Opportunistic Routing Based Scheme with Multi-layer Relay Sets in Cognitive Radio Networks

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***Abstract*—Opportunistic routing schemes have their advantages if applied in cognitive radio networks (CRNs), since the reliability is better ensured. However, it is impractical and inefficient to directly use opportunistic routing protocols in CRNs. In this paper, we propose a framework of applying opportunistic routing in CRNs. Our framework builds the multi-layer relay sets for each sender, instead of one general relay set, as seen in other wireless networks. A relay set on one layer refers to the set of nodes that are able to help relay on one channel. Moreover, to select a data transmission channel, each sender considers the channel quality as well as the potential reliability brought by the corresponding relay set. In order to better adjust to the situations when PUs suddenly become active during data transmission, we have each sender maintain one main relay set and one backup relay set. It effectively reduces the channel switching and relay set reselection cost during data transmission. We also give an effective adaptation scheme for each sender when all the relay sets fail. Finally, the simulation results indicate the superior performance of our scheme.**

Index Terms*—Cognitive radio networks, opportunistic routing, relay set selection, evaluation.

I. INTRODUCTION

Cognitive radio networks (CRNs) [1] improve the efficiency of channel utilization by enabling secondary users (SUs), or nodes, to transmit data packets on channels that are assigned to primary users (PUs). However, the key constraint is that the active PU sessions cannot be interfered with by SUs. Therefore, SUs need to quit from those channels once the corresponding PUs become active.

One of the important, and also challenging, issues is the routing problem in CRNs [2]. The difficulties lie on the unpredictable PU activities and uncontrollable break links. Different from traditional wireless networks, in which the broken links are usually caused by nearby interferences or physical environments, links in CRNs face the suddenly active PUs. Even though the sender and receiver are capable of building a link, they cannot transmit data due to PUs. Moreover, there are multiple channels at each node in CRNs. This is different from the traditional multi-channel wireless networks. The available channel sets on each node in CRNs are different from each other, and are also dynamic. For them to communicate with each other, the sender and receiver must tune in to the same channel. If there is no overlap in their available channel sets, they cannot communicate.

With the above special challenges brought by CRNs, finding a stable route using the unstable links is very difficult, which makes reliability a main concern. This brings us to consider the application of opportunistic routing, which has been proven to be useful in increasing the routing reliability in many other wireless networks. However, applying it in CRNs comes with both advantages and challenges.

Advantages of Opportunistic Routing. The main advantage of opportunistic routing protocols involves the improvement of data transmission reliability in wireless networks. When the data transmission between the sender and the receiver fails, other nodes that have overheard the data can help to forward the packet. With the help of relay nodes, the overall reliability is improved. In CRNs, end-to-end routes between sources and destinations are likely to be broken by the suddenly active PUs. Opportunistic routing does not rely on any single route, and has the potential to improve such situations in CRNs. Therefore, the influences of channel dynamics on routing are weakened, when the data transmission task is distributed to multiple relay nodes.

Challenges of Applying on CRNs. Given the promising benefits brought by opportunistic routing, it cannot be directly applied on routings in CRNs. There are two main challenges. Firstly, the relay nodes need to listen to the same channel that the sender is using. Otherwise, it cannot overhear the packets, or help to relay the failed packets. In other wireless networks, it is not difficult to have all nodes working on the same channel. However, in CRNs, the available channel set on every node varies. Therefore, the relay node selection has to be channel aware. Secondly, if PUs become active, nodes in a relay set that are using the same channels are likely to be useless, since PUs have higher privileges to use the channels. This impairs the reliability of the relay set. Specifically, if all of the nodes or partial nodes are within the interference range of the suddenly active PUs, they need to quit using that channel, and are unable to forward the packets.

