STOD-RP: A Spectrum-Tree Based On-Demand Routing Protocol for Multi-Hop Cognitive Radio Networks

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[*]*Abstract*—**A unique challenge for routing in cognitive radio networks is the collaboration between the route selection and spectrum decision. To solve this problem, in this paper a Spectrum-Tree base On-Demand routing protocol (STOD-RP) is proposed where a spectrum-tree is built in each spectrum band. The formation of the spectrum-tree addresses the cooperation between spectrum decision and route selection in an efficient way. In addition, a new route metric is proposed as well as a fast and efficient spectrum-adaptive route recovery method. Simulation results show that our proposed STOD-RP reduces the control overhead and shortens the average end-to-end delay significantly.**

I. INTRODUCTION

Recent spectrum measurements [1] show that the fixed spectrum assignment policy is becoming unsuitable for today's wireless communication. According to the Federal Communications Commission (FCC) report [3