Efficient Spectrum Matching Based on Spectrum Characteristics in Cognitive Radio Systems

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Abstract—QoS is a very important issue in cognitive radio systems. We present and discuss spectrum matching algorithms to support QoS for cognitive radio users. This work is carried out in the context of a dynamic changing spectrum. In this paper, we propose efficient spectrum matching algorithms, which have low-complexity and quite good performance, based on statistical characteristics of spectrum bands. Those are classified random matching algorithm and greedy algorithm. The classified random matching algorithms would match the most suitable spectrum class to a proper user and randomly choose a spectrum within the class. And, using greedy algorithm, the best spectrum out of available spectrum bands will be chosen whenever a new user joins. The proposed algorithms provide QoS for cognitive radio systems through the reduction of spectrum handoff probability and improvement of fairness. Performance analysis and simulation results validate the efficiency of the proposed algorithms.

Index Terms—cognitive radio, spectrum management, QoS

I. INTRODUCTION

DEMAND of wireless communication is growing very rapidly. It has led intense research and development efforts towards an efficient way that spectrum utilization can be improved to satisfy this growing demand. Because, the present communication systems which have very limited bandwidth will not be able to satisfy the growing demand. The only way to follow up the rapid growth of demand in the future is that we improve the efficiency of the spectrum, because frequency spectrum is very valuable and scarce resource. Even though the spectrum resource is very limited and the demand is growing very rapidly, we still have an opportunity to overcome the limitation. What is remarkable is that regulatory agencies in various countries including the Federal Communications Commission in the United States found that most of the radio frequency spectrum were inefficiently utilized. Fig. 1 shows the power spectral density (PSD) from 0 to 6 GHz bands of which actual measurements were taken in downtown Berkeley at California, United States [2][3]. This analysis reveals low level usage of allocated spectrum with utilization ranging from 15% to 85% as a result of the vast temporal and geographic variations. As illustrated in Fig. 1, the frequency bands in the spectrum at frequencies over 3 GHz are largely unoccupied most of the time, and some other frequency bands are only partially occupied. Therefore, we can try to improve spectrum efficiency by using spectrum sharing of those frequency bands. The solution is cognitive radio.

Cognitive radio is a paradigm for wireless communication which is seen as the solution to the current low utilization of the radio electromagnetic spectrum. This concept of cognitive radio was first presented in the paper by Joseph Mitola III and Gerald Q. Maguire, Jo. [6]. The cognitive radio was considered as an application on top of a software-defined radio (SDR) platform which is a fully recongurable wireless black-box that automatically changes its communication parameters in response to network and user demands. An SDR is a radio in which the properties of carrier frequency, signal bandwidth, modulation and network access are defined by software. And, the cognition is the technique which is applying dynamic situations via collecting the information of surroundings and the self-learning. And, the cognitive radio is detecting spectrum hole and sharing it without harmful interference with other users. Whenever primary user uses this spectrum, secondary user would be switched to other spectrum without any interference to primary user. The cognitive radio devices measure a spectrum interruption from primary user with periodical interval during secondary user uses certain spectrum. If the device senses the primary user, secondary user should switch into other channel in a given time or to be dropped. Therefore, to improve the quality of service of secondary user, a novel algorithm which could decrease the dropping rate of secondary user is presented.

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To realize cognitive radio and improve spectrum efficiency, spectrum management is a very important issue. Spectrum management basically means the capturing of the best available spectrum to meet user communication requirements. We classify the functions of spectrum management into spectrum sensing, spectrum analysis, and spectrum decision. Spectrum sensing is to find out available spectrum band for secondary users. Usually, spectrum sensing is described as a detection problem in physical layer. And, spectrum analysis and decision is to allocate a spectrum band to a proper user. In addition to these basic functions of spectrum management, some new spectrum management functions are required considering the dynamic spectrum characteristics. However, until now, a lot of works on the spectrum management problem are focused on the interference minimizing problem for primary system users. Because, the primary system user basically should not be affected by the secondary users of cognitive radio systems. This is the basic policy of cognitive radio systems. However, the issue on the spectrum management is moving towards providing service QoS to not only primary users but also secondary cognitive radio users, considering the characteristics of spectrum bands.

