Subcarrier Allocation Algorithms Based on Graph-Coloring in Cognitive Radio NC-OFDM System

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Abstract—Cognitive Radio (CR) system can be combined with Non-Contiguous Orthogonal Frequency Division Multiplexing (NC-OFDM) technology to improve the spectrum utilization efficiency. In this paper, we introduce graph-coloring theory and max-min algorithm in multiuser OFDM system to CR NC-OFDM system for subcarrier allocation to gain the better system performance. We build a subcarrier allocation model based on graph-coloring theory. And then, considering the interference between cognitive users (CUs) and time and space difference between the available spectrums of CUs as two constraints, we propose the rand algorithm, greedy algorithm and Max-Min algorithm for subcarrier allocation in CR NC-OFDM system. The rand algorithm is simple, but can’t optimize system throughput. The greedy algorithm can gain the best throughput performance but has poor fairness performance. The Max-Min algorithm can not only achieve better throughput performance but also good user fairness.

Keywords- Cognitive Radio; NC-OFDM; graph-coloring model; subcarrier allocation

I. INTRODUCTION

With the rapid increase of the number of wireless users and the requirement for wireless communication, the available spectrum resource is becoming more and more insufficient. In recent years, Cognitive Radio (CR) has attracted wide attentions as a spectrum sharing technology, which can take effective use of spectrum resource [1-2]. CR system can appecerce wireless communication environment, change parameters in real time and adaptively, and use the spare spectrum effectively.

The frequency band, which is allocated to the licensed user (LU) but is unused in some time and places, is called a “spectrum hole” [3]. In CR system, Cognitive Users (CUs) transmit data through spectrum holes, so the available spectrum which can accessed by CUs are always noncontiguous and scattered frequency bands with different width. Because of the adaptability to noncontiguous frequency environment, Non-Contiguous Orthogonal Frequency Division Multiplexing (NC-OFDM) technology becomes a promising transmission technology for CR system [4]. NC-OFDM [5] improved traditional OFDM technology. It transmits data only on the corresponding noncontiguous subcarriers to spectrum holes and sets zero for the subcarriers used by licensed users (LUs). Thus NC-OFDM technology can not only take full use of the available frequency resource but also avoid the interference with LUs.

Resource allocation is one of the key technologies in CR system. Current research on spectrum allocation of CR system is most based on the fact that the frequency band used by each user is contiguous. Moreover the current spectrum allocation algorithms for CR system are most about channel assignment [6] and few algorithms consider the subcarrier allocation between CUs. In [4], the authors research the spectrum utilization in CR NC-OFDM system and propose a spectrum aggregation algorithm by which CR system aggregate spectrum fragments together to form available channels and maximize the number of the available channels. In [4], a greedy algorithm, which aggregates the available spectrum fragments from low spectrum region to high spectrum region, is used to allocate spectrum. The algorithm in [4] can improve the spectrum utilization efficiency, but it doesn’t consider the different available channels for different CUs and the interference between CUs, so the algorithm needs to be improved to be more adaptive to CR system.

Graph-coloring model is one of the important models for spectrum allocation in CR system, which considers the interference between CUs and time and space difference between the available spectrums of CUs. The current graph-coloring model for CR system is based on channel assignment. In this paper we introduce the graph-coloring theory to CR NC-OFDM system for subcarrier allocation and build a subcarrier allocation model based on graph-coloring. And under the interference constraints of graph-coloring model, we propose the rand algorithm, greedy algorithm and Max-Min algorithm for subcarrier allocation in CR NC-OFDM system. The Max-Min algorithm combines max-min algorithm in multiuser OFDM system.

The rest of the paper is organized as follows. We introduce the current graph-coloring model for spectrum allocation in CR system, the correlative algorithms based on graph-coloring model and max-min algorithm for subcarrier allocation in multiuser OFDM system in Section II. We describe the proposed subcarrier allocation model based on graph-coloring in CR NC-OFDM system in Section III. In Section IV, we propose three subcarrier allocation algorithms adaptive to CR NC-OFDM system. The simulation results are presented in Section V. We discuss future work and conclude in Section VI.
II. CURRENT MODEL AND ALGORITHMS

A. Graph-coloring model and the distributed greedy algorithm based on graph-coloring model [6]

Graph-coloring model is one of the important models for spectrum allocation in CR system. The spectrum allocation strategy based on graph-coloring model, which is built under the corresponding interference restraints, abstracts the CR network topology as a graph. In the graph the vertexes represent the CUs, and edges represent the interferences between vertexes so that no channels can be assigned simultaneously to any adjacent nodes. We also associate every vertex to a set of colors, which represents the available spectrum resource for the vertex. Because of the different location of the vertexes, the associated resource of the different vertexes is different.

