efficient solution for dynamic spectrum allocation. However, most of the existing research work has only considered the bandwidth requirement [21] as the simplified Quality of Service (QoS) uniform assumption for spectrum allocation, ignored SUs' specific QoS requirements for different wireless multimedia applications [10], such as delay, jitter and packet loss. If the QoS requirements of SUs can not be satisfied, SUs will repeatedly handoff to other spectrum channels for their successful transmissions. As a result, the number of SUs using the spectrum will be decreased, spectrum utilization can not be improved efficiently and SUs' spectrum handoff rate will be increased. Furthermore, Some of the existing spectrum allocation methods focus on maximizing of spectrum utilization, and others may consider minimizing of SUs' spectrum handoff rate, which are normal optimization objectives in CR networks and have always been considered independently, However, a good spectrum allocation method should have the ability to co-optimize these two objectives. To the best of our knowledge, this two-objective co-optimization problem has not been sufficiently discussed in previous work.

In this paper, we propose a Two-tier Cooperative Spectrum Allocation (TCSA) method for SUs' wireless multimedia transmission over CR networks. This method considers SUs' specific QoS requirements (including delay, jitter, packet loss and bandwidth) as constraint conditions for spectrum allocation, and targets to achieve the co-optimization of spectrum utilization and SUs' spectrum handoff rate. The TCSA method consists of two functional parts: one is a Spectrum Adjacency Ranking algorithm implemented at the SUs' CRN_Terminals to satisfy SUs' QoS requirements for different wireless multimedia applications; and the other is a centralized Max Hyper-weight Matching algorithm implemented at the Cognitive Engines (CRN_CE) of CR networks to co-optimize spectrum utilization and SUs' spectrum handoff rate. As illustrated in Fig. 1, SU_1 and SU_2 periodically detect spectrum availability and application requests. Following that, they run the Spectrum Adjacency Ranking algorithm to rank the order of available spectrum regions according to their QoS requirements. CRN_CE collects the spectrum ranking information from SU_1 and SU_2, and then run the Max Hyper-weight Matching algorithm to co-optimize spectrum utilization and SUs' spectrum handoff rate. Finally the spectrum allocation decisions are returned to SU_1 and SU_2.

We make two major contributions in this paper. Firstly, we take several spectrum characterization parameters into account to represent the quality of available spectrum regions, including spectrum capacity, packet loss, delay and jitter. Then based on spectrum conditions and SUs' application requests, we propose a Spectrum Adjacency Ranking algorithm (detailed in Section 4.1) to rank the order of available spectrum regions with the aim of satisfying SUs' QoS requirements for different wireless multimedia applications, this algorithm applies the theory of the TOPSIS method [8]. Secondly, we propose a Max Hyper-weight Matching algorithm (detailed in Section 4.2) to solve the co-optimization problem of spectrum utilization and SUs' spectrum handoff rate. By introducing a new compound objective *Hyper-weight* to each edge of the bipartite graph *G*, this algorithm translates the two-objective 0–1 programming problem into a Maximum Weight Prefect

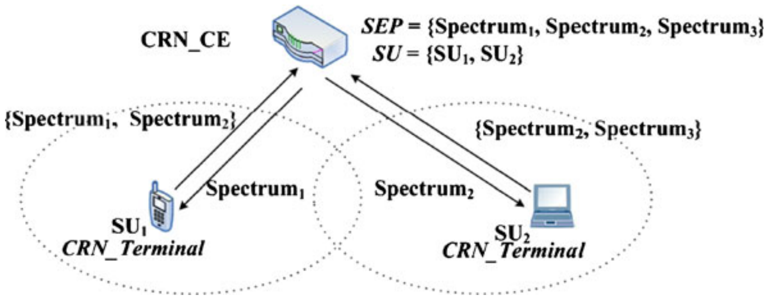


Fig. 1 Working scenario of the TCSA method

Matching problem, which can be solved by using the Hungarian Algorithm [15]. *G* is composed of the SUs set *SU* and the available spectrum regions set *SEP*. This algorithm has a low computing complexity of $O(n^3)$ rather than $O(n!)$.

The remainder of this paper is organized as follows. The next section introduces the related research work of dynamic spectrum allocation in CR networks and summarizes the problems have not been solved yet. Section 3 describes the Cognitive Radio system model which we considered. Section 4 proposes our dynamic spectrum allocation solution TCSA in detail. Section 5 describes several simulation experiments and presents our performance evaluation results. Finally, section 6 concludes the paper.