II. QoS Provisioning Spectrum Management for Cognitive Radio

The terminology of spectrum hole is a frequency band which can be utilized by secondary users (cognitive radio users) when it is not being used by primary users (incumbent user). By using empty spectrum bands that are originally assigned to a primary user, spectrum bands can be shared among many users and spectrum utilization can be improved. This is the basic philosophy of cognitive radio. In cognitive radio systems, the performance can be more enhanced through efficient spectrum management schemes. One of the most efficient ways for spectrum management is intelligent spectrum assignment considering the characteristics of spectrum bands. If a spectrum hole is assigned to a secondary user without considering the characteristics of spectrum holes, many secondary users may suffer from frequent spectrum handover. If a spectrum hole can not hold until the data transmission for a service of a secondary user is completed, the secondary user should change spectrum hole to continuing. In the case of real-time service, it is even more harmful for providing QoS. Besides, assigning a spectrum hole which has a long holding time and large bandwidth to a secondary user who requires only small data rate and short service time is exceedingly inefficient in view of resource management. Here, holding time of a spectrum hole means the available period in which a secondary user can occupy the spectrum band. We present spectrum matching algorithms which consider user QoS and spectrum characteristics to assign spectrum efficiently.

The most important issue for QoS provision of cognitive radio systems is to match the most suitable spectrum hole to a secondary user. The optimal matching can provide QoS and improve the system performance by minimizing the spectrum handover probability. The spectrum handover is defined in this paper as an event that a secondary user moves to another spectrum hole because of appearance of primary users. Each spectrum hole has different characteristics such as holding time and bandwidth because the primary service of each spectrum has different service pattern and different service rate. Holding time of a spectrum hole is usually assumed to be exponentially distributed with parameter $\lambda$. Fig. 2 shows the occupied spectrum holes. Then, spectrum handover condition in this case is expressed as follows.

$$p^h = P(t_{hold} < T_{req})$$

(1)

where $t_{hold}$ is the holding time of a spectrum hole, and $T_{req}$ is time duration required to support a service, which can be expressed as follows.

$$T_{req} \approx \frac{M}{B \cdot \log(1 + SINR)}$$

(2)

where $M$ is the amount of service traffic, $B$ is the bandwidth of a spectrum hole, and $SINR$ is the signal to interference and noise ratio of the user occupying the spectrum hole.

Spectrum handover occurs when the required service time, $T_{req}$ is less than the holding time, $t_{hold}$, of the spectrum hole which is allocated for the service. Therefore, the probability that spectrum handover occurs in the case that service $i$ is allocated to spectrum hole $j$ is expressed as,

$$p^{h}_{i,j} = \int_{0}^{T_{req,i}} \lambda_j e^{-\lambda_j t} dt = 1 - e^{-\lambda_j T_{req,i}}$$

(3)

where $T_{req,i}$ is the required service time for user $i$.

Also, the probability that QoS is provided to the system is calculated using the spectrum handover probability. Let us say that QoS is provided when every user does not experience spectrum handover. Then, this probability is given as,

$$p_{QoS} = \prod_{i=1}^{N} (1 - p^{h}_{i,j})$$

(4)

(Optimal matching)
Optimal spectrum matching means that $p_{QoS}$ is minimized. Therefore, we can formulate the optimal matching algorithm as follows.

$$\max p_{QoS} = \prod_{i=1}^{N} (1 - p_{i,j}^h)$$

subject to:

- $H_1 \cdots H_M$ spectrum hole
- $S_1 \cdots S_N$ service

$$\sum_{j=1}^{M} x_{H_jS_k} = 1, \ \forall S_k$$

$$x_{H_jS_k} \in \{0, 1\}, \ \forall S_k, \ \forall H_j$$

If spectrum hole $H_j$ and service $S_k$ are matched, $x_{H_jS_k}$, which reflects the matching link between the spectrum and the service, is 1. That means that service $i$ is matched with spectrum hole $j$. And, all the spectrum holes should be assigned to only one service by constraint equation (6).

