Efficient Channel Assignment Under Dynamic Source Routing in Cognitive Radio Networks

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***Abstract*—The channel assignment problem is one of the most important issues in cognitive radio networks (CRNs). Under a SINR-driven model, we consider channel assignments in a network using dynamic source routing (DSR). In this unicasting model, channel assignments are conducted in a relatively small scale of nodes, which are on the chosen route. In addition, we can make use of the route reply (RREP) message in DSR to estimate the SINR and the maximum data transmission rate of nodes on the chosen route. In this way, the source node can conduct the channel assignment in a more efficient way. We propose two algorithms for the single route and multi-route channel assignments, where the multi-route scheme uses alternative nodes to help transmitting. We give a complexity analysis of two algorithms and an extension of reducing complexity for the multi-route channel assignment algorithm. Finally, we conduct simulations of our two algorithms under networks with different densities and show that the performance of our algorithms is efficient.**

***Index Terms*—channel assignment, cognitive radio networks, dynamic source routing, piggyback, SINR estimation.**

I. Introduction

It is well-known that the current static allocation of channels in wireless networks is inefficient. The measurement by the FCC in the U.S. shows that 70% of the allocated channels is not utilized. The growing need of novel applications for channels requires a better channel allocation scheme. Fortunately, the cognitive radio technology makes it feasible to utilize channels more efficiently in an opportunistic way. The cognitive radio nodes in a network can sense the available spectrums and make use of them dynamically. To realize *cognitive radio networks* (CRNs), one of the most challenging problems [1] is assigning available channels so that certain optimization objectives can be achieved.

There are two types of users in CRNs: *primary users* and *secondary users*. We refer to nodes as secondary users in our paper. Channel assignment problems are about assigning channels among secondary users without disturbing primary users. Many works have been done regarding channel assignment [2], [3], [4] recently. The traditional approaches towards the channel assignment problem for large networks focus on using auction theory, game theory or graph theory to assign channels [5], [6]. These works usually use a simplified SINR model, construct a conflict graph or assign channels among nodes according to different utility objectives. In this way, they can avoid the interference both among primary users and secondary users. These works usually simplify the interference constraints and do not take accumulative interference into consideration. [7] is an exception in that it takes accumulative interference into consideration. However, our paper is different because we assign channels under *dynamic source routing* (DSR) [8]. We not only consider accumulative interference, but also build a probabilistic estimation about the SINR.

Among previous works done on combining routing and channel assignment, [9], [10], [11] are about assigning channels among nodes with multiple network interface cards. They do not consider cognitive radio networks and have their own routing scheme. Their approaches have no prediction about nodes' actions and are fixed in the channel assignment process to some extent.

In this paper, we consider a scenario where a network is using DSR. We adopt a SINR-based physical model in our problem. The previous channel assignment methodologies may still be applied, but with less efficiency. This is because routes in the network are dynamic and the set of nodes that needs to be assigned channels varies at different times. In addition, there are mainly two phases in DSR: route detection and route maintenance. We can make use of these phases to gather information about nodes along the route and achieve a more efficient channel assignment scheme.

We first propose a channel assignment approach under a single route model. We use the route reply message (RREP) sent back by the destination node to gather the estimated preference of each node to different channels. The source node can estimate the SINR of each node on a certain channel along the route based on predicting their choices among channels. We give the correctness and complexity analysis of our algorithm. Then, we extend to a multi-route model based on the formation of a multistage graph. We use a locking/unlocking scheme to assign channels for nodes on a multi-route. Then, we give the complexity analysis and an extended approach to keep the complexity low. The main contributions of our paper lie in the following four aspects:

- We make use of *piggyback* information in the RREP packet, define the probability of each node choosing a certain channel and use a realistic physical model to estimate the SINR.
- We prove that the single route channel assignment problem under our model is NP-hard and give the complexity analysis of our proposed approach.
- We extend to solve a multi-route channel assignment

by converting it to the single route channel assignment problem. We apply a locking/unlocking scheme.

- We propose an extension to reduce the complexity of multi-route channel assignment and give an upperbound.

The rest of our paper is organized as follows: In Section II, we introduce related works. In Section III, we give the preliminaries about our paper: the SINR related and multi-stage graph. We define our problem in Section IV. Section V introduces the channel assignment algorithm based on a single route scheme and gives the complexity analysis. Section VI is about the multi-route channel assignment scheme, and complexity analysis. We discuss extensions of our model in Section VII. In Section VIII, we show the simulation results of our algorithms. Finally, in Section IX, we conclude our paper.

II. Related Works

We organize the related work into three categories. The first category is the physical model in cognitive radio networks. The second category is about existing channel assignment approaches combined with a routing algorithm. The last category is related to the proactive route maintenance.

Work by [12] analyzes the throughput capacity of a wireless network in the physical driven model and also achieves an approximation factor. A feasible scheduling approach under a physical driven model for throughput improvement in wireless mesh networks is adopted in [13]. [14] models the accumulative interference and investigates the relationship between the network density and the sensing requirements to meet an interference constraint. A physical driven model which takes the accumulative interference into consideration, is proposed in [7]. Our model differs from previous research because we estimate the SINR based on the probability of a node choosing a channel.

Some works have been done on channel assignment with routing together. [9] develops a centralized channel assignment scheme and bandwidth allocation combined with routing algorithms for multi-channel wireless mesh networks. Each node in their model is equipped with multiple network interface cards. [11] presents a routing and channel assignment protocol for multi-channel multi-hop wireless networks. It balances channels by having each node select channels based on its load information. In [10], the authors propose a distributed channel assignment and routing scheme in multi-channel multi-hop wireless networks. The channel cost metric (CCM) is introduced, which reflects the interference cost and is defined as the sum of expected transmission time. Our approach is different and we utilize the piggyback information in dynamic source routing and make the prediction about each node's choice. We mainly focus on the channel assignment phase.

There are also many works done to extend DSR. Dai and Wu in [15] make use of communication locality and propose a new routing scheme, called *proactive route maintenance*. Routing information is disseminated along active routes and advertised by active nodes on the routes. Alternative paths are dynamically discovered and maintained by active nodes and their one-hop neighbors. In this way, they achieve the high delivery ratio, low latency and fair load distribution.