In [6], the authors propose a List-Coloring based channel allocation algorithm for open-spectrum wireless networks, which aims to gain the most allocated channels under the definite interference constraints. The authors adopt distributed network and propose distributed greedy algorithm and distributed fair algorithm. The distributed greedy algorithm aims to maximize the channel utilization and the distributed fair algorithm considers fairness mainly. We introduce the distributed greedy algorithm into the subcarrier allocation in CR NC-OFDM system. The greedy algorithm in [6] performs that the nodes whose available channel list includes the same channel are ranked according to their link degrees from low to high and then the channel are allocated to the node with the lowest link degree. When a tie exists, the number of assigned channels of each node is used to break the tie. Nodes with less assigned channels have higher priority. If the nodes have the same number of assigned colors, ties are broken randomly. The algorithm can result in very unfair allocation. Node with lower link degrees will obtain more resource in general.

B. Max-min algorithm in multiuser OFDM system

We apply the max-min algorithm in multiuser OFDM system to CR NC-OFDM system in this paper. In research literatures related to multiuser OFDM, two classes of united optimization techniques are proposed for adaptive resource allocation, namely: 1) margin adaptive (MA); and 2) rate adaptive (RA) [7]. The objective of RA is to maximize each user’s error-free capacity with a total transmit power constraint.

Mathematically, the RA optimization problem is formulated as

\[
\max \sum_{k=1}^{K} \sum_{n=1}^{N} \frac{B}{N} \log_2 \left(1 + \frac{p_{k,n} h_{k,n}^2}{N_0 B N} \right),
\]

subject to

\[
\sum_{k=1}^{K} \sum_{n=1}^{N} p_{k,n} \leq P_{\text{total}},
\]

\[
p_{k,n} \geq 0, \forall k \in \{1,...,K\}, \forall n \in \{1,...,N\},
\]

where \(N_0\) is the power spectral density of Additive White Gaussian Noise (AWGN), \(B\) and \(P_{\text{total}}\) are the total available bandwidth and power respectively, \(p_{k,n}\) is the power allocated for user \(k\) in the subcarrier \(n\), \(h_{k,n}\) is the channel gain for user \(k\) in subcarrier \(n\), and \(p_{k,n}\) can only be either 1 or 0, indicating whether subcarrier \(n\) is used by user \(k\) or not. Equation (5) shows that each subcarrier can only be used by one user.

Based on RA optimization Rhee proposes max-min algorithm [8], which finds the optimized subcarrier and power allocation and maximizes the minimum of all users’ throughput. The algorithm is formulated as

\[
\max \min_{p_{k,n} \geq 0} \sum_{k=1}^{K} \sum_{n=1}^{N} \frac{B}{N} \log_2 \left(1 + \frac{p_{k,n} h_{k,n}^2}{N_0 B N} \right),
\]

subject to

\[
\sum_{k=1}^{K} \sum_{n=1}^{N} p_{k,n} \leq P_{\text{total}},
\]

\[
p_{k,n} \geq 0, \forall k \in \{1,...,K\}, \forall n \in \{1,...,N\},
\]

where \(S_k\) is the set of indices of subcarriers assigned to user \(k\), the other parameters’ meaning is the same with (1).

Because finding the answer of (6) is very complex, Rhee proposed a suboptimal algorithm. The algorithm allocates the subcarrier with high channel gain for every user to its best ability and chooses the user with the minimal throughput preferentially to allocate subcarrier in each iteration process. The detailed steps are as follows:

1) Allocate the equal power for every subcarrier so that every user has the similar data rate;

2) Allocate the subcarrier with the best channel performance for each user in turn;

3) Allocate a subcarrier for the user with the minimal rate every time according to the objective of maximizing the minimal rate so as to maximize the capacity.