In our paper, we propose an opportunistic routing framework for CRNs. We make the opportunistic routing practical by constructing multi-layer relay sets for every sender, instead of a single relay set. The multi-layer relay sets are on the channel scale. The notion of "layer" here is motivated by the layered graph in [3], in which nodes having the same available channel are on the same layer. We give the novel definition of the relay set weights, and propose an efficient algorithm for relay set selections. In addition, to improve the reliability and reduce the potential channel switch delay, instead of selecting only one relay set on a channel, we select a backup relay set. We give an adaptation scheme, considering the situation when

PUs on the same channel as the relay set become suddenly active. The main contributions of our work are:

- We propose an efficient routing framework based on multi-layer relay sets, with the channel dynamics taken into account, and make the application of opportunistic routing on CRNs implementable.
- Instead of selecting the transmission channel and relay sets separately, we give the algorithm for the selection of relay sets and transmission channels together, which considers both the channel quality and the potential reliability of relay sets.
- In order to better suit the dynamic environment of CRNs, we present an adaptation approach with fewer interruptions to the data transmission when facing the suddenly active PUs.

II. Related Works

A. Existing Opportunistic Routing Works in CRNs

Works in [4]–[6] apply opportunistic routing for CRNs. Authors in [4] proposed the routing protocol, SAOR, which defined a routing metric based on sensing results for constructing opportunistic links. An opportunistic cognitive routing (OCR) protocol is proposed in [5]. The senders select their next hop relays based on the location information and channel usage statistics. A routing metric, called cognitive transport throughput (CTT), is given to estimate the potential relay gain of each relay candidate. The model in [6] focused on the energy efficiency in CRNs, and is formulated as two Stackelberg games. The above works usually select the relay sets based on the probabilistic estimation of relay nodes' abilities on all channels. However, the opportunistic forwarding scheme requires the relay node to overhear on the same channel. Different from them, we consider the channel and relay selections in two phases, and build the relay sets in multiple layers.

B. Relay Set Selection in Other Wireless Networks

The relay set selections in classical opportunistic routing protocols are discussed in [7]–[9]. The relay set of the ExOR protocol [7] is based on the metrics of the estimated transmission count (ETX) to reach the destination. Network coding is applied on the opportunistic routing, as proposed in [8], with the similar relay set selection approach in ExOR. SOAR in [9] selects relay sets with the consideration of preventing diverging paths. The ETX constraints are applied on the relay node selections. Due to the special channel dynamics in CRNs, as discussed in Section I, the above relay set selection algorithms cannot be directly applied for CRNs. Our framework gives an efficient algorithm to solve this problem, and improves the reliability of the relay sets.

III. System Model

A. Network Environment

Suppose that there are N nodes (SUs) in the network and the total available channel set is M. We assume that there is a common control channel (CCC). Nodes in our model only use the CCC to exchange very short messages so that the overhead on the CCC is limited. Our work can also adjust to the networks without a CCC, simply by applying the approach in [10], to find the home channel for control message exchanges. There are also a number of PUs randomly distributed in the network. Each PU is assigned with a channel and is randomly active on that channel. When a PU becomes active, nodes within the PU's interference range cannot use that channel.

We assume that there are pairs of source and destination nodes in the network, and we consider the routing scheme for one pair. The applied routing protocol is the opportunistic routing scheme, which enables the potential forwarders to help forward packets, and improves the overall reliability. When the source tries to send data packets to the destination, it would perform spectrum sensing, select the relay set, and then transmit the data.

B. Problem Formulation

For two nodes i and j ($i, j \in N$) to formulate a single link, denoted as ij, there are two constraints that they must satisfy: 1) The SINR value from i to j must be above a threshold β; 2) The channel used by link ij is not currently occupied by any PU within its interference ranges. The two constraints can be formulated as:

$$SINR_{ij}^m = \frac{S_i^m G_{ij}}{\sum_{k \in N_i \& k \neq j} a_k^m S_k^m G_{kj} + I_0} > \beta, \quad (1)$$

$$m \in M_i \cap M_j, \quad (2)$$

where $SINR_{ij}^m$ is the SINR value from i to j on channel m ($m \in M$); S_i^m is the transmission power of i on m; G_{ij} is the transmission gain from i to j; a_k^m is the indicator, which equals 1 only if node k also uses channel m, and equals 0, otherwise; G_{kj} is the transmission gain from k to j; N_i is the neighbor set of node i; I_0 is the average noise power; M_i, M_j is the available channel set at i and j, respectively, which is the set of channels not occupied by any PU within their interference range. The maximum transmission rate of ij on m is (Shannon's capacity theorem):

$$V_{ij}^m = W log_2(1 + SINR_{ij}^m), \quad (3)$$

where W is the carrier bandwidth. The objective of our routing protocol is to minimize the end-to-end delay. Considering the dynamics of CRNs and the unpredictable activities of PUs, it is impractical to find a static and optimal route to achieve the objective. Therefore, we give a heuristic solution based on the opportunistic routing, which efficiently reduces the delay of reaching the destination even facing suddenly active PUs.