III. Preliminaries

In this section, we introduce two preliminaries. One is the SINR model related and another is about the multistage graph.

A. SINR Model

For a node n working on a certain channel m, the value of $SINR_{n,m}$ in n's operation area generally follows the following expression:

$$SINR_{n,m} = \frac{S_n}{\sum_{j \neq n} a_{m,j} I_{j,n} + N_0},$$

where S_n is the minimum received signal strength in n_i's coverage area; $a_{m,j}$ equals 1 when j is using m and 0 otherwise; $I_{j,n}$ is the maximum interference strength a node j can produce to any receiver in n's coverage area; N_0 is the noise level.

More precisely, $S_n = P_n/Q_{n,n}$, where P_n denotes n's transmission power, and $Q_{n,n}$ denotes the maximum pathloss from transmitter n to any position in its operation area. $I_{j,n} = P_j/Q_{j,n}$, where $Q_{j,n}$ denotes the smallest pathloss from j to any position in n's operation area.

The maximum achievable data transmission rate R of a given channel can then be computed based on the given $SINR$ using Shannon's capacity theorem:

$$R = W \log_2(1 + SINR),$$

where W is the carrier bandwidth.

We use the above two expressions in the following sections to estimate the SINR and choose channels based on the data transmission rate.

B. Multistage Graph

A multistage graph is a graph $G = (V, E)$:

- V is partitioned into $K \geq 2$ disjoint subsets $\{V_1, V_2, ..., V_K\}$;
- If (a, b) is in E, there exists an i such that either both a and b in V_i or a is in V_i and b is in V_{i+1};
- $|V_1| = |V_K| = 1$. The vertex s in V_1 is called the source; the vertex t in V_K is called the sink.

A subset in the multistage graph is called a stage. Fig. 1 is a simple example where node n_i is a stage. A more complex example is shown in Fig. 3. $\{n_i, a_1^i, a_2^i\}$ is a stage.

IV. Problem Formulation

In this section, we define the problem scenario and assumptions of our model. We briefly describe our model and also give the constraints and objective.

We consider a CRN using DSR under the SINR-driven interference model. Each node in the network has a operation area and it must be heard by any point in its operation area. There are two major phases during routing: route discovery and route maintenance. A route reply would only be generated if the message has reached the destination node. Each node in the network is a cognitive radio node and has the ability to choose its own channel.

Each node in our network has its own operation range and it uses a certain amount of transmission power to transmit to nodes in its operation area through one channel.The SINR of any node within a certain node's transmission range should be greater than the SINR threshold. Also, we assume that there is a common channel in the CRN. The source node broadcasts a route request message through the common channel. All of the other nodes also send the probing message on the common channel until the destination node is reached. The destination node would send the route reply message. We use $M = 1, 2, ...$ to denote the set of available channels and $N = 1, 2, ...$ to denote the set of nodes on the chosen route. Some nodes cannot use the same channel due to interference. We denote a single node with $n_i \in N$ and a channel $m_i \in M$. After the source node receives the route reply, it would assign $|M|$ channels among $|N|$ nodes on the chosen route. Each node would be assigned to a channel used for transmitting. After performing the channel assignment, the source node would know the throughput of this route. Our approach is a two-stage, best-effort scheme. First, find the best route, in terms of hop counts, to the destination without considering channel conditions and rates. Then, optimally select channels based on rates of the selected path. Clearly, these two stages do not constitute a global optimization, but they represent a good heuristic as is confirmed through our simulation.

In our model, there are several constraints:

- For each node n using channel m along the route, to make sure it can transmit successfully to any node in its operation area, the SINR of any point in its operation range should be above a threshold, $SINR_{n,m} > \beta$.
- For each node, the transmission rate coming in should equal the transmission rate going out, $f^{in}_{n,m'} = f_{n,m}$.
- For each node, the transmission data rate $f_{n,m}$ cannot exceed the maximal transmission rate $c_{n,m}$ on its assigned channel, $f_{n,m} \leq c_{n,m}$.

Under the constraints, our objective is to maximize the throughput of the selected route. The source node would compute the best channel assignment result based on the information brought back by the route reply.

V. Single Route Channel Assignment Model

In this section, we propose a single route channel allocation algorithm under DSR. We would first analyze the hardness of this problem. Then, we would describe two main parts of our algorithm. Finally, we would give correctness and performance analysis.

A. Hardness Analysis

We now analyze the hardness of single route channel assignment problem under different SINR models.

1) Simple SINR Model: Given a chosen route, if we do not consider accumulative interference, each node would make its own choice independently. Let f denote the final throughput and c_{n_i,m_i} denote the maximal transmission rate of node n_i assigned with channel m_i. The problem can be formulated as follows:

$$\text{maximize } f_{s,m_0},$$
$$\text{subject to: } f_{n_i,m_i} \leq c_{n_i,m_i}$$
$$\forall n_i \in N, f^{in}_{n_i,m_{i-1}} = f_{n_i,m_i}$$
$$SINR_{n_i,m_i} = \frac{S_{n_i}}{I_0 + N_0} > \beta,$$

where I_0 is the interference caused by other nodes, not on the chosen route, working on the same channel with n_i. I_0 is a constant for a given time. f_{s,m_0} is the transmission rate of source node s on channel m_0, c_{n_i,m_i} is the maximal transmission rate of node n_i on channel m_i, $f^{in}_{n_i,m_{i-1}}$ is the transmission rate coming into n_i and f_{n_i,m_i} is the output transmission rate. Given $SINR_{n_i,m_i}$, $c_{n_i,m_i} = W \log_2(1 + SINR_{n_i,m_i})$. This becomes a linear programming problem and can be solved in polynomial time [16].