The algorithm is used in the condition of the largest fairness, namely the proportional factor of each user rate is equal.

III. SYSTEM MODEL

We improve the current graph-coloring model based on channel allocation in CR system [6] and build a graph-coloring model based on subcarrier allocation in CR NC-OFDM network.
Fig. 1 shows the topology structure of CR NC-OFDM system. There are 4 LUs I, II, III, IV are present. And the five vertexes 1-5 represent five different CUs. In addition, there are 12 subcarriers available to CR system, named A1, A2, A3, A4, B1, B2, B3, B4, C1, C2, C3, C4, which are used by LUs I-IV. For instance, LU I uses subcarrier A1, A2, A3, A4 and LU II and IV use subcarrier B1, B2, B3, B4 simultaneously because they are far from each other.

For interference avoidance, subcarriers used by CUs cannot be utilized by LUs in vicinity. Therefore, we assume that the CUs within certain interference ranges of the LUs I-IV cannot reuse the same subcarriers. In the Fig.1, the interference range of a LU is illustrated by dashed circle. The CUs within the circle cannot use the subcarriers used by the LU. For instance, Node 2 is within the interference range of LU II, who uses subcarrier B1, B2, B3, B4. Therefore, subcarriers B1, B2, B3, B4 are not available for Node 2. Also for node 3, it is within the circles of LU I and II at the same time, so the available subcarriers are only C1, C2, C3, C4. In addition, due to the interference between CUs, if two CUs are near from each other they cannot use the same subcarriers simultaneously. Therefore in Fig.1 the CUs sharing subcarrier B1, B2, B3, B4 is allocated to user m when there exists a m-colored edge between them. Different subcarriers become different colors in the graph and L represents the set of available colors for every node, which is obtained according to the working status, allocation and the power coverage of LUs.

IV. PROPOSED SUBCARRIER ALLOCATION ALGORITHMS FOR CR NC-OFDM SYSTEM

We propose the rand algorithm, greedy algorithm and Max-Min algorithm based on graph-coloring for subcarrier allocation in CR NC-OFDM system. The rand algorithm, which is simple, makes rand subcarrier allocation under CR constraints and thus can’t optimize the throughput performance. The objective of the greedy algorithm and Max-Min algorithm is to maximize the system throughput. We formulate the optimization objective of maximizing CR NC-OFDM system capacity as follow

\[
\max \sum_{n=1}^{N} \sum_{m=1}^{M} x_{n,m} \frac{B}{N_{tot}} \log_2 \left( 1 + \frac{P_{n,m} h_{n,m}^2}{N_0 B} \right),
\]

where B represents bandwidth of CR NC-OFDM system, \( N_{tot} \) presents the total subcarrier number of the CR NC-OFDM system, \( p_{n,m} \) represents the transmit power of user n in subcarrier m, \( h_{n,m} \) represents the channel gain of the subcarrier m for the user n, \( x_{n,m} \) is the element of the subcarrier allocation matrix, and \( N_0 \) is the power spectral density of AWGN.

We suppose that every user demands the same data rate requirement, so we take the average power allocation strategy. Assume that the total power of CUs is \( P_{tot} \), thus the power of each subcarrier is \( p = \frac{P_{tot}}{M} \), where M represents the number of the subcarriers used by CUs.

Suppose a CR NC-OFDM network with N CUs sharing M spare subcarriers. We describe the subcarrier allocation model by the following matrices:

- **Subcarrier availability** \( L = \{ l_{n,m} \mid l_{n,m} \in \{0,1\} \} \), which represents the subcarrier availability, and where n is the user index (from 1 to N), and m is the subcarrier index (from 1 to M). The element \( l_{n,m} = 1 \) means that subcarrier m is available to user n and \( l_{n,m} = 0 \) means not.

- **Subcarrier allocation** \( X = \{ x_{n,m} \mid x_{n,m} \in \{0,1\} \} \), which represents the assignment. The element \( x_{n,m} = 1 \) if subcarrier m is allocated to user n. The subcarrier allocation matrix must satisfy some interference constraints:

\[
x_{n,m} \cdot x_{k,m} = 0 \text{ if } c_{n,k,m} = 1, \forall n, k \leq N, m \leq M
\]
To simplify the description, define \( H_{n,m} = \frac{K_{n,m}^2}{B N_0} \) representing the signal noise ratio gain of the user \( n \) in the subcarrier \( m \).