The objective function $p_{QoS}$ is expressed as follows.

$$p_{QoS} = \prod_{i=1}^{N} (1 - p_{i,j}^h)$$

$$= \exp(-\sum_{i=1}^{N} \lambda_j T_{req,i})$$

Therefore, we can replace the objective function which is in the form of exponential function shown in equation (5) with following terms.

$$\min \sum_{i=1}^{N} \lambda_j T_{req,i}$$

The new objective function is a linear function. That means the optimized matching can be found through the optimization of the linear programming, which is much easier to solve.

Under the above constraints, optimal matching would be expressed as follows.

$$\hat{S}_j = \arg \{ \max_i x_{H_iS_j} \}$$

where $\hat{S}_j$ is the chosen spectrum hole for service $j$.

Even though optimal matching is desirable, the optimal matching is not practically applicable for spectrum hole matching. Because we should totally know what service will be generated in the future for the optimal matching. However, the perfect expectation of future traffic is not possible. For this reason, we introduce efficient and practical algorithms.

III. HEURISTIC MATCHING ALGORITHMS

A. Cost-minimized matching

Previously, a heuristic matching algorithm using an efficient cost function is proposed in [1]. The main idea of [1] is to allocate a spectrum hole while minimizing the cost function. The cost function is summarized as the difference between the expected hole time and the expected service time. The algorithm is described as follows.

(Cost minimized matching)

for $k = 1$ : number of user

for $j = 1$ : number of spectrum hole

$$T_{req,k,j} = \frac{M_k}{B_j \cdot \log(1 + SINR_j)}$$

$$\lambda_{k,j}^g = \frac{\ln \hat{P}}{T_{req,k,j}}$$

end

$$\hat{H}_k = \arg \{ \min_j | \lambda_j - \lambda_{k,j}^g | \}$$

end

This algorithm is quite efficient. However, it requires much computational complexity. Here, we propose more efficient heuristic algorithms.

B. Greedy matching

The second heuristic algorithm assigns a secondary user the best spectrum at the instance the service traffic is generated.

$$\hat{H}_k = \arg \{ \max_j \lambda_j \}$$

where $\hat{H}_k$ is the chosen spectrum hole for service $k$.

Using this algorithm, spectrum holes will be assigned in the order of incoming service. All available spectrum holes are arranged in the order of quality, namely the decreasing order of $\lambda_j$. And, a secondary user snaps the best spectrum hole in the order of incoming time. It means the first user could get the best spectrum hole. Therefore, this matching would provide the best spectrum hole ever for some users. However, for some other users, QoS would not be guaranteed in heavy traffic load situation. This is not the only service fairness problem, but also resource inefficiency problem. Because, assigning a spectrum hole which has a higher holding time and large bandwidth to a user who requires lower QoS might be exceedingly inefficient in view of resource management. The performance of this algorithm will be shown in the next section.

(Greedy matching)

for $k = 1$ : number of user

$$\hat{H}_k = \arg \{ \max_j \lambda_j \}$$

end

C. Classified matching

The third heuristic algorithm that we propose in this paper randomly assigns a spectrum hole to a secondary user within a proper spectrum class. Compared to cost-minimized algorithm that we have been considering as an efficient way for optimal
matching, this approach will assign a spectrum hole in a quite simple manner. Even though cost-minimized matching algorithm could give almost optimal matching fit to secondary users, computation complexity would be high. Therefore, we try a simple and efficient approach to reduce the complexity. First, a service would be matched to spectrum class that we have classified into \( n \), and then, a spectrum hole will be assigned randomly within the class by using classified matching algorithm.