2) Complex SINR Model: We now consider the accumulative interference under the SINR model. To a certain node n_i on the chosen route, the interference caused by other nodes working on the same channel would be taken into consideration. Now the problem can be defined as:

$$\text{maximize } f_{s,m_0},$$
$$\text{subject to: } f_{n_i,m_i} \leq c_{n_i,m_i}$$
$$\forall n_i \in N, f^{in}_{n_i,m_{i-1}} = f_{n_i,m_i}$$
$$SINR_{n_i,m_i} = \frac{S_{n_i}}{\sum_{j \neq i} a_{m_i,n_j} I_{n_j,n_i} + I_0 + N_0} > \beta,$$

where a_{m_i,n_j} equals 1 when n_i is using m_i, $\forall n_j \in \{\text{nodes on the chosen route}\}$. Otherwise, it equals 0. Therefore, it considers the choices of nodes on the chosen route.

Theorem 1. *The single channel assignment problem under the complex SINR model is NP-hard.*

Proof. Given $SINR_{n_i,m_i} > \beta$, we have:

$$\frac{S_{n_i}}{\sum_{j \neq i} a_{m_i,n_j} I_{n_j,n_i} + N_0} > \beta$$
$$\sum_{j \neq i} a_{m_i,n_j} I_{n_j,n_i} < \frac{S_{n_i}}{\beta} - N_0.$$

Now we can use the reduction from the known NP-hard problem. The General Precedence Constrained SM-RCPSP in [17] is NP-hard and can be reducted here. The S_i in SM-RCPSP can be represented by the maximal interference among i nodes that are currently assigned channels. Then, the $l_{i,j}$ in

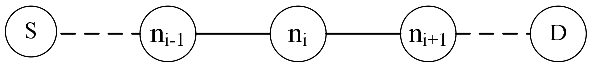

Fig. 1. An example of single route.

SM-RCPSP is the increased interference caused by $j-i$ new assigned nodes. ■

In the next part, we make use of the characteristics of DSR and propose an efficient approach.

B. Single Route Channel Assignment Algorithm

There are two main phases in DSR: route discovery and route maintenance. During the route maintenance phase, the destination node would send back a route reply message. Each node on the chosen route can *piggyback* some information to that message. Therefore, the source node can make use of the piggybacked information and assign channels for each node on the route. In general, there are mainly three phases in our approach:

- The source node sends the route request (RREQ) packet through the common channel. After the destination node receives RREQ, it chooses one single route.
- The destination node sends back a route reply (RREP) packet. Each node on the path would piggyback its own estimated preference of each channel to the RREP and forward it to the next-hop node, which is nearer to the source node, on the chosen route through the common channel.
- The source node receives the RREP, including each node's information on the route. It estimates the SINR of each node and calculates the transmission rate based on the estimated SINR. It assigns a channel to each node. The source node distributes the channel assignment result through the common channel.

For example, in Fig. 1, after destination node D chooses one route, it would send back a RREP along this route. Node n_i would piggyback its preference of each channel and forward to node n_{i-1}. Next, we introduce our approach from two aspects:

- Piggyback: the detailed information of each node piggybacked by RREP;
- Assignment: the channel assignment method after the source node receives the piggybacked information.

1) Piggyback: the piggybacked information is about each node's preference to channels. Definition 1 defines the estimated preference of each node to a certain channel. We denote such preference through a probabilistic way.

Definition 1. *The preference of node n_i on channel m_i is the probability of n_i choosing m_i as its preferred channel to transmit, denoted by p_{n_i,m_i}:*

$$p_{n_i,m_i} = \frac{W \log_2(1 + SINR^0_{n_i,m_i})}{\sum_{j=1}^{M} W \log_2(1 + SINR^0_{n_i,m_j})},$$

where:

$$SINR^0_{n_i,m_j} = \frac{S_{n_i}}{\sum_{n_k \notin N} a_{m_j,n_k} I_{n_k,n_i} + N_0}.$$

$SINR^0_{n,m}$ is the current minimum SINR in node n's operation area using channel m. The interference is caused by other nodes, $\{n_k\}$, in the network besides nodes on the chosen route. Thus, $W\log_2(1 + SINR^0_{n,m})$ is the minimum transmission rate in n's operation area using m. Here, if a channel's availability dynamically changes or a primary user suddenly appears, the SINR of that channel would become 0. This would result in the preference of that channel turning into 0. Therefore, the node would not choose a channel suddenly occupied by a primary user. Besides, we can easily prove that:

$$\sum_{\forall m_i \in M} p_{n_i,m_i} = 1.$$

For example, in Fig. 1, after node n_i receives the RREP, it would first add its preference of M channels, $p_{n_i,m_i}, \forall m_i \in M$, to the RREP and then forward to node n_{i-1}.

2) Assignment: after the source node receives the RREP, it would assign channels to each node on the route starting from the source node. First, it divides each node into M virtual nodes. Each virtual node occupies a channel. For example, node n_i is divided into $n_i^1, n_i^2, ..., n_i^M$. Virtual node $n_i^{m_i}$ denotes that n_i occupies channel m_i. Then, the channel assignment on this single route becomes Fig. 2. There is no vertical link between virtual nodes of a same node. Definition 2 gives the conditions to form horizontal links.

Definition 2. *If nodes n_{i-1} and n_i are adjacent nodes along the route and n_i is the next hop of n_{i-1}, the horizontal link $(n_i^{m_i}, n_{i-1}^{m_{i-1}}), \forall m_i, m_{i-1} \in M$ only exists if the estimated SINR at any position in the operation area of nodes n_i is above the threshold β. The estimated $SINR_{n_i,m_i}$ is computed as:*

$$\frac{S_{n_i}}{\sum_{j=1}^{i-1} p'_{n_j,m_i} I_{n_j,n_i} + \sum_{k=i+1}^{N} p_{n_k,m_i} I_{n_k,n_i} + I_0 + N_0},$$

where:

$$p'_{n_j,m_i} = \begin{cases} 0 & m_i \in M' \\ \frac{W\log_2(1+SINR_{n_j,m_i})}{\sum_{k=1,k\notin M'}^{M} W\log_2(1+SINR_{n_j,m_k})} & m_i \notin M' \end{cases};$$

M' is the set of channels that $SINR_{n_j,m'_k} \le \beta, \forall m'_k \in M'$.