IV. Multi-layer Opportunistic Routing Framework

A. Framework Overview

The underlying motivation of applying opportunistic routing in CRNs is to build a reliable route under the dynamic channel availability environment. We make use of the basic idea of opportunistic routing, and give our framework, specifically for

CRNs, which considers the channel dynamics and communication efficiency. The overview of our framework is:

- The sender of each link first performs spectrum sensing and sends a request to its neighbors through CCC. The neighbors of the sender reply with their location and channel information;
- The sender selects two relay sets on two channels for data transmission: one is the main relay set; the other is the backup relay set;
- The sender notifies the nodes in the selected main relay set, assigns them priorities, and applies the opportunistic based routing protocol;
- When the transmission fails due to the suddenly active PUs, the sender adjusts the affected main and backup relay sets, and reselects them if necessary.

From the source node, each sender repeats the above process until it reaches the destination. The reason for selecting two relay sets will be explained later. The above process contains three main issues that need to be solved, which will be discussed in the following subsections:1) How the senders and receivers efficiently exchange their information; 2) How the relay sets are selected on different channels; 3) How the routing is performed on the selected relay sets, and how the relay sets should be adjusted when facing suddenly active PUs.

B. Information Exchange

The primary goal of information exchange is for the sender receiving the channel availabilities and the location information of the its neighbors. We assume that each node knows its current location, which is easy to implement considering many wireless devices nowadays have GPS functions. Since the source, S, knows the location of the destination, D, it can pass the location information to its next hops. Therefore, each node along the path is able to calculate its distance to D. For a node i, we use l_i to denote its location, d_i to denote the distance of i and the destination, and Ad_{ij} to denote the distance advanced to the destination node from i to j.

Suppose that node i is a sender, N_i is the set of its one-hop neighbors, and $j \in N_i$. The communication process among i and j is shown in Fig. 1, which contains:

1) Node i sends a request to nodes in N_i. The request message contains d_i and l_D (location of destination D);
2) Nodes in N_i receive the request, and calculate their distances to the destination D;
3) If $j \in N_i$, and $d_j < d_i$ which means Ad_{ij} is greater than 0, j replies l_j, and its sensing results, which represent the available channel set M_j to i.

Both the request and reply messages are sent through CCC. They follow the CSMA/CA mechanism in IEEE 802.11. To reduce the communication load on CCC, only nodes that are closer to the destination reply to the sender.

C. Multi-layer Relay Set Selection

To increase the routing reliability when facing the suddenly active PUs, multi-layer relay sets are selected according to different channels. For a sender i, we use R_i^m to denote its relay set on the layer of channel m, where $m \in M_i$. The definition of R_i^m is as follows:

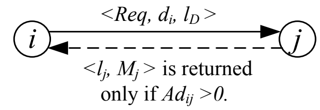


Fig. 1. Communication process between i and j, $j \in N_i$.

Definition 1. ***Relay set on one layer:*** *For a node j, if $j \in R_i^m$, it must satisfy that: 1) $m \in M_j \cap M_i$; 2) $j \in N_i$; 3) $Ad_{ij} = d_i - d_j > 0$, where Ad_{ij} is the distance advanced to the destination node.*

Based on the information exchange phase, the above two constraints can be easily verified by i. Therefore, i can calculate the R_i^m, $\forall m \in M_i$. One thing to notice is that, for $m, m' \in M_i$, it is possible that $R_i^m \cap R_i^{m'} \neq \varnothing$, which means that a node can be in more than one relay set. Then, the next step is to select the main and the backup relay sets from R_i^m, $\forall m \in M_i$. The basic idea here is to find a way to define the weight of each relay set, and to select the two maximum ones.