2 Related works

The issue of dynamic spectrum allocation is an important research topic in CR networks. In [1] Akyildiz and Lee point out that SUs of CR networks require the capability to access a spectrum channel, based on spectrum availability and internal (possibly external) policies. Also, in [29] Zhao and Sadler provide an overview of major technical issues in spectrum opportunity sharing and indicate the complexity of the topic and the diversity of existing technical approaches.

Some of the existing research work focus on maximizing of spectrum utilization [5, 28, 30]. In [30] Zheng and Cao propose a device-centric spectrum management scheme and five spectrum decision rules are presented to regulate users' access, trading off fairness and utilization with communication costs and algorithm complexity. In [28] the authors introduce the concept of a time-spectrum block to model spectrum reservation, which is used to present a theoretical formalization of the spectrum allocation problem in CR networks. This method addresses not only which spectrum should transmit, but also how wide a spectrum band to transmit.

In addition, some spectrum allocation methods are aiming to minimize SUs' spectrum handoff rate. In [2] the authors propose three admission control schemes to dynamically adjust the number of SUs in CR networks with the aim of decreasing the spectrum handoff probability of SUs. In [13] Jo and Cho present a heuristic matching algorithm to allocate a spectrum hole while minimizing difference between expected spectrum holding time and expected service time. The algorithm requires much computational complexity, so in [12] they propose more efficient greedy and classified matching algorithms.

Due to the importance of SUs' QoS requirements, in [26] the authors discuss the issue of considering both user request priorities and channel conditions in the context of spectrum allocation and propose a novel graph theoretic matching algorithm to support QoS requirements among SUs. Other related research work has begun to discuss the design challenges and principles for multimedia and delay-sensitive data transmission over CR networks [3]. In [6] the authors propose a utility function involved delay-sensitive characteristics of multimedia data and formulate the spectrum allocation problem as an auction game. In [22] authors take multimedia intra refreshing rate as optimization objective to satisfy multimedia transmission in a CR system. In [23–25] the authors considers various rate requirements and delay deadlines of multimedia users for delay-sensitive multimedia applications transmitting over CR networks, and further investigate the problem of multi-user resource management in multi-hop CR networks for delay-sensitive applications. Authors in [4] propose a distributed QoS-aware MAC protocol for multi-channel CR networks supporting multimedia applications. In [19] the authors propose a low complexity video transcoder algorithm for distribution of digital video contents to mobile terminals. However, they are mainly focus on the optimization of different QoS objectives and have not sufficiently considered the normal optimization objectives of CR networks.

From the above, it can be seen that several problems have not been properly solved yet. Firstly, it is not sufficient to characterize spectrum channels only by channel capacity in CR networks. A sophisticated method should consider multiple characterization parameters and determine a reasonable weight for each one. Secondly, considering the importance of SUs' QoS requirements, especially delay, jitter, packet loss and large bandwidth requirements for different wireless multimedia applications, new spectrum allocation methods should have the ability to satisfy SUs' QoS requirements for different wireless multimedia applications. Finally, compared to most of the existing dynamic spectrum allocation methods which only focus on the optimization of single-objective spectrum utilization or SUs' handoff rate simply, new spectrum allocation methods should consider the co-optimization of spectrum utilization and SUs' spectrum handoff rate.

3 System model

As illustrated in Fig. 2, we consider a time-slotted CR network model, where spectrum allocation decisions are made at the beginning of each time slot. In this CR network, we assume that $SU = \{x_1, x_2, x_3 \dots x_n\}$ is a set of SUs, where x_i denotes the i^{th} SU and n is the number of SUs. All the SUs are distributed randomly in a specific area and the number of SUs will change with the spectrum allocation period. In addition, we assume that $SEP = \{y_1, y_2, y_3 \dots y_M\}$ is a set of available spectrum regions, where y_j denotes the j^{th} available spectrum region and M is the categories of available spectrum regions owned by different primary networks in this area. For the j^{th} available spectrum region y_j, it consists of S_j secondary spectrum channels and each secondary spectrum channel s_j can support downlink data rate r_j, so the total number of secondary spectrum channels in this CR network is $S = \sum_j S_j$. Then the key problem of dynamic spectrum allocation is to construct an efficient mapping between secondary users and secondary spectrum channels.

In order to solve this problem, the following assumptions are made. Firstly, we suppose that there is a centralized CRN_CE in this CR network to control the whole spectrum allocation and accessing processes. This CRN_CE can be a physical entity or a functional entity. Secondly, all the secondary users are responsible for periodically detecting the spectrum availability and the application requests. Prefect spectrum sensing is assumed, since much research work has been done on spectrum sensing and we mainly focus on the issue of dynamic spectrum allocation.