I_{n_j,n_i} is the maximum interference strength a node n_j can produce to any receiver in n_i's coverage area. S_{n_i} is the minimum received signal strength across n_i's coverage area. I_0 is the interference caused by other nodes in the network besides nodes on the chosen route. N_0 is the noise level. Nodes $n_j, j \in [1, i-1]$ are the previous hops of node n_i along the route. Nodes $n_k, k \in [i+1, N]$ are the following hops of node n_i. p_{n_k,m_i} is the information of node k's probability of choosing channel m_i, brought by the RREP. p'_{n_j,m_i} is the modified probability of node n_j choosing m_i. This is

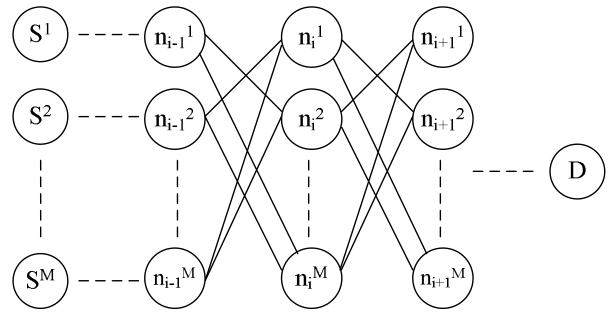

Fig. 2. Virtual nodes of single route.

because after the piggyback phase, the previous nodes have made initial choices about preferred channels based on their estimation and excluded some previous horizontal links. So the p'_{n_j,m_i} is the reevaluated probability for each node on a certain channel based on $SINR_{n_j,m_i}$ instead of $SINR^0_{n_j,m_i}$. It is more precise than the previous estimated value p_{n_j,m_i}.

According to Definition 2, the source node forms the links among virtual nodes under the first constraint stated in Section IV. It would then compute the route based on the transmission rate on each channel. The expression of the computing transmission rate is $W \log_2(1+SINR)$, as is stated in Section III.

When assigning channel m_i to a node n_i, previous nodes of n_i have been assigned channels. We use two metrics for channel assignment. One is the maximal interference that the current node can cause to the previous node on a channel. The maximal interference caused by current node n_i depends on the distance. Therefore, we save the location information of the node assigned channel m_i, which is the nearest to n_i. Another is the extra maximal allowable interference of previous nodes on a certain channel. The extra maximal allowable interference of node n_j, which is among the previous nodes of n_i on the chosen route and also working on m_i, T_{n_j,n_i,m_i}, is computed based on Definition 2 as:

$$\frac{S_{n_j}}{\beta} - \sum_{l=1}^{i} a_{n_l,m_i} I_{n_l,n_j} - \sum_{k=i+1}^{N} p_{n_k,m_i} I_{n_k,n_i} - I_0 - N_0$$

The channel assignment process is shown in Algorithm 1. Array $L[m_i]$ keeps the nearest node assigned $m_i, \forall m_i \in M$. Array $T[m_i]$ saves the maximal allowable interference of previous nodes on $m_i, \forall m_i \in M$. After a node is assigned one channel, both the arrays of L and T would be updated. The virtual links are formed and there is only one virtual node linked to the next-hop node. For example, if $n_i^{m_i}$ has a link to the next hop, then n_i is assigned channel m_i.

For example, when assigning channels to n_i in Fig. 1, n_i maintains a set of channels. Its estimated SINR is larger than the threshold β. It would start from the channel with the maximal transmission rate, which can be computed through the SINR. Then, n_i would compute its maximal possible

Algorithm 1 Channel Assignment of Single Route

node n_i = source S, n_{i+1} = next hop of n_i
$T[m_i]$: an array of size $|M|$, each element is the maximal allowable interference on m_i
$L[m_i]$: an array of size $|M|$, each element is the nearest node to next hop on channel m_i
while $n_{i+1} \neq$ destination D **do**
  while n_i is not assigned any channel **do**
    m_i = the channel with highest transmission rate
    if $I_{n_i,L[m_i]} < T[m_i]$ **then**
      assign m_i to n_i
  if $n_i \neq S$ **then**
    n_{i-1} = n_i's previous hop
  $n_{i-1} = n_i$,$n_i = n_{i+1}$, n_{i+1} = nexthop of n_i
  Update $T[m_i]$ with minimal $T_{n_j,n_i,m_i}, \forall n_j \in \{$previous nodes of n_i working on the $m_i\}$
  $L[m_i] = n_i$
  Update $SINR_{n_i,m_i} \forall m_i \in M$ based on previous nodes' choices

interference $I_{n_i,L[m_i]}$ caused to its nearest node $L[m_i]$, which is assigned m_i. This is also the upperbound of interference that n_i can cause to any previous node. $T[m_i]$ maintains that the lowerbound of the interference can be taken among all previous nodes assigned to m_i. If n_i wants to choose m_i, and $I_{n_i,L[m_i]}$ is lower than the lowerbound of interference that previous nodes on m_i can take, m_i is assigned to n_i. Otherwise, n_i would choose the one with the highest transmission rate among the remaining channels. In the last step, after moving to the next hop, it would first update its SINR estimation on each channel based on previous nodes.

After the source node completes the above process, it would determine the throughput of the chosen route based on the minimum among maximal transmission rate of all the chosen links. This ensures that the last constraint of Section IV is satisfied. We give the correctness and complexity analysis in the following subsection.

C. Correctness and Complexity Analysis

First, we would prove that our algorithm above satisfies all of the constraints. f is the throughput after the channel assignment process is completed. $\{c_{n_i,m_i}, n_i \in N\}$ is the set of channel assignment results.

Theorem 2. $f_{n_i,m_i} \le c_{n_i,m_i}, \forall n_i \in N.$

Proof. Since $f_{n_i,m_i} \le f_{s,m_0} \le min\{c_{n_i,m_i}\}, \forall n_i \in N,$
$f_{n_i,m_i} \le c_{n_i,m_i}, \forall n_i \in N.$ ■

This is obvious. Next, we need to prove that the SINR of each node after assigning channels is above the threshold.

Theorem 3. $SINR_{n_i,m_i} > \beta, \forall n_i \in N.$

Proof. We can prove this by showing that after a certain node n_i is newly assigned channel m_i, $SINR_{n_i,m_i} > \beta$. For nodes before n_i that have already been assigned with channel m_i, also satisfy the SINR constraint.