Firstly, for a sender i, we should define the weight of its potential relay node j, where $j \in R_i^m$:

Definition 2. ***Weight of a relay node:*** *For a node i, the weight of its potential relay node j, U_{ij}^m, is defined as:*

$$U_{ij}^m = (V_{ij}^m)^\alpha \times Ad_{ij}, \tag{4}$$

where $j \in R_i^m$, V_{ij}^m is the maximum transmission rate in Eq. (3), and $\alpha > 0$ is the weight factor, which is used to control the weights of V_{ij}^m and Ad_{ij} in calculating U_{ij}^m.

Secondly, for a single node j, which is a potential relay node of i, it has a possibility of failing. The failure can be caused by a communication error or a suddenly active PU within j's interference area. We use p_j^m to denote the success transmission probability of j on channel m, which is calculated statistically from the historical data of j on channel m, and is influenced by the PU active probabilities.

Thirdly, based on the general architecture of opportunistic routing, in a relay set R_i^m, nodes with higher values of Eq. (4) relay the packet first. A node with a lower value only helps to relay the packets if all the higher ones fail. We will discuss the routing process in detail later. Here, we define the weight of a relay set, by using the weight and success transmission probability of each node:

Definition 3. ***Weight of a relay set:*** *For node i, the weight of its relay set, R_i^m, $\forall m \in M_i$, is defined as:*

$$W(R_i^m) = \sum_{j \in R_i^m} \left[\left(\prod_{k \in R_i^m \& U_{ik}^m > U_{ij}^m} (1 - p_k^m) \right) \times p_j^m \times U_{ij}^m \right]$$

U_{ik} and U_{ik}^m are defined in Definition 2. p_k^m and p_j^m are the success transmission probabilities of k and j on channel m, respectively. Also, the above equation shows that a node j only helps to relay if all k ($k \in R_i^m$ and $U_{ik}^m > U_{ij}^m$) fail.

Algorithm 1 Main and backup relay sets selection for node i.

Input: $R_i^m, \forall m \in M_i$, $U_{ij}^m, \forall j \in R_i^m$;

Output: R_i^a, main relay set; R_i^b, backup relay set;

$R_i^a = null$, $R_i^b = null$, $tmpA = 0$, $tmpB = 0$;
for every $m \in M_i$ **do**
  Sort nodes in R_i^m based U_{ij}^m, $j \in R_i^m$;
  Calculate $W(R_i^m)$;
  if $W(R_i^m) > tmpA$ **then**
    $tmpA = W(R_i^m)$;
    $R_i^a = R_i^m$;
  else if $W(R_i^m) > tmpB$ **then**
    $tmpB = W(R_i^m)$;
    $R_i^b = R_i^m$;
return R_i^a, R_i^b;

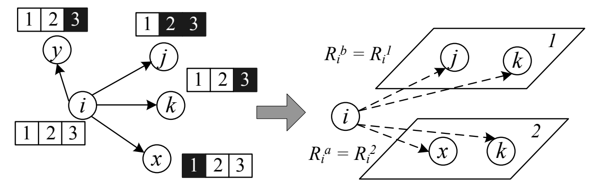


Fig. 2. The main and backup relay sets can overlap.

TABLE I
THE PARAMETER SETTINGS OF THE EXAMPLE IN FIG. 2.

Nodes in N_i	y	j	k	x
Advanced distance to destination	−0.5	0.6	0.8	0.7
Maximum transmission rate	10	9	6	8

Having the weight definition of relay sets, Algorithm 1 shows the complete algorithm for a sender i to select its main and backup relay sets, R_i^a, R_i^b. Here, a is the channel used by the main relay set, b is the channel used by the backup relay set, $a, b \in M_i$, and $a \neq b$. Algorithm 1 takes the relay node set of each channel R_i^m, and $U_{ij}^m, \forall j \in R_i^m$ as inputs. The variable $tmpA$ is used to store the maximum weight so far when executing the loop. Similarly, $tmpB$ is used to store the second maximum weight so far. After the loop is finished, the one with the maximum weight is selected as the main relay set, R_i^a, and the second maximum is the backup relay set, R_i^b. It is possible that $R_i^a \cap R_i^b \neq \varnothing$. The motivations of selecting main and backup relay sets, instead of one relay set only, are discussed in the next subsection.