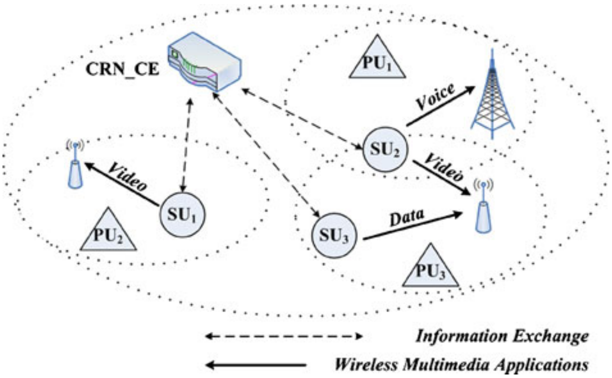


Fig. 2 Illustration of the considered system model

Finally, we assume the arrivals of SUs and PUs are both subject to Poisson processes and in order to avoid causing interference to PUs' transmissions, once a PU is detected, SUs are supposed to carry out spectrum handoff immediately.

In particular, SUs in our system model could support multiple wireless multimedia applications: voice, video flow and data transmission. We suppose that voice has the strictest QoS requirements (delay <50 ms, jitter <5 ms, packet loss <3%, bandwidth 9.6 kbps). Video flow consumes more bandwidth 90 kbps and delay less than 200 ms. Data transmission only requires the transmission bandwidth to be 120 kbps.

4 Proposed method

We propose a Two-tier Cooperative Spectrum Allocation (TCSA) method to handle the spectrum allocation problem for SUs' wireless multimedia transmission over CR networks. This method takes multiple influence parameters into account to formulize the spectrum characterization and consists of two functional parts: one is a Spectrum Adjacency Ranking algorithm implemented at the SUs' CRN_Terminals, to satisfy the SUs' QoS requirements for different wireless multimedia applications; and the other is a Max Hyper-weight Matching algorithm implemented at the CRN_CE of CR networks, to co-optimize spectrum utilization and SUs' spectrum handoff rate. Therefore, with the cooperation between SUs and CR networks, TCSA can construct an efficient dynamic spectrum allocation solution for SUs wireless multimedia transmission.

4.1 Spectrum adjacency ranking algorithm at CRN_terminals

In this section, we characterize the quality of available spectrum regions using multiple influence parameters, including spectrum capacity, packet loss, delay and jitter. According to current spectrum conditions and SUs' application requests, we propose a Spectrum Adjacency Ranking algorithm to rank the order of available spectrum regions, with the aim of satisfying SUs' QoS requirements for different wireless multimedia applications. This algorithm utilizes the theory of TOPSIS method [8] to construct the theoretically best and worst solutions for the problem respectively, and then try to select from the feasible solution set the solution which is closest to the theoretically best solution and farthest from the theoretically worst solution.

For the i^{th} secondary user, suppose that there are m available spectrum regions in the feasible solution set $Sep_i = \{y_1, y_2, y_3 ... y_m\}$, $m < M$ and $Sep_i \in SEP$. Each spectrum region y_j is described by a set of k parameters $y_j = \{y_{j,1}, y_{j,2}, y_{j,3} ... y_{j,k}\}$ where $y_{j,l}$ represents the l^{th} parameter of the j^{th} available spectrum region. All these parameters will be considered in this Spectrum Adjacency Ranking algorithm. Let $W = \{w_1, w_2, w_3 ... w_k\}$ be the vector of weights corresponding to the k parameters where w_l is the weight of the l^{th} parameter. Therefore, the available spectrum regions and the parameters form an $m \times k$ matrix $B = [b_{j,l}]_{m \times k}$. We multiply matrix B with the parameter weight vector W to derive the decision matrix $C = [c_{j,l}]_{m \times k}$, where $c_{j,l} = w_l \times b_{j,l}$. Then, we construct the theoretically best solution C^+ and the worst solution C^-, $C^+ = \{c_1{}^+, c_2{}^+, c_3{}^+ \dots c_k{}^+\}$, $C^- = \{c_1{}^-, c_2{}^-, c_3{}^- \dots c_k{}^-\}$

$$c_l^+ = \max\{c_{j,l} | j = 1, \dots, m\} = w_l \max\{b_{j,l} | j = 1, \dots, m\} = w_l b_l^+ \tag{1}$$

$$c_l^- = \min\{c_{j,l} | j = 1, \dots, m\} = w_l \min\{b_{j,l} | j = 1, \dots, m\} = w_l b_l^- \tag{2}$$