The classification of spectrum holes is necessary as a preliminary process. Then, a suitable spectrum class would be matched to a secondary user by using the information of required service time. After that, a spectrum hole will be randomly assigned to the secondary user within the chosen class. Then, \( n_k \), which is the matched class for secondary user \( k \), is given as follows.

\[
n_k = \arg \left\{ \min_n \left| \lambda_{C_n} - T_{\text{req}_k} \right| \right\} \tag{11}
\]

where \( C_n \) shows class index, \( \lambda_{C_n} \) is the average value of \( \lambda \) parameters of spectrum holes in spectrum class index \( n \), and \( T_{\text{req}_k} \) is the required service time for user \( k \).

With above equation, classified matching algorithm would assign a user a proper spectrum hole according to following process.

\[
\text{(Classified matching)}
\]

for \( k = 1 : \text{number of user} \)

for \( j = 1 : \text{number of spectrum hole} \)

for \( n = 1 : \text{number of spectrum class} \)

\[
C_n[j] = \arg \left\{ \min_j \left| \lambda_{C_n} - \lambda_j \right| \right\}
\]

end

end

for \( n = 1 : \text{number of spectrum class} \)

\[
n_k = \arg \left\{ \min_n \left| \lambda_{C_n} - T_{\text{req}_k} \right| \right\}
\]

end

\[
H_k = \text{Rand} \left( C_{n_k} \left[ j \right] \right)
\]

end

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed algorithms for spectrum management. To analyze the performance of the proposed algorithms, we assume the following situation: There are \( N \) available spectrum holes of which duration periods are different. Holding time of each spectrum hole is exponentially distributed with rate parameter \( \lambda_i \) for spectrum hole \( i \). And, the bandwidth of each spectrum hole is given as \( B_i \). Using the \( N \) spectrum holes, \( k \) services should be supported. The amount of each service traffic is described as \( M_i \), and the signal to interference and noise ratio of user \( i \) is given as \( SINR_i \). The required service time for user \( i \), \( T_{\text{req}_i} \) is obtained from equation (2). Each service will be allocated to an available spectrum hole. In the case that the primary service traffic appears in a certain spectrum hole, the secondary user who was being supported by the spectrum hole should look up another spectrum hole to keep the service connection and move to a new spectrum hole. We define this event as spectrum handover.

A. Simple Case Approach

First of all, a simple case approach is given to see the performance of optimal spectrum matching. The number of spectrum holes, \( N \), can be large in general. However, we assume \( N \) is a small number in this simple case approach. This simple case approach is enough to verify the performance of the proposed spectrum hole matching algorithm. In the general case which will be shown later, we can verify the performance by using cost optimization programming. However, in this simple case approach, we consider a case of \( N = 4 \). We assume that the following parameters are given, which are shown in Table 1.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SIMPLE CASE APPROACH PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_1 = 150 )</td>
<td>( T_{\text{req}_1} = 3 )</td>
</tr>
<tr>
<td>( \lambda_2 = 1/100 )</td>
<td>( T_{\text{req}_2} = 5 )</td>
</tr>
<tr>
<td>( \lambda_3 = 1/200 )</td>
<td>( T_{\text{req}_3} = 13 )</td>
</tr>
<tr>
<td>( \lambda_4 = 1/1000 )</td>
<td>( T_{\text{req}_4} = 30 )</td>
</tr>
</tbody>
</table>

Here, we additionally assume that all the users have static channel. Therefore, the channel quality of user is not changing drastically. This behavior can simplify the analysis to show the performance of the optimal matching for an instance. In this case, the required time to support each service depends only on \( M_i \). Let us assume that \( T_{\text{req}_i} \) is the required time for the service which is calculated by equation (2). In this situation, we can easily find the optimal spectrum hole matching. The expected holding time of a spectrum hole with parameter \( \lambda \) is expressed as \( \frac{1}{\lambda} \). Each service is matched to the spectrum hole which has the closest average holding time to the required time. And, that results in the optimal matching. We compare the performance of the optimal matching that is achieved by a proposed heuristic algorithm, cost-minimized matching with the performances of random case and worst case.