One possible example is shown in Fig. 2. On the left side of Fig. 2, node i's neighbor set $N_i = \{y, j, k, x\}$. The total channel set is $\{1, 2, 3\}$. The available channels on each node are labeled in white squares. The advanced distance to the destination by each node in N_i is listed on the second row of Table I. The third row of Table I is the maximum transmission rate on each channel. For simplicity, we set the same maximum transmission rates for all three channels, the weight factor in Definition 2 to be 1, and the success probability of relaying of all nodes in Definition 3 to be 0.5. Since the distance advanced to the destination by node y is -0.5, j is not contained in R_i^m, $\forall m \in \{1, 2, 3\}$, based on Definition 1.

Using this example, since $M_i = \{1, 2, 3\}$, the inputs for Algorithm 1 are: 1) $m = 1$: $R_i^1 = \{j, k\}$, $U_{ij}^1 = 0.54$, $U_{ik}^1 = 0.48$; 2) $m = 2$: $R_i^2 = \{x, k\}$, $U_{ix}^2 = 0.56$, $U_{ik}^2 = 0.48$; 3) $m = 3$: $R_i^3 = \{x\}$, $U_{ix}^3 = 0.56$. Based on Definition 3, the weights of relay sets on each layer are: $W(R_i^1) = 0.5 \times 0.54 + 0.5 \times 0.5 \times 0.48 = 0.39$, $W(R_i^2) = 0.5 \times 0.56 + 0.5 \times 0.5 \times 0.48 = 0.4$, and $W(R_i^3) = 0.5 \times 0.56 = 0.28$. After running Algorithm 1, the main relay set R_i^a equals R_i^2, which contains nodes x and k, and the backup relay set R_i^b equals R_i^1, which contains nodes j and k. The results are shown on the right side of Fig. 2. Each layer is the relay set on one channel. Here, node k is in both the main and the backup relay sets. It means that, if the sender i sends data through channel 2, node k would overhear the packet and help forward the data if necessary. If the sender i sends on channel 1, k would perform a similar task. Details of forwarding on different relay sets will be discussed in the next subsection.

In addition, we give the analysis of Algorithm 1:

Theorem 1. *The time complexity of relay selection at node i is $O(|M_i| \cdot \mathcal{R}_i \cdot log\mathcal{R}_i)$, where $\mathcal{R}_i = max\{|R_i^m|\}$, $\forall m \in M_i$.*

Proof. The complexity for each R_i^m is $O(|R_i^m| \cdot log|R_i^m|)$. The complexity for calculating $W(R_i^m)$ in the sorted $\{R_i^m\}$ is $O(|R_i^m|)$, since $\{R_i^m\}$ is sorted and the previous calculating results can be used. Therefore, the overall complexity with all $m \in M_i$ taken into account is $O(|M_i| \cdot \mathcal{R}_i \cdot log\mathcal{R}_i)$, where $\mathcal{R}_i = \max\{|R_i^m|\}$, $\forall m \in M_i$. □

D. Routing Scheme and Relay Set Adaptation

From the discussions in the previous subsections, each sender now has its main and backup relay sets. When a sender receives data packets from its upstream nodes, the process of relaying is similar as in [7]. The procedure of our scheme based on our specific relay set selection and relay node priority definition is denoted as $Proc$, which is summarized as follows:

1) Sender i assigns each node j in the main relay set, R_i^a, with a priority, which is the value of U_{ij}^a in Definition 2;
2) Node i includes the IDs of nodes in R_i^a, which are sorted according to their priorities, and sends to the nodes in R_i^a through CCC. The receivers in R_i^a tune in to channel a and keep listening;
3) Node i sends the packet on channel a. After receiving the packet, each node in R_i^a sets a time window, and listens on channel a. The lengths of the time window are reversely proportional to the nodes' priority order;
4) When the time window expires, the relay node sends an ack and forwards the packet if and only if no node in R_i^a with a higher priority has sent an ack.