The expression (11) can be simplified as
\[
\max_{x_{n,m}} \sum_{n=1}^{N} \sum_{m=1}^{M} x_{n,m} \frac{B}{N_{tot}} \log_2(1 + pH_{n,m}) .
\] (12)

User rate \( R_n \) is defined as:
\[
R_n = \sum_{m=1}^{M} x_{n,m} \frac{B}{N_{tot}} \log_2(1 + pH_{n,m}) .
\] (13)

A. Rand Algorithm

The rand algorithm allocates the subcarriers to the users randomly, the interference between CUs and the different available spectrum for different CUs being considered as two constraints. The algorithm allocates subcarrier for each node from the available subcarrier list in turn. After subcarrier \( m \) is allocated to node \( n \), the system updates the allocation matrix \( X \) and checks the neighborhood nodes of node \( n \). If the node \( n \) and \( k \) would interfere with each other when they use subcarrier \( m \) simultaneously, the system sets subcarrier \( m \) unavailable for node \( k \) in the available subcarrier matrix \( L \). The system allocates subcarriers for nodes circularly following the preceding steps until all the subcarriers are allocated. The detailed steps are described in TABLE I.

<table>
<thead>
<tr>
<th>TABLE I. RAND ALGORITHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1. initialize the system parameters: user rate</td>
</tr>
<tr>
<td>( R_n = 0(n \in {1,2,...,N}) ), ( x_{n,m} = 0 ), ( p = \frac{P_{int}}{M} ).</td>
</tr>
<tr>
<td>Step 2. allocate subcarrier for each user in turn:</td>
</tr>
<tr>
<td>for ( n = 1,2,...,N )</td>
</tr>
<tr>
<td>if the available subcarrier list of user ( n ) is not empty</td>
</tr>
<tr>
<td>then</td>
</tr>
<tr>
<td>allocate subcarrier ( m ) to user ( n ) from the available subcarrier list randomly;</td>
</tr>
<tr>
<td>update the allocation matrix ( X ): ( x_{n,m} = 1 );</td>
</tr>
<tr>
<td>set subcarrier ( m ) unavailable for user ( n ) to avoid repeated allocation in the next turn: ( l_{n,m} = 0 );</td>
</tr>
<tr>
<td>update the user rate: ( R_n = R_n + \frac{B}{N_{tot}} \log_2(1 + pH_{n,m}) );</td>
</tr>
<tr>
<td>if ( c_{n,k,m} = 1 ) then</td>
</tr>
<tr>
<td>set subcarrier ( m ) unavailable for user ( k ): ( l_{k,m} = 0 );</td>
</tr>
<tr>
<td>end if</td>
</tr>
<tr>
<td>end if</td>
</tr>
<tr>
<td>end for</td>
</tr>
<tr>
<td>Step 3. allocate subcarriers for nodes circularly according to step 2 until all the subcarriers are allocated.</td>
</tr>
</tbody>
</table>

B. Greedy Algorithm

The greedy algorithm for CR NC-OFDM system is proposed according to the current distributed greedy algorithm based on graph-coloring model of CR system [6]. The algorithm allocates every subcarrier in turn. The algorithm ranks the nodes whose available list include the same subcarrier according to their link degrees from low to high and then allocate the subcarrier to the node with the lowest link. When a tie exists, the number of assigned subcarriers of each node is used to break the tie. Nodes with less assigned subcarriers have higher priority. If the nodes have the same number of assigned colors, ties are broken randomly. After subcarrier \( m \) is allocated to node \( n \), the system updates the allocation matrix \( X \) and checks the interference matrix \( C \). If user \( n \) and \( k \) can’t use subcarrier \( m \) simultaneously, the system sets the subcarrier \( m \) unavailable for the node \( k \) in the available subcarrier matrix \( L \).

The detailed steps are described in TABLE II.