For each available spectrum region, we compute its distance to the theoretical best solution d_j^+ and its distance to the theoretical worst solution d_j^- using (3) and (4). Finally, the variable of adjacency N_j can be computed using (5).

$$d_j^+ = \sum_{l=1}^{k} (c_{j,l} - c_l^+)^2 = \sum_{l=1}^{k} w_l^2 (b_{j,l} - b_l^+)^2 \qquad j = 1, 2, 3 \ldots m \tag{3}$$

$$d_j^- = \sum_{l=1}^{k} (c_{j,l} - c_l^-)^2 = \sum_{l=1}^{k} w_l^2 (b_{j,l} - b_l^-)^2 \qquad j = 1, 2, 3 \ldots m \tag{4}$$

$$N_j = \frac{d_j^-}{d_j^- + d_j^-} \qquad j = 1, 2, 3 \ldots m \tag{5}$$

As can be seen from (5), the variable of adjacency N_j indicates how close the selected spectrum is to the theoretically best solution and how far it is from the theoretically worst solution. Thus, the larger the value of N_j, the better the solution. For each SU, we rank the available spectrum regions in descending the order of the values N_j and try to select the spectrum region with a larger value.

Before we operate the Spectrum Adjacency Ranking algorithm, another necessary preparation work is to reasonably determine the weights of the k different parameters, since these weights greatly influence the ranking process. We demonstrate a weight self-generation mechanism to automatically compute the weights of these k parameters.

From (5), it can be seen that the variable of adjacency N_j is inversely proportional to d_j^+. This means the smaller value of d_j^+, the better the solution. Therefore, we construct the objective function as follows:

$$\begin{aligned} &objects : \ \min \sum_{j=1}^{m} d_j^+ = \sum_{j=1}^{m} \sum_{l=1}^{k} (b_{j,l} - b_l^+)^2 w_l^2 \\ &s.t. \qquad : \sum_{l=1}^{k} w_l = 1 \end{aligned} \tag{6}$$

Applying the Lagrange multiplier method to the above objective function, we get the partial derivative Eq. 7.

$$f_{lagrange}(w, \lambda) = \sum_{j=1}^{m} \sum_{l=1}^{k} (b_{j,l} - b_l^+)^2 w_l^2 - \lambda (\sum_{l=1}^{k} w_l - 1) \tag{7}$$

According to the theory of the Lagrange multiplier method, the extreme value points must be contained in the solutions of Eq. 7. Let $\frac{\delta f_{lagrange}}{\delta w} = 0, \frac{\delta f_{lagrange}}{\delta \lambda} = 0$, so we get:

$$\begin{cases} 2 \sum_{j=1}^{m} (b_{j,l} - b_l^+)^2 w_l - \lambda = 0 \qquad 1 = 1, 2, 3 ... k \\ \sum_{l=1}^{k} w_l - 1 = 0 \end{cases} . \tag{8}$$

By solving the above multivariate linear equations, we can finally arrive at:

$$w_l = \frac{1}{\sum_{l=1}^{k} \frac{1}{\sum_{j=1}^{m} (b_{j,l} - b_l^+)^2} \times \sum_{j=1}^{m} (b_{j,l} - b_l^+)^2} \tag{9}$$

Obviously, $w_l \geq 0$ and the weights computed by (9) will achieve the minimum value of objective function (6). Thus, we use (9) to determine the weights of multiple parameters and apply the results into the parameter weight vector W of the Spectrum Adjacency Ranking algorithm.

4.2 Max hyper-weight matching algorithm at CRN_CE

CRN_CE is a centralized control entity and its function is to construct a spectrum allocation mapping between the SUs set *SU* and the available spectrum regions set *SEP*, based on the spectrum ranking information from SUs. This mapping problem can be expressed as:

$$\begin{aligned} &objects: \ \max \ \min \mathrm{U_j} \\ &s.t. \qquad : \mathrm{U_j} = \frac{\sum_{i,s_j} x_{i,requirement} \times a_i^{(j,s_j)} \times N_{\mathrm{i,j}}}{\mathrm{y_{j,capacity}}} \\ &\qquad\qquad a_i^{(j,s_j)} \in \{1,0\} \\ &\qquad\qquad \textstyle\sum_i a_i^{(j,s_j)} \le 1 \\ &\qquad\qquad \textstyle\sum_{s_j,j} a_i^{(j,s_j)} \le 1 \\ &\qquad\qquad \mathrm{s_j} \in \{1,2,\ldots,S_j\} \end{aligned} \tag{10}$$