Here, since i and its relay nodes in R_i^a all work on channel a after the information exchange in Steps (1) and (2), ack messages are all sent through a. In this way, the burden of the CCC is reduced. Also, since the IDs of Step (2) are sorted

Algorithm 2 Relaying process for sender i.

Input: R_i^a, R_i^b, M_i;

1. i uses R_i^a and calls $Proc$;
2. **if** No ack is received within time γ **then**
3. $\quad R_i^a = R_i^b$; i calls $Proc$;
4. $\quad$ **if** No ack is received within γ **then**
5. $\quad\quad i$ runs Algorithm 1 with $M_i = M_i - \{a, b\}$;
6. $\quad\quad$ Update R_i^a, R_i^b, and go to Step 1;
7. $\quad$ **else**
8. $\quad\quad i$ runs Algorithm 1 with $M_i = M_i - \{a\}$;
9. $\quad\quad$ Update R_i^a, R_i^b;

according to the nodes' priorities, each node in Step (3) can set its time window length based on the priority order without requiring any extra information. We also apply the scheme in [11], and set the transmission range of the acknowledgements to be twice that of the packets. Therefore, nodes in R_i^a can receive the acknowledgement of each other's, and no extra copies of the data exist in the network.

Due to the channel dynamics of CRNs, it is possible that all nodes in R_i^a fail to relay packets upon the suddenly active PUs on channel a. Under this situation, the sender i would use the backup relay set, R_i^b, and make the corresponding adjustments.

Algorithm 2 gives the relay overview and also the possible relay set adaptation. The value of γ is equal to the longest time window length set by the relay nodes in R_i^a and R_i^b. Algorithm 2 considers three underlying situations: 1) No extra work needs to be done if the main relay set succeeds; 2) If the main relay set fails, the backup relay set is used. If the backup relay set works, then i only needs to reselect both sets with $M_i = M_i - \{a\}$, after the transmission, which means the execution of $Proc$ is completed; 3) If the backup relay set also fails, then i needs to eliminate a and b from M_i, reselect both sets using Algorithm 1, and repeat the process. The relaying process is repeated until it reaches the destination.

V. Performance Evaluation

A. Simulation Settings

1) Network settings: We randomly distribute nodes in a 200×200 unit square. Each node's range is randomly assigned from $[30, 50]$. The data transmission rate for each node is 2 Mbps without PUs and 0 with PUs. The transmission rate on the CCC is 512 kbps. The total number of channels varies from 4 to 8. We set the distance between the source and destination node to be 180. Each packet size is 512 bytes. The estimated relay success probability of each node (e.g., p_j^m in the definition of the relay set weight) depends on the number of PUs on the same channel within its interference range, which is 2 times its transmission range. We treat the number of PUs as the preknown information from historical data, and set the success probability on each channel as $1/(1+\text{number of PUs in the interference range})$ for the relay set weight calculation. The value of α in Eq. 4 is set to be 1. It can be different values, based on different application scenarios. We also set the channel switch time as 80us, and the minimum sensing duration for each node is 5ms. We randomly distribute 10 PUs in each channel. The coverage of each PU is 80. Initially, each PU is randomly set to be active or inactive. The average PU off duration varies from 100 ms to 500 ms.