\text{(Optimal case)}\] We intuitively know that the optimal matching for 4 services is as follows: Service 1 \( \rightarrow \) Spectrum hole 1, Service 2 \( \rightarrow \) Spectrum hole 2, Service 3 \( \rightarrow \) Spectrum hole 3, and Service 4 \( \rightarrow \) Spectrum hole 4. Because, the holding time of each spectrum hole is arranged with the increasing order of the subscript(\( \frac{1}{\lambda_1} < \frac{1}{\lambda_2} < \frac{1}{\lambda_3} < \frac{1}{\lambda_4} \)) and the required time of each service is arranged with the increasing order of the subscript, too(\( T_{\text{req}_1} < T_{\text{req}_2} < T_{\text{req}_3} < T_{\text{req}_4} \)). This optimal matching is also performed by a proposed heuristic algorithm, namely cost-minimized matching. In the optimal case, the probability of providing QoS, \( p_{\text{QoS}} \), is as follows.

\[
p_{\text{QoS}} = \prod_{i=1}^{4} (1 - p_{i,i}) \tag{12}
\]

\[
= e^{-\lambda_1 T_{\text{req}_1}} e^{-\lambda_2 T_{\text{req}_2}} e^{-\lambda_3 T_{\text{req}_3}} e^{-\lambda_4 T_{\text{req}_4}}
\]

\[
= 0.7893
\]

(\text{Random case})\] Define \( p_i \) as the probability of spectrum handover of service \( i \) in the case that service \( i \) is matched to a
certain spectrum hole. We can say that \( p_i \) is the mean value of each \( p_{i,j} \), which means the probability of spectrum handover in the case that service \( i \) is matched to spectrum \( j \). With random matching algorithm, the probability that spectrum handover does not occur, \( p_{QoS}^r \), can be calculated using equation (13).

Here, \( n! \) matchings are possible in this case. Therefore, we calculate the average of all possible matchings.

\[
p_{QoS}^r = \text{avg}[\prod_{i=1}^{4} (1 - p_i^h)] \tag{13}
\]

\[
= \frac{1}{4!} \sum_{i=1}^{4} 1 - p_i^h \left( \prod_{j=1, j \neq i}^{4} (1 - p_{1,j}^h) \prod_{k=1, k \neq i, j}^{4} (1 - p_{3,k}^h) \prod_{l \neq i, j, k}^{4} (1 - p_{4,l}^h) \right) 
= \frac{1}{4!} \sum_{i=1}^{4} e^{-\lambda_i T_{req,1}} \left( \prod_{j=1, j \neq i}^{4} e^{-\lambda_j T_{req,2}} \prod_{k=1, k \neq i, j}^{4} e^{-\lambda_k T_{req,3}} \prod_{l \neq i, j, k}^{4} e^{-\lambda_l T_{req,4}} \right) 
= 0.6370
\]

(Worst case) The worst matching happens when the service with maximum required time is allocated to the spectrum hole with minimum holding time. We can intuitively know that the optimal matching for 4 services is as follows: (Service 1 \( \rightarrow \) Spectrum hole 4), (Service 2 \( \rightarrow \) Spectrum hole 3), (Service 3 \( \rightarrow \) Spectrum hole 2), and (Service 4 \( \rightarrow \) Spectrum hole 1). Because, the holding time of each spectrum hole is arranged with the increasing order of the subscript \((\frac{1}{N_1} < \frac{1}{N_2} < \frac{1}{N_3} < \frac{1}{N_4})\) and the required time of each service is arranged with the decreasing order of the subscript \((T_{req,4} > T_{req,3} > T_{req,2} > T_{req,1})\). This worst matching is the lower bound of random matching. The probability of providing QoS in the worst case, \( p_{QoS}^w \), is given as,