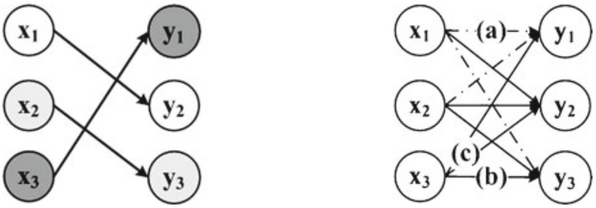
As illustrated above, based on the QoS requirements, the objective function maximizes the minimum spectrum utilization of all the available spectrum regions. U_j represents spectrum utilization of the j^{th} available spectrum region. $N_{i,j}$ is the adjacency of the j^{th} available spectrum region satisfying the i^{th} SU, which is calculated in Section 4.1. Element $a_i^{(j,s_j)}$represents the i^{th} SU occupying the ${s_j}^{th}$ secondary spectrum channel of the j^{th} available spectrum region which records the mapping result between set *SU* and set *SEP*.

Although the above algorithm can achieve the maximum spectrum utilization easily, it ignores to consider the reduction of SUs' spectrum handoff rate. However, if the spectrum handoff rate of SUs is ignored, SUs may be allocated to new spectrum channels at a new decision period, even if the current spectrum channels can still satisfy their transmission requirements. Frequent spectrum changing will bring a crucial performance overhead. How to achieve the co-optimization between spectrum utilization and SUs' spectrum handoff rate is a more complex problem.

We propose a Max Hyper-weight Matching algorithm to solve this two-objective problem without increasing computing complexity compared to a single-objective matching problem. We introduce other two $N \times N$ matrices, O and P to indicate the original and new mapping, in which N is the maximum value of SUs' number n and secondary spectrum channels' number S. Element $O_i^{(j,s_j)}$and $P_i^{(j,s_j)}$ represent the matching results between the i^{th} SU and the ${s_j}^{th}$ secondary spectrum channel of the j^{th} available spectrum region respectively. Then this two-objective optimization problem can be modeled as:

$$\begin{aligned} &objects: \ \max \ \min \mathrm{U_j} \\ &\qquad\qquad \max \textstyle\sum O_i^{(j,s_j)} \times P_i^{(j,s_j)} \\ &s.t. \qquad : \mathrm{U_j} = \frac{\sum_{i,s_j} x_{i,requirement} \times P_i^{(j,s_j)} \times N_{\mathrm{i,j}}}{\mathrm{y_{j,capacity}}} \\ &\qquad\qquad \textstyle\sum_i O_i^{(j,s_j)} = \sum_i P_i^{(j,s_j)} = 1 \\ &\qquad\qquad \textstyle\sum_{j,s_j} O_i^{(j,s_j)} = \sum_{j,s_j} P_i^{(j,s_j)} = 1 \\ &\qquad\qquad O_i^{(j,s_j)} \in \{1,0\} \\ &\qquad\qquad P_i^{(j,s_j)} \in \{1,0\} \\ &\qquad\qquad \mathrm{s_j} \in \{1,2,\ldots,S_j\} \end{aligned} \tag{11}$$

This is a two-objective 0–1 programming problem and has a complexity of $O(n!)$. However, we will show that this problem can be solved by our Max Hyper-weight



(a) *SU*/*SEP* Prefect Matching (b) The Hyper-weight Assignment

Fig. 3 Matching between SUs and available spectrum regions (**a**) *SU*/*SEP* Prefect matching (**b**) The Hyper-weight assignment

Matching algorithm more efficiently, without the loss of accuracy. As illustrated in Fig. 3(a), each mapping is a perfect matching in bipartite graph *G* composed by set *SU* and set *SEP*. We assign a *Hyper-weight* to each edge $< x_i, y_j^{s_j} >$, according to spectrum utilization and whether the edge is in the original mapping. Firstly, to prevent spectrum utilization loss, we use (10) to calculate another new optimal spectrum utilization. Referring to Fig. 3(b), for the edge whose utilization is smaller than the new optimal one, we set the corresponding *(a)Hyper-weight* = *0*. Then taking the spectrum handoff rate as an optimization goal, the *Hyper-weight* assignment should show the preference of the original edges. Thus, we assign the edges in the original mapping *(b)Hyper-weight* = *N*+ *1*; and others *(c)Hyper-weight* = *N*.

To achieve the co-optimization between spectrum utilization and SUs' spectrum handoff rate, we only need to maximize the sum of all the edges' *Hyper-weights*. Thus, we translate this problem into a Maximum Weight Perfect Matching problem in a bipartite graph, which can be solved by using the Hungarian Algorithm [15]. The proposed Max Hyper-weight Matching algorithm has a complexity of $O(n^3)$, which is determined by the complexity of the Hungarian Algorithm.