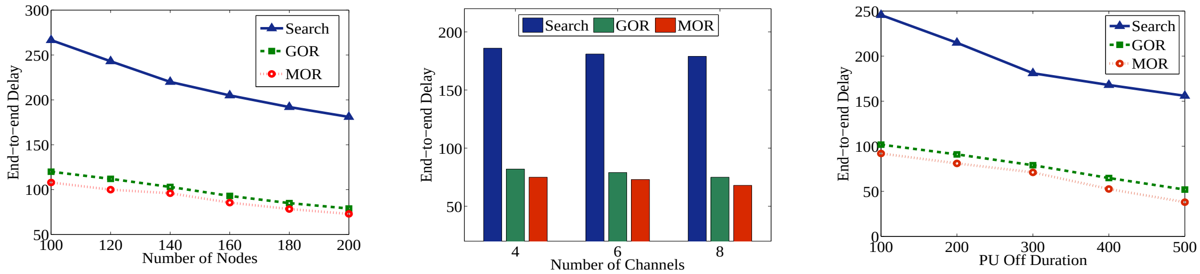
2) Evaluation metrics: There are three performance metrics that are used for our evaluation, end-to-end delay, packet delivery ratio, and relay-to-sensing ratio. We also implemented two other protocols, Search and GOR, for comparison with our protocol (shortened as MOR). Search in [12] selects a route with minimum latency before the data transmission happens. When a link on the selected route becomes broken because of the suddenly active PUs, Search would recalculate the route to reach the destination. In GOR [13], the sender first determines the channel for data transmission, based on whether the channel is available, and the associated success probability. We use the same success probability calculation for our model, according to the number of PUs. After the channel is selected, the sender selects a relay node on that channel.

B. Simulation Results

1) End-to-end delay: In Fig. 3(a), the number of nodes is changed from 100 to 200. The end-to-end delay shows that our protocol takes the lowest delay among the three. When the number of nodes increases, the end-to-end delay decreases. This is because the node density increases and more nodes are available to be selected as the relay nodes. In Fig. 3(b), we increase the number of channels from 4 to 8. Our protocol takes the smallest delay among the three. Also, the end-to-end delay decreases slightly when the number of channels increases. This is because more channels create more choices for data transmission on a single link. It reduces the rerouting probability of each node since the channel switching is more likely to recover the link when PUs become active. In Fig. 3(c), we increase the PU off duration from 100 ms to 500 ms, which means the PUs are less active and the channel availabilities become more stable. The end-to-end delay decreases for all three protocols and our protocol shows the least delay.

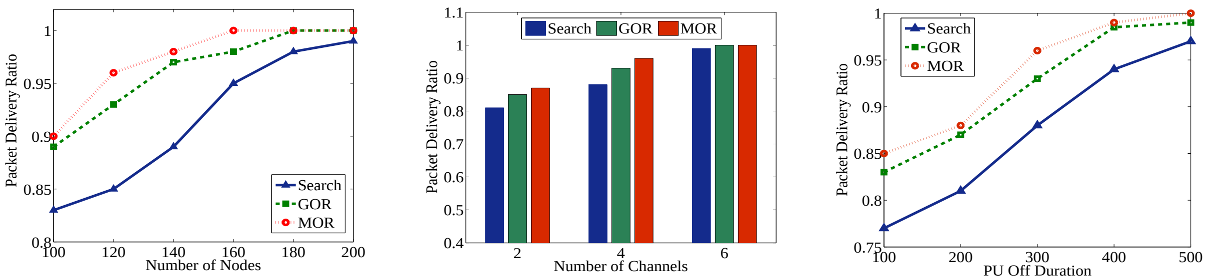
2) Packet delivery ratio: We compare the packet delivery ratio in Fig. 4. In Fig. 4(a), the number of nodes is changed from 100 to 200. MOR has the highest delivery ratio among the three and Search has the lowest. The packet delivery ratio of all three protocols increases when the number of nodes becomes larger. This is because more nodes mean more relay options and better guarantees on the packet delivery ratio. In Fig. 4(b), the number of channels varies from 2 to 6. All three protocols show larger delivery ratios when the total number of channels increases. In Fig. 4(c), the PU off duration is changed from 100 ms to 500 ms. From the results, we can see that the three lines increase when the PU off duration becomes larger. MOR is the highest delivery ratio among the three. All three protocols are more than 90% when the PU off duration is larger than 400 ms. Overall, our protocol has the highest packet delivery ratio among the three.

3) Relay-to-sensing ratio: Relay-to-sensing ratio is the number of successful relay transmissions to the total number



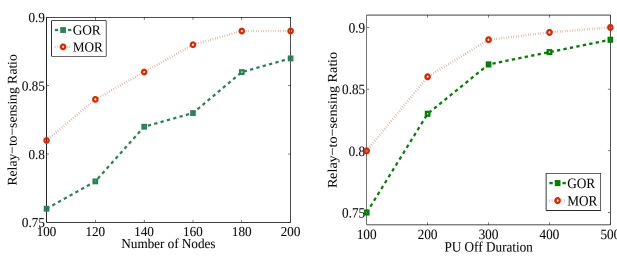
(a) change nodes (b) change channels (c) change PU off duration

Fig. 3. Comparison of end-to-end delays under different network parameters.