In the channel assignment phase of Algorithm 1, we would update p' after each node is assigned with a channel. From Definition 2, the computation of p' takes the channel assignment results of all previous nodes into consideration. That is, when computing $SINR_{n_i,m_i}$, the interference caused by previous nodes on the single chosen route working on the same channel is considered. Therefore, $SINR_{n_i,m_i} > \beta$.

Then, we need to show that previous nodes assigned with m_i also satisfy the SINR constraint. In Algorithm 1, $I_{n_i,L[m_i]}$ is the maximal interference n_i caused to previous nodes on channel m_i. For any n_j that has been assigned m_i on this route, $I_{n_i,n_j} < I_{n_i,L[m_i]}$. Since $I_{n_i,L[m_i]}$ is less than T_{n_j,n_i,m_i}, I_{n_i,n_j} is less than T_{n_j,n_i,m_i} for any n_j transmitting on m_i, which ensures the interference caused by n_i would not make the SINR of its previous nodes below than β. ■

Now we give the analysis of the complexity of our algorithm, which is shown in Theorem 4.

Theorem 4. *The worst case complexity of Algorithm 1 is* $O(|M||N|^3)$.

Proof. The complexity of steps 5 and 6 in Algorithm 1 is $O(|M||N|)$. The worst case scenario in step 13 would be to update T for the most times, which happens when the following example situation comes up:

$$m_1 -> n_1, m_2 -> n_2, m_1 -> n_3, m_2 -> n_4, ...$$

The total update times would be:

$$1 + 1 + 2 + 2 + ... + \frac{|N|}{2} + \frac{|N|}{2} = O(|N|^2)$$

Therefore, the worst case complexity is $O(|M||N|^3)$. ■

If we find the optimal result by searching all of the different choices, the complexity would be $O(|M|^{|N|})$. Our algorithm is significantly more efficient than the complexity view when $|M| > |N| > 4$.

We can also have a analysis about the information overhead and computation complexity of the source node. For each node along the route, the information piggybacked is its preference on each available channel. This is a $|M| \times 1$ metric, which is relatively small. Then, the total information given to the source node is a $|M| \times |N|$ metric. From the above analysis, the computation complexity is $O(|M||N|^3)$. Therefore, the information overhead and computation complexity of the source node is not significant.

VI. Multi-Route Channel Assignment Model

In this section, we first introduce our channel allocation model based on multi-route DSR [15]. It is an extension to the single route and each node chooses its neighbors to help transmit. We would introduce how to convert the multi-route assignment problem to the single route assignment problem above. Then, we give the complexity analysis.

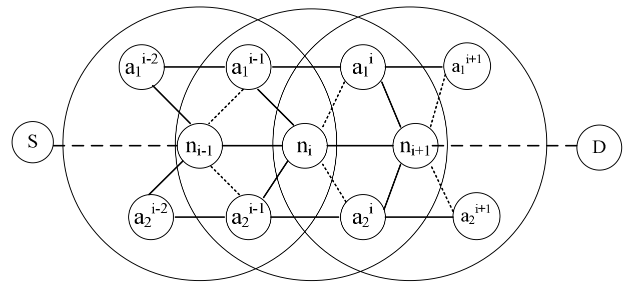

Fig. 3. Multi-route with alternative nodes.

A. Multi-Route Formation

Compared to the single route, the multi route scheme has two kinds of nodes: (1) base nodes on the main route; (2) alternative nodes on the alternative route. After the destination node chooses a single route, nodes on this chosen route all become base nodes. Each base node chooses its one-hop neighbors to be alternative nodes to help with transmitting. In this way, the throughput is improved and the delay is reduced. We give the specific definition of alternative nodes in our model.

Definition 3. *For node n_i, if there exists a one-hop neighbor which is not included as the alternative node of n_i's previous nodes, then this node is n_i's alternative node, denoted as a^i_j, $j \in [1,$ number of n_i's alternative nodes$]$.*

This definition avoids that a node becomes two base nodes' alternative node at the same time. We call this a^i_j being "charged" by node n_i. For example, in Fig. 3, although nodes $a^{i-1}_1, a^{i-1}_2, a^i_1, a^i_2$ are all n_i's one-hop neighbors, only a^i_1, a^i_2 are n_i's alternative nodes. This is because n_{i-1} is the previous node of n_i and a^{i-1}_1, a^{i-1}_2 are already charged by n_{i-1}.

The main process is similar to the single route model. The first phase is still the source node sending a RREQ request to reach the destination node. After the destination node chooses a route, it would send back a RREP. Each node on the chosen route now is the base node. When it receives a RREP, it needs to piggyback not only its own probability to choose a certain channel, but also another two aspects of information: (1) its alternative nodes; (2) the probability of alternative nodes choosing a certain channel. From Definition 3, two adjacent base nodes have no overlap of alternative nodes. Each alternative node would send its probability of choosing a certain channel to its charging base node. Then, the base node would add all of the information to the RREP and forward it to its next hop on the main route. In Fig 3, n_i would add n_i, a^i_1 and a^i_2's probability of choosing each channel to the RREP.

Now the channel assignment problem is to assign channels for both base nodes and alternative nodes.

Algorithm 2 Channel Assignment Among Alternative Nodes

```
base node $n_i$ = source $S$, $n_{i+1}$ = next hop of $n_i$ along the main route
$T[m_i]$: an array of size $|M|$, each element is the maximal allowable interference on $m_i$
$L[m_i]$: an array of size $|M|$, each element is the nearest node to next hop on channel $m_i$
Lock all the stages
while $n_{i+1} \neq$ destination $D$ do
    Unlock the set charged by $n_i$, lock previous stage
    $A_i$ = set of $n_i$'s alternative nodes
    while $\exists a_i^j \in A_i$ having no channel assigned do
        $a_i^k$ = $n_i$'s alternative node having no channel assigned with the highest ID
        Update $p'$ and $SINR_{a_i^k, m_i}, \forall m_i \in M$
        Choose the channel $m_i$ with highest transmission rate for $a_i^k$
        if $I_{a_i^k, L[m_i]} < T[m_i]$ then
            assign $m_i$ to $a_i^k$
        Update $T[m_i]$ and $L[m_i]$
    $n = n'$, $n'$ = next hop of $n$ along the main route
```

B. Conversion

The multi-route channel assignment problem can be solved by converting to the single route channel assignment problem with the help of the multistage graph.

As stated in the above part, each base node on the main route charges a set of alternative nodes. We now define the concept of *stage* in our multi-route problem in Definition 4.

Definition 4. *A stage consists of a base node n_i and the set of alternative nodes $\{a_j^i\}$ charged by n_i.*

The links are either within a single stage or within adjacent stages whose base nodes are adjacent in the main route. Each stage is regarded as a node in single route model. Then, the multi-route is converted to a single route. For example, nodes n_i, a_1^i and a_2^i are treated as a single node in Fig. 3.

We now need to make modifications to the SINR estimation in Definition 2. For each base node, the previous nodes that have influences on its SINR contain both the previous main nodes and previous alternative nodes. The same applies for the SINR calculation of alternative nodes. Previous main nodes and alternative nodes also have influence to its channel choosing probability. Thus, when computing the estimated SINR, we should actually include all of the nodes - base nodes and alternative nodes - in previous stages. Now we define an order to calculate each node's estimated SINR and its probability to choose a certain channel. Starting from the source node, the stage in which the base node is nearer to the source node is computed prior to other stages. During a single stage, the base node would be computed first. It would assign each alternative node an ID, shown in Fig. 3. The alternative node with the higher ID number would be computed before other alternative nodes. In Fig. 3, nodes n_i, a_1^i and a_2^i would be computed before n_{i+1}, a_1^{i+1} and a_2^{i+1}. In addition, n_i would be computed before a_1^i and a_2^i. a_2^i would be computed before a_1^i due to a_2^i's ID 2 is higher than a_1^i's ID 1. Therefore, for a base node, when using Definition 2, the p'_{n_j,m_i} should include all of the nodes in the previous sets. For an alternative node, the p'_{n_j,m_i} would include two aspects: (1) all of the nodes in the previous stages; (2) all of the nodes in the same set computed before it.

TABLE I
SIMULATION SETTINGS

Number of nodes	$[100, 300]$
operation range of each node	500
Number of channels	$[100, 300]$
TX power	23 dBm
Noise power	-98 dBm
SINR threshold	10 dB

C. Locking/Unlocking Scheme

In order to avoid overhearing issues among two adjacent stages, we apply a locking/unlocking scheme when assigning channels among different stages.

The source node would assign channels first along the main route, using Algorithm 1. After that, it would assign channels for each alternative node using Algorithm 2. The constraints in Algorithm 2 of $T[m_i]$ and $L[m_i]$ have the same meaning as in Algorithm 1. The update of $L[m_i]$ needs to calculate the minimum distance with the next alternative node to choose which node to store. Each time it would unlock one stage to assign channels and keep other stages locked; nodes in the locked stages would not transmit data so that the unlocked stage would not be interfered with when computing the SINR. After finishing one stage, it would move to the next stage which is charged by the next base node along the main route.

D. Complexity Analysis

The complexity of our multi-route channel assignment approach is $O(|M|(|N| \times |N_a|)^3)$, where N_a is the alternative node set of a stage with the most alternative nodes among all of the stages. That is, $|N_a|$ is the upperbound of the number of alternative nodes in a single stage. It is obvious that the complexity would be very large when the number of alternative nodes is large in each set.

VII. Extensions

In the above models, in both the single route and multi-route model, the performance would be relatively low if the network is very dense. Therefore, it would be more effective if we can select part of the nodes to assign channels to. Next, we discuss the extensions for the two models.

In the single route model, we can first construct a virtual backbone using the approach in [18]. In [18], Dai and Wu propose a scheme of clustering by using an adjustable transmission range to construct a virtual backbone. They use one stage to form clusters and another stage to prune via MP (marking process) and Rule k. Generally, they first

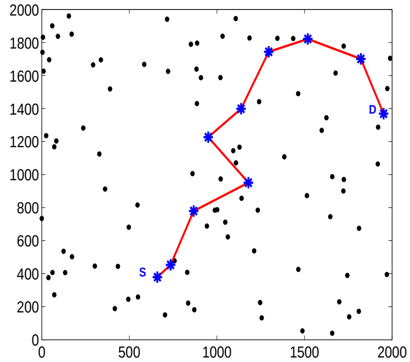

Fig. 4. nodes and route

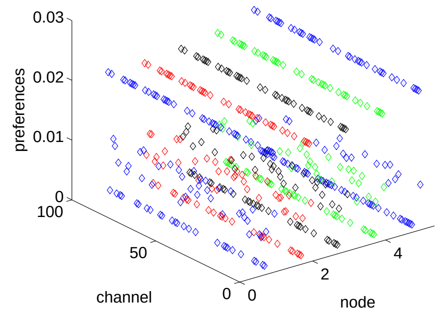

Fig. 5. initial preferences

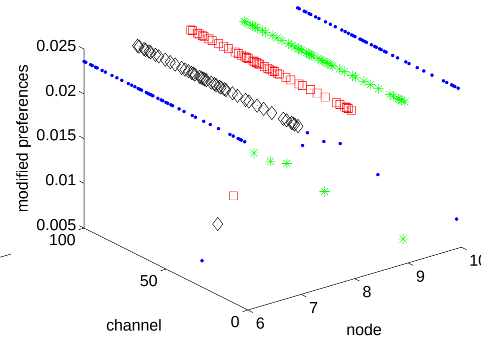

Fig. 6. modified preferences

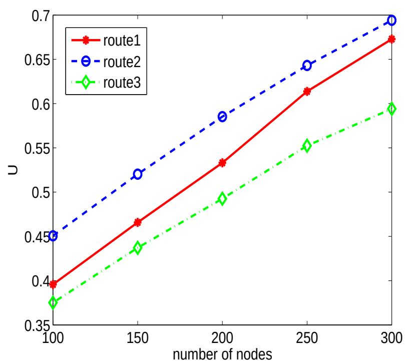

Fig. 7. U of varying nodes

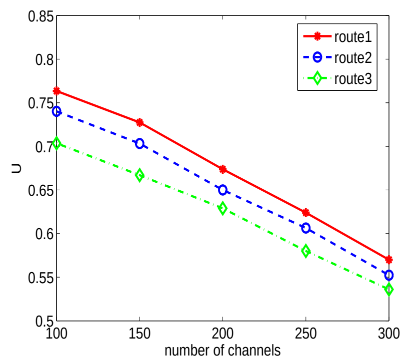

Fig. 8. U of varying channels

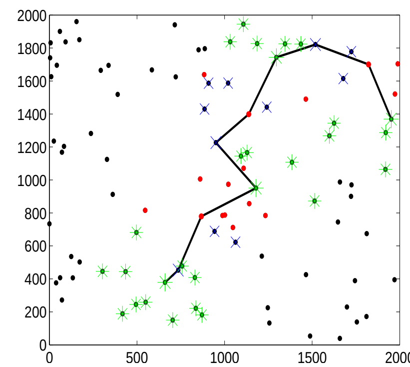

Fig. 9. base and alternative nodes

reduce the network density through clustering using a short transmission range r_1. Then, neighboring cluster heads are connected using a long transmission range r_2. In this way, neighboring cluster heads are connected without using any gateway selection process. [18] proves that the connectivity among cluster heads(alternative nodes) is kept. Then, the nodes on the chosen route in our model between the source and the destination would be nodes on the backbone, which are the marked cluster heads in [18]. Through this way, the number of nodes on the chosen route would become much less.

In the multi-route model, we can deduct the number of alternative nodes in each stage. This can be done through constructing a virtual backbone for the neighbor set of each base node using the 2-stage backbone construction in [18]. In each set, we only choose the cluster heads as alternative nodes. Therefore, we can exclude many nodes as alternative nodes and keep the number of alternative nodes low. [18] proves that the number of cluster-heads each base node can have is at most $((r_1+2r_2)/r_1)^2$, where r_1 is the 1-stage transmission range and r_2 is the 2-stage transmission range. Usually, the complexity of our multi-route algorithm is reduced to $O(|M|((r_1+2r_2)/r_1)^3)$.

VIII. Simulation

In this section, we perform the simulations for the single route model, multi-route model and the extension of applying virtual backbones. Also, we implement an optimal algorithm, which gets the optimal result via an exhaustive search.

A. Simulation Settings & Methodology

We randomly distribute nodes in a $2,000 \times 2,000$ unit square. Some of the nodes are busy at a certain channel and some of the nodes are idle. We randomly choose a source and a destination. Then, we generate the route along which the channel assignment is conducted. The settings of our simulation parameters is shown in Table I.

The two parameters, number of nodes and number of channels, are tuneable. To compare our algorithm with the optimal algorithm, we change one of the two parameters and compare the algorithms using the metric:

$$U = \frac{f_{s,m_0}}{f^o_{s,m_0}},$$

where f_{s,m_0} is the transmission rate of our algorithms at the source node, and f^o_{s,m_0} is the transmission rate of the optimal algorithm at the source node. Obviously, the higher U is, the closer our algorithm is to the optimal results.

B. Simulation Results

In this part, we first present the simulation results of the single route channel assignment model. Then, the results of the multi-route channel assignment model are given.

1) Single Route: we initiate with 100 nodes and 100 channels. The generated route is shown in Fig. 4. Here, the number of nodes on the chosen route is 10. Then, the initial preferences of each node are shown in Fig. 5. Due to the

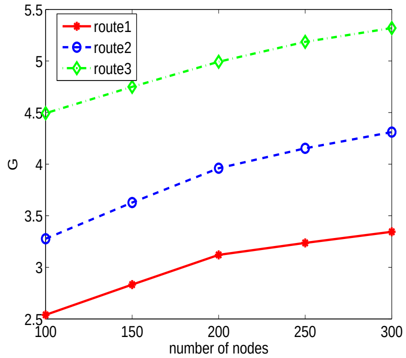

Fig. 10. G of varying nodes

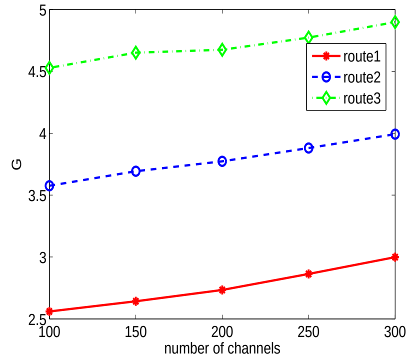

Fig. 11. G of varying channels

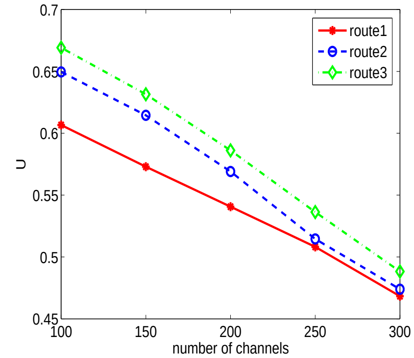

Fig. 12. U of varying nodes

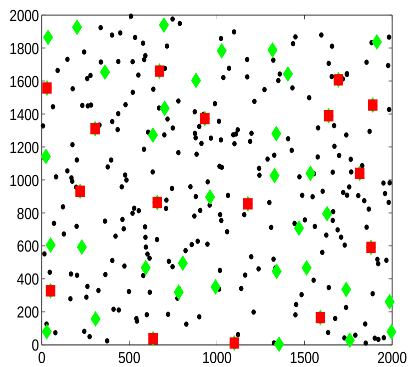

Fig. 13. virtual backbone

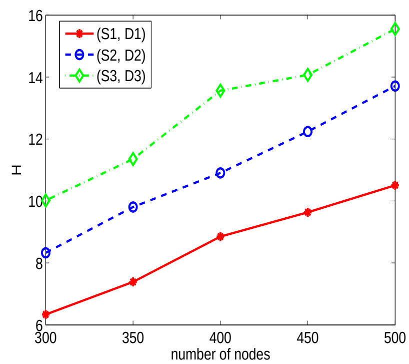

Fig. 14. H of single route

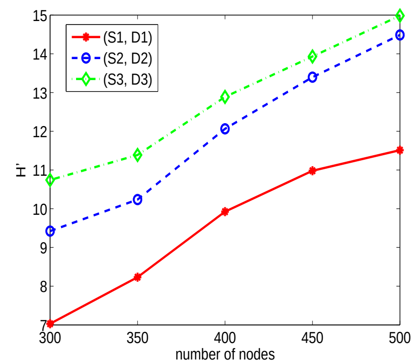

Fig. 15. H' of multi-route

consideration of clarity, we only show the five nodes here. From Fig. 5, each node can exclude some channels easily (initial preferences = 0).

Based on these settings, we perform our Algorithm 1 from source node to destination node. At a certain point, the preferences of nodes that have not been assigned channels are shown in Fig. 6. Here, we choose the 6th node from the source on the chosen route. The previous node has made choices. Their choices modify the preferences of later nodes. The modified preferences are based on a more precise SINR estimation. We only show the preferences greater than 0, which are much less than Fig. 5. Therefore, the complexity of assigning channels to later nodes is reduced.

Then, we change the two parameters: number of nodes and number of channels. Each time we generate a new topology and three new routes, we compute the metric U on each route by applying our single route algorithm and the optimal algorithm. Fig. 7 shows the results after varying the number of nodes from 100 to 300. When the number of nodes is increased, there would be more interferences in the network; our algorithm is closer to the optimal result. In Fig. 8, the number of channels is changed from 100 to 300 and the number of nodes is kept at 200. From the two figures, our algorithm achieves almost 60% of the optimal results.

2) Multi-route: we use the same setting as the single route. First, we identify the alternative nodes along the main route in Fig. 4. The results are shown in Fig. 9. We use three colors to distinguish every three adjacent base nodes on the chosen route. Each node's alternative nodes are in the same color. From the figure, two adjacent nodes on the main route have no overlap of their alternative nodes.

Then, we analyze the results after assigning channels for both base nodes and alternative nodes. First, we compare the throughput between the multi-route model and the single route model along three generated routes. The metric used for comparison is as follows:

$$G = \frac{f^{mul}_{s,m_0}}{f^{sin}_{s,m_0}},$$

where f^{mul}_{s,m_0} is the transmission rate at the source node under the multi-route model and f^{sin}_{s,m_0} is under the single route model. We change the two parameters: the number of nodes from 100 to 300 and the number of channels from 100 to 300. When the number of nodes is changed, the number of available nodes is also changed proportionally. Fig. 10 and Fig. 11 are the results of three different routes. It is obvious that the throughput of the route is increased under the multi-route model compared to single route model.

Moreover, we conduct the optimal algorithm which searches exhaustively and finds the optimal assignment for both base nodes and alternative nodes. We compute the metric U with $f_{s,m_0} = f^{mul}_{s,m_0}$. We change the number of channels from 100 to 300. The values of U are shown in Fig. 12. Our algorithm achieves almost 55% of the optimal results.

C. Virtual Backbones

We consider the $2,000 \times 2,000$ network with 300 nodes. Then, we use the 2-stage approach in [18] and construct the backbone in Fig. 13. Both the green nodes and red nodes are cluster heads. However, the green ones are the unmarked nodes in [18]. Only red nodes construct the virtual backbone. The number of nodes on the virtual backbone is much less compared to the total node number 300.

Then, we run the single route algorithm both before and after applying the backbone. Here, we compare the following metric:

$$H = \frac{I_{avg}^{sin}}{I_{avg}^{vb}},$$

where

$$I_{avg}^{sin} = (\sum_{j=1}^{N_{sin}} \sum_{i=1, i \neq j}^{N_{sin}} I_{n_i,n_j})/|N_{sin}|,$$

$$I_{avg}^{vb} = (\sum_{j=1}^{N_{vb}} \sum_{i=1, i \neq j}^{N_{vb}} I_{n_i,n_j})/|N_{vb}|.$$

N_{sin} is the set of nodes on the single route without the backbone. N_{vb} is the set of nodes on the route consisting of backbone nodes. We choose three different pairs of source and destination nodes, $(S_i, D_i), i \in [1, 3]$. The distance between the source node and the destination node of each pair is different from each other: $d_{S_1,D_1} < d_{S_2,D_2} < d_{S_3,D_3}$. For each pair, we generate the route and compute H by varying the number of nodes in the network. The result is shown in Fig. 14. The more nodes there are, the less average interference there is for each node on the route of the backbone compared to the the route not using the backbone. The longer the distance, the better the algorithm applied with the backbone.

We also run the multi-route algorithm before and after using the backbone. We compare the following metric:

$$H' = \frac{I_{avg}^{mul}}{I_{avg}^{\prime vb}},$$

where

$$I_{avg}^{mul} = (\sum_{j=1}^{N_{mul}} \sum_{i=1, i \neq j}^{N_{mul}} I_{n_i,n_j})/|N_{stage}|,$$

$$I_{avg}^{\prime vb} = (\sum_{j=1}^{N_{vb}} \sum_{i=1, i \neq j}^{N_{vb}} I_{n_i,n_j})/|N_{stage}|.$$

N_{mul} is the set of nodes, including base nodes and alternative nodes. N_{vb} is the set of nodes, including base nodes and alternative nodes, where alternative nodes are the backbone nodes on each stage. As for the single route, we also choose three pair of $(S_i, D_i), i \in [1, 3]$, where $d_{S_1,D_1} < d_{S_2,D_2} < d_{S_3,D_3}$. The result is shown in Fig. 15. The more nodes, the less average interference there is for each stage with backbones compared to each stage without backbones. The longer the distance, the better the stage using the backbone.

IX. Conclusions

In this paper, we consider the channel assignment problem under dynamic source routing in cognitive radio networks. We make use of piggybacked information to collect information of each node on the chosen route. Also, we propose a mechanism to estimate the SINR, which is used to determine the probability of each node choosing a certain channel. Two models are presented: single route model and multi-route model. We show how to convert the multi-route model into the single route model. Moreover, we propose a locking/unlocking scheme for channel assignment in the multi-route model. Specific simulations are conducted to show the performance of our algorithm. Results show that our algorithms achieve almost 60% of the optimal algorithm in terms of transmission rate.

Acknowledgments

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