Another necessary work needed before is to normalize the bipartite graph *G*, because a graph has a perfect matching if and only if the matching-generating polynomial is of degree *N* for a graph on *N* nodes. Thus, if $n < S$, we add additional *S-n* SUs to the set *SU* and set the corresponding weight to 1, as shown in Fig. 4(a); else if $n > S$, we add additional *n-S* secondary channels to the set *SEP* and set the corresponding weight to 0, as shown in Fig. 4(b).

The pseudo-code of the Max Hyper-weight Matching algorithm is illustrated in Algorithm 1. Note that, by adjusting the threshold of the reference optimal spectrum utilization, we can balance the tradeoff between spectrum utilization and SUs' spectrum handoff rate.

```
Algorithm 1: Max Hyper-weight Matching
Input: SUs set SU and available spectrum regions set SEP
Output: Mapping with maximum spectrum utilization and minimum SUs' spectrum handoff rate
1: Compose a bipartite graph G of set SU and set SEP;
2: Calculate a new optimal spectrum utilization;
3: Set Hyper-weight for each edge in graph G:
    (a) Hyper-weight = 0, if the original edge is not satisfying;
    (b) Hyper-weight = N+ 1, if the edge is satisfying and in the original mapping;
    (c) others Hyper-weight = N;
4: Run Hungarian Algorithm to solve the Maximum Weight Perfect Matching problem
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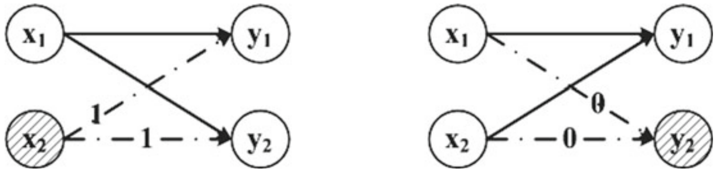

(a) Graph Normalization (n<S) (b) Graph Normalization (n>S)

Fig. 4 **a** Graph normalization ($n < S$) **b** Graph normalization ($n > S$)

4.3 The complete procedure of the TCSA method

As shown in Fig. 5, we consider a two SUs spectrum allocation scenario to illustrate the complete procedure of the TCSA method. The sensing modules on CRN_Terminal periodically detect the spectrum availability and application requests. Following that, it runs the Spectrum Adjacency Ranking algorithm to rank the order of available spectrum regions according to the QoS requirements for different wireless multimedia applications, and forwards the spectrum ranking information to the CRN_CE of CR networks. CRN_CE runs the Max Hyper-weight Matching algorithm to construct a spectrum allocation solution between SUs set *SU* and feasible spectrum set *SEP*, with the aim of achieving the co-optimization of spectrum utilization and SUs' spectrum handoff rate, and then returns the allocation decision to each SU.

5 Performance evaluation

To evaluate the performance of TCSA method, we design a simulation scenario. We assume that SUs' and PUs' arrivals are both subject to Poisson processes, all the SUs are distributed randomly in a specific area and the location of SUs will change with the spectrum

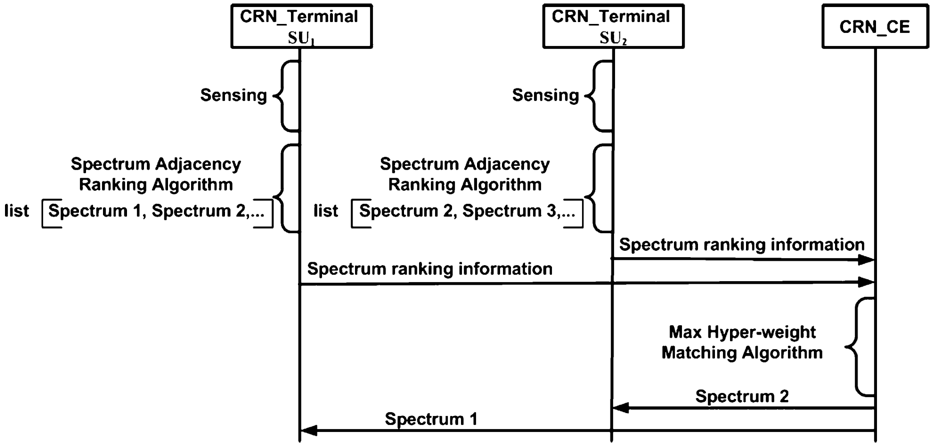

Fig. 5 Complete implement procedure of the TCSA method