<table>
<thead>
<tr>
<th>TABLE II. GREEDY ALGORITHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1. initialize the system parameters: user rate</td>
</tr>
<tr>
<td>( R_n = 0(n \in {1,2,...,N}) ), ( x_{n,m} = 0 ), ( p = \frac{P_{int}}{M} ).</td>
</tr>
<tr>
<td>Step 2. allocate each subcarrier in turn:</td>
</tr>
<tr>
<td>for ( m = 1,2,...,M )</td>
</tr>
<tr>
<td>if the available subcarrier list include subcarrier ( m ) then</td>
</tr>
<tr>
<td>rank the nodes whose available list include subcarrier ( m ) according to their link degrees from low to high;</td>
</tr>
<tr>
<td>if a tie (the same lowest link degrees) exists then</td>
</tr>
<tr>
<td>if the nodes have the same number of assigned subcarriers then</td>
</tr>
<tr>
<td>choose node ( n ) randomly;</td>
</tr>
<tr>
<td>else</td>
</tr>
<tr>
<td>choose node ( n ) with the least assigned subcarriers;</td>
</tr>
<tr>
<td>end if</td>
</tr>
<tr>
<td>else</td>
</tr>
<tr>
<td>choose node ( n ) with the lowest link degrees;</td>
</tr>
<tr>
<td>end if</td>
</tr>
<tr>
<td>update the allocation matrix ( X ): ( x_{n,m} = 1 );</td>
</tr>
<tr>
<td>set subcarrier ( m ) unavailable for user ( n ) to avoid repeated allocation in the next turn: ( l_{n,m} = 0 );</td>
</tr>
<tr>
<td>update user rate: ( R_n = R_n + \frac{B}{N_{tot}} \log_2(1 + pH_{n,m}) );</td>
</tr>
<tr>
<td>if ( c_{n,k,m} = 1 ) then</td>
</tr>
<tr>
<td>set subcarrier ( m ) unavailable for user ( k ): ( l_{k,m} = 0 );</td>
</tr>
<tr>
<td>end if</td>
</tr>
<tr>
<td>end if</td>
</tr>
<tr>
<td>end for</td>
</tr>
</tbody>
</table>
C. Max-Min Algorithm

We apply the suboptimal algorithm of max-min algorithm proposed by Rhee [8] to CR NC-OFDM system and with the combination of the constraints in graph-coloring model we propose a subcarrier allocation algorithm adaptive to CR NC-OFDM system, which is named Max-Min algorithm in this paper.

The optimization objective of the proposed Max-Min algorithm is to maximize the minimum of all users’ throughput, which is formulated mathematically as:

$$\max \min_{n} \sum_{m \in S_n} \frac{B}{N_{w}} \log_2 (1 + pH_{n,m}),$$  \hspace{1cm} (14)

where $S_n$ is the set of indices of subcarriers assigned to user $n$, the other parameters’ meaning is the same with (12).

The Max-Min algorithm allocates a subcarrier with the largest channel gain in the available subcarrier list for each CU first. And then for each time the algorithm chooses the user with minimal transmit rate to allocate the subcarrier with the largest channel gain in the available list until all the subcarriers are allocated. The algorithm guarantees the fairness of the users.

The detailed steps are described in TABLE III.

TABLE III. MAX-MIN ALGORITHM

| Step 1. initialize the system parameters: user rate $R_n = 0 \left( n \in \{1,2,\ldots,N\} \right)$, $x_{n,m} = 0$, $p = \frac{P_w}{M}$.

Step 2. allocate a subcarrier for each user in turn:

for $n = 1,2,\ldots,N$

if the available subcarrier list for user $n$ is not empty

choose subcarrier $m$ in the available subcarrier list of user $n$, $m = \arg \max_{m \in \left[1,2,\ldots,M\right]} h_{n,m}$;

update allocation matrix $X$: $x_{n,m} = 1$;

set subcarrier $m$ unavailable for user $n$: $l_{n,m} = 0$;

update user rate: $R_n = R_n + \frac{B}{N_{tot}} \log_2 (1 + pH_{n,m})$;

if $c_{n,k,m} = 1$ then

set subcarrier $m$ unavailable for user $k$: $l_{k,m} = 0$;

end if

end if

end for

Step 3. allocate the residual subcarriers:

while there are residual subcarriers to allocate

choose user $n$ in the users whose available subcarrier list is not empty, $n = \arg \min_{n \in \left[1,2,\ldots,N\right]} R_n$;

choose subcarrier $m$ in the available subcarrier list of user $n$, $m = \arg \max_{m \in \left[1,2,\ldots,M\right]} h_{n,m}$;