\[
p_{QoS}^w = \prod_{i=1}^{4} (1 - p_{i,4-i}) \tag{14}
= e^{-\lambda_1 T_{req,4}} e^{-\lambda_2 T_{req,3}} e^{-\lambda_3 T_{req,2}} e^{-\lambda_4 T_{req,1}} 
= 0.4774
\]

From the simple case approach, we can see that the proposed cost-minimized matching algorithm is very efficient in the sense of increasing the probability that can provide QoS. The probability of providing QoS is increased by 65% in this case. It means that the probability of spectrum handover is drastically reduced through the optimal matching performed by the proposed spectrum hole management algorithm. And the results of this simple case approach address how important the intelligent matching is to improve QoS of cognitive radio systems.

However, the heuristics do not always guarantee the optimal matching. \( N \) can be much larger in general case. In the case of large \( N \), it would be exceedingly complicated to find an optimal case with mathematical analysis. Therefore, we evaluate the performance of the proposed spectrum management algorithms through computer simulations and optimization for general cases.

**B. General Case Approach**

In this section, we generalize the spectrum hole matching problem, and the performances of the proposed heuristic algorithms are evaluated. Three heuristic algorithms are proposed for spectrum management. Then, we assume that there are \( N \) spectrum holes and \( k \) users to evaluate the performance in general case. Computer simulations are performed to evaluate the performance of each algorithm. From the simulations, the expected number of spectrum handover and fairness performance are evaluated for each proposed heuristic matching algorithm.

In the simulation of spectrum matching algorithms, \( \lambda \) of each spectrum hole is uniformly distributed in \([1/2000, 1/200]\), and \( T_{req} \) of each service is also uniformly distributed in \([10, 300]\). When \( N = 40 \), the expected number of handover is shown in Fig. 3.

Fig. 3 shows the expected number of spectrum handover according to the number of users. The number of users can mean traffic load. Then, we can see that random matching algorithm shows the worst performance. In light traffic load situation, greedy algorithm shows the best performance. Because the users have chance to acquire spectrum holes of good quality in case of light traffic load. However, in heavy traffic load situation, the greedy algorithm shows the worst performance among the three proposed heuristic algorithms. This is because greedy algorithm in heavy traffic load situation is almost the same as random matching algorithm. Cost-minimized matching algorithm is the best in heavy traffic load, also pretty good in light traffic load. And, even though classified matching algorithm is worse compared with cost-minimized matching algorithm, it is much better compared with random matching. All the three heuristic algorithms improve the performance in terms of decreasing the expected number of handover compared with random matching. It results in the enhanced QoS for cognitive radio systems.

We also observe the fairness of the spectrum handover probability for each user. Jain’s fairness index is used as a metric to derive the fairness performance of the proposed heuristic algorithms. Then, Fig. 4 shows the fairness performance of
the spectrum matching algorithms according to the number of users.

As shown in Fig. 4, random matching algorithm shows the worst fairness performance. And, the other proposed algorithms provide better fairness. Among them, classified matching algorithm outperforms the other matching algorithms in view of fairness. And, greedy algorithm shows worse fairness performance compared to the other proposed heuristic algorithms, and its performance would be the worst like random matching algorithm in full traffic load situation. That is because greedy algorithm becomes exactly the same as random matching algorithm in full load situation.

V. CONCLUSIONS

The simulations confirm that the proposed spectrum hole matching algorithms greatly outperform the conventional random matching algorithm with respect to expected number of handover and fairness. Consequently, the decreases of spectrum handover probability and fairness improvement of the proposed algorithms could enhance the performance of cognitive radio system.

REFERENCES