Table 1 Spectrum parameters

	capacity (Kbps)	delay (ms)	jitter (ms)	packet loss
Spectrum1	4000	150~500	10	<5%
Spectrum2	5000	140~500	20	<5%
Spectrum3	4500	130~500	15	<5%
Spectrum4	2000	37~50	3	<1%
Spectrum5	96	35~50	4	<1%
Spectrum6	1000	43~50	3	<1%

allocation period. As mentioned in Section 3, we support three different wireless multimedia applications in our simulation and the required service time of each application follows a shifted negative exponential distribution. In addition, two different kinds of spectrum regions are provided in our simulation: Spectrum regions {1, 2, 3} are assumed to be ISM bands, and the other three spectrum regions {4, 5, 6} are assumed to be cellular communication bands. Their initialization parameters are illustrated in Table 1. Parameters such as bandwidth capacity and delay will change during the performance period.

Based on this simulation scenario, we evaluate the performance of TCSA method on SUs' throughput and SUs' spectrum handoff rate, which are commonly used as evaluation objectives in CR networks. Also, we compare the performance of TCSA method with the other Random matching algorithm and Cost minimized algorithm [13].

Figure 6 depicts the spectrum allocation solutions for different wireless multimedia applications as a function of performance periods using the TCSA method. Due to PU's occupancy or SU's mobility, one secondary spectrum channel can not always satisfy one SU's transmission requirements, TCSA has the ability to make new spectrum allocations or spectrum handoff decisions according to the spectrum availability. Based on the QoS requirements for different wireless multimedia applications, including delay, jitter, packet

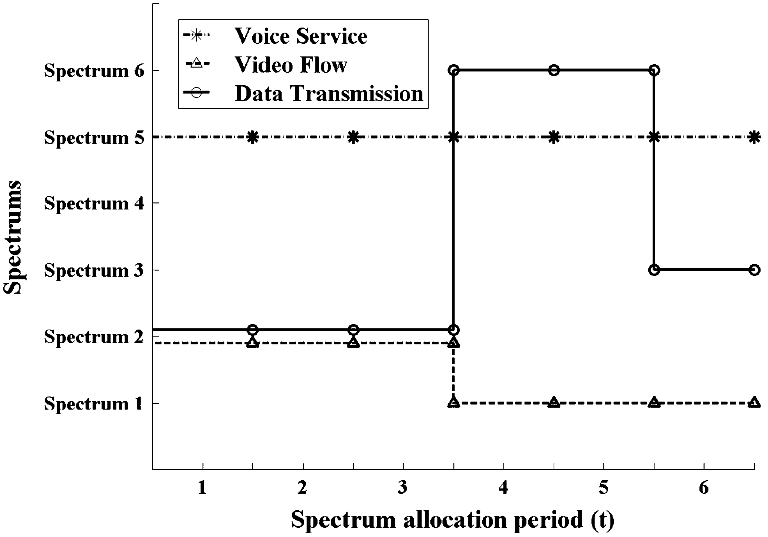

Fig. 6 Spectrum allocation and handoff

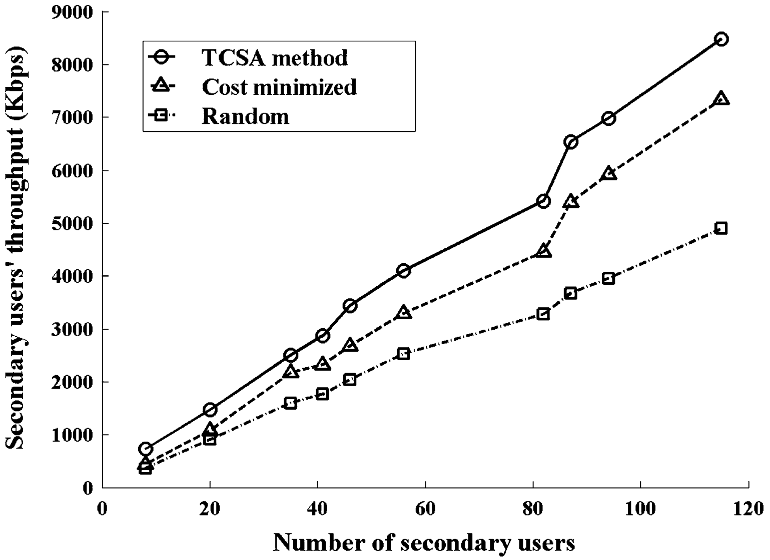

Fig. 7 Change of SU's throughput as a function of number of SUs

loss and bandwidth, TCSA always chooses a stable cellular communication spectrum for voice transmission, at the same time it prefers to select the ISM band spectrum regions for Video flow and data transmission. In addition, considering the overhead of frequent spectrum handoff, TCSA attempts to maintain the original spectrum allocation solution instead of having to make a spectrum handoff.

Figure 7 indicates throughput as a function of the number of SUs for different spectrum allocation methods. Compared to Random matching algorithm, Cost minimized algorithm

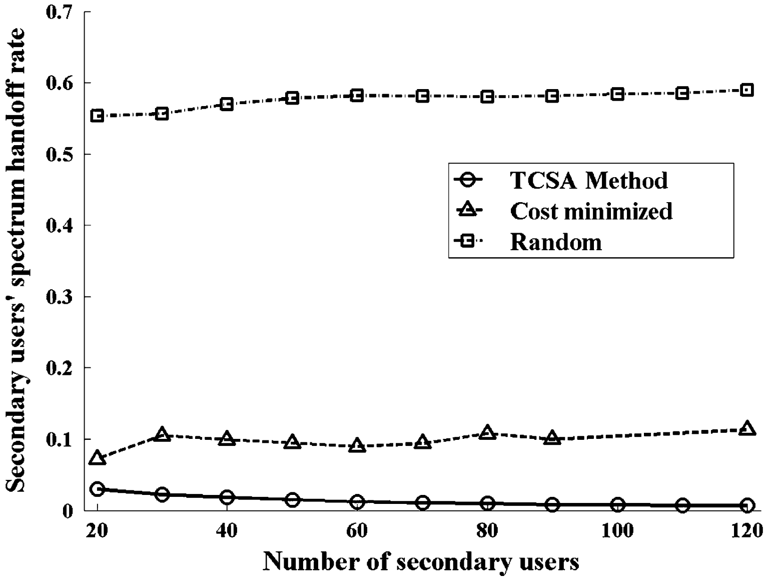

Fig. 8 Change of spectrum handoff rate as a function of number of SUs

considers the difference between the required service time and the channel holding time as a spectrum allocation factor, which can partly improve the performance of CR networks. However, it is only based on service bandwidth requirement, and it ignores the importance of other QoS requirements such as delay, jitter and packet loss. As a result, SU may be allocated to a secondary channel which can not satisfy their transmission requirements. Compared to the Cost minimized algorithm, the TCSA method considers multiple influence parameters for spectrum characterization. According to SUs' QoS requirements for different wireless multimedia applications, the TCSA method constructs a more efficient spectrum allocation solution and improves the throughput of the entire CR network by 23% on average.

Figure 8 illustrates SUs' spectrum handoff rate as a function of the number of SUs for different spectrum allocation methods. Random matching algorithm ignores the performance overhead of spectrum handoff, so it brings frequent spectrum handoffs. In comparison, Cost minimized algorithm contains a spectrum channel reservation scheme to minimize the spectrum handoff probability, and TCSA method includes a Max Hyper-weight Matching algorithm to co-optimize spectrum utilization and SUs' spectrum handoff rate, which both prefer to maintain an original spectrum allocation rather than making a new decision. Therefore the SUs can be served more seamlessly. Compared with Cost minimized algorithm, TCSA method considers SUs' QoS requirements more comprehensively and makes the spectrum allocation more efficient. It reduces the spectrum handoff rate by 8.1% and gets a low spectrum handoff rate of 1.7% on average.

6 Conclusion

In this paper, we propose a Tow-tier Cooperative Spectrum Allocation (TCSA) method to solve dynamic spectrum allocation problem for secondary users' wireless multimedia transmission over Cognitive Radio networks. This method takes multiple spectrum characterization parameters into account to represent the quality of available spectrum regions. Then based on current spectrum conditions and secondary users' application requests, an Adjacency Ranking algorithm is considered to satisfy secondary users' QoS requirements for different wireless multimedia applications, including delay, jitter, packet loss and bandwidth requirement. Furthermore, a Max Hyper-weight Matching algorithm is contained to achieve the co-optimization between spectrum utilization and secondary users' spectrum handoff rate. With the cooperation between secondary users and Cognitive Radio networks, TCSA can construct an efficient dynamic spectrum allocation solution for secondary users' wireless multimedia transmission over Cognitive Radio networks. Simulation results show that, compared with the Cost minimized algorithm, TCSA can improve the performance of Cognitive Radio networks in terms of secondary users' throughput by 23% and spectrum handoff rate by 8.1%, without any increase of the computing complexity.

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