update allocation matrix $X$: $x_{n,m} = 1$;

set subcarrier $m$ unavailable for user $n$: $l_{n,m} = 0$;

update user rate: $R_n = R_n + \frac{B}{N_{tot}} \log_2 (1 + pH_{n,m})$;

if $c_{n,k,m} = 1$ then

set subcarrier $m$ unavailable for user $k$: $l_{k,m} = 0$;

end if

end while

V. SIMULATION RESULT

We simulate the proposed algorithms to compare the performance of the algorithms. We build the CR simulation platform based on CR NC-OFDM system by MATLAB. The configuration simulation environment parameters are as follows: the bandwidth of CR system is 4MHz, the system is divided to 256 subcarriers, the transmit power of each subcarrier is 1/64 W and the power spectral density of AWGN is -80dBW/Hz. We choose 6 paths irrelevant Rayleigh fading channel and suppose the channel power fades exponentially with $e^{-l}$, where $l$ represents the sequence number of the multipath. The maximal Doppler shift is 30 Hz. Suppose the channel estimation is perfect. The other simulation parameter configure is as follows:

TABLE IV. PARAMETER CONFIGURATION

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>User number $N$</td>
<td>Choose 4, 8, 12, 16, 20 respectively</td>
</tr>
<tr>
<td>Available subcarrier number $M$</td>
<td>Choose 16, 32, 48, 64, 80 respectively</td>
</tr>
<tr>
<td>Interference matrix $C$</td>
<td>Create 0,1 binary symmetrical matrix randomly</td>
</tr>
<tr>
<td>Available subcarrier matrix $L$</td>
<td>Create 0,1 binary matrix randomly</td>
</tr>
</tbody>
</table>

In Fig.2, we show the throughput performance of the greedy algorithm, Max-Min algorithm and rand algorithm with the different user number. The greedy algorithm has the best performance and the Max-Min algorithm has the better performance than the rand algorithm. Fig.3 shows the fairness performance of the three algorithms with 12 users. For greedy algorithm, the CUs rate fluctuates much. Some users’ rate gains over 6kbps, but some users’ rate can’t reach 1kbps. For the Max-Min algorithm and rand algorithm, the CUs rate fluctuates less and the users have average transmit rate comparatively. From Fig.2 and Fig.3 we can see that, because the greedy algorithm chooses the user with the minimal link degrees to allocate subcarrier each time, the subcarriers can be used by users simultaneously as many as possible, and as a result, the system obtains higher capacity. But the users with high degrees can only obtain little spectrum resource so the algorithm results in large unfairness. The Max-Min algorithm allocates subcarrier for the user with the minimal rate preferentially every time and chooses the subcarrier with the largest channel gain so the
system obtains good throughput and fairness performance at the same time.

![Figure 2](image1.png)

**Figure 2.** Throughput performance comparison of three algorithms

![Figure 3](image2.png)

**Figure 3.** Fairness performance comparison of three algorithms

VI. CONCLUSION

Applying NC-OFDM technology to CR system can improve the spectrum utility and avoid the interference to LUs. The effective subcarrier allocation between users is a key problem. We introduce graph-coloring theory to the subcarrier allocation of CR NC-OFDM system and build the subcarrier allocation model based on graph-coloring model. With the two constraints of interference between CUs and time and space difference between the available spectrums of CUs, we propose the rand algorithm, greedy algorithm and Max-Min algorithm for subcarrier allocation in CR NC-OFDM system, the two later algorithms of which are based on the objective of maximizing system throughput. From the simulation we can see, the greedy algorithm obtains the best throughput gain with the sacrifice of user fairness, and the Max-Min algorithm has less throughput gain than the greedy algorithm but obtains good fairness. In this paper we take the average allocation for the subcarrier power on the premise of the same rate requirement for all users. Therefore, the future work can research the united subcarrier and power allocation based on the user proportional rate constraints. In addition the throughput gain of the proposed Max-Min algorithm is not very obvious, so the future work can consider the influence of the node link degrees in the algorithm so as to improve throughput performance. Moreover we don’t consider the dynamic change of spectrum in this paper, so researching the subcarrier allocation of CR system with the rapid changing network topology is another part of the future work.

REFERENCES