(a) change nodes (b) change channels (c) change PU off duration

Fig. 4. Comparison of packet delivery ratio under different network parameters.



(a) (b)

Fig. 5. Relay-to-sensing ratio with different parameters.

of sensing times. The larger value of the relay-to-sensing ratio means that the relay sets are more reliable and the reselections of relay sets are less reliable. Here, we only show the comparison results of GOR and MOR, since Search takes many more relay reselections. In Fig. 5(a), the number of nodes changes from 100 to 200. GOR and MOR show larger relay-to-sensing ratios when the number of nodes increases. In Fig. 5(b), the PU off duration varies from 100 ms to 500 ms. When the PU off duration becomes larger, GOR and MOR both show a better performance, and MOR is better than GOR. Moreover, the gap between MOR and GOR is reduced when the number of nodes or the PU off duration increases.

VI. Conclusions

We propose our opportunistic routing based scheme with multi-layer relay sets of the channel scale in CRNs. We present our algorithms for the relay set selections, which take the PU activities into consideration. Each sender retains two relay sets, which are the main relay set and the backup relay set. We also give the adaptation scheme when PUs become active on the data transmission channel. Moreover, we conduct extensive simulations for performance evaluation. The simulation results show that our protocol is very efficient and outperforms others.

References

[1] I. Akyildiz, W. Lee, M. Vuran, and S. Mohanty, “Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey,” *Computer Networks*, 2006.

[2] M. Cesana, F. Cuomo, and E. Ekici, “Routing in cognitive radio networks: Challenges and solutions,” *Ad Hoc Networks*, 2011.

[3] C. Xin, B. Xie, and C.-C. Shen, “A novel layered graph model for topology formation and routing in dynamic spectrum access networks,” in *Proc. of IEEE DySPAN*, 2005.

[4] S.-C. Lin and K.-C. Chen, “Spectrum aware opportunistic routing in cognitive radio networks,” in *Proc. of IEEE GLOBECOM*, 2010.

[5] Y. Liu, L. Cai, and X. Shen, “Spectrum-aware opportunistic routing in multi-hop cognitive radio networks,” *IEEE Journal on Selected Areas in Communications*, 2012.

[6] B. Cao, J. Mark, Q. Zhang, R. Lu, X. Lin, and X. Shen, “On optimal communication strategies for cooperative cognitive radio networking,” in *Proc. of IEEE Infocom*, 2013.

[7] S. Biswas and R. Morris, “ExOR: Opportunistic multi-hop routing for wireless networks,” in *Proc. of ACM Sigcomm*, 2005.

[8] S. Chachulski, M. Jennings, S. Katti, and D. Katabi, “Trading structure for randomness in wireless opportunistic routing,” in *Proc. of ACM Sigcomm*, 2007.

[9] E. Rozner, J. Seshadri, Y. Mehta, and L. Qiu, “SOAR: Simple opportunistic adaptive routing protocol for wireless mesh networks,” *IEEE Transactions on Mobile Computing*, 2009.

[10] Y. Dai, J. Wu, and C. Xin, “Virtual backbone construction for cognitive radio networks without common control channel,” in *Proc. of IEEE Infocom*, 2013.

[11] M. Lu, F. Li, and J. Wu, “Efficient opportunistic routing in utility-based ad hoc networks,” *IEEE Transactions on Reliability*, 2009.

[12] K. R. Chowdhury and M. D. Felice, “SEARCH: A routing protocol for mobile cognitive radio ad-hoc networks,” *Computer Communications(Elsevier)*, 2009.

[13] Y. Liu, L. X. Cai, , and X. Shen, “Joint channel selection and opportunistic forwarding in multi-hop cognitive radio networks,” in *Proc. of IEEE GLOBECOM*, 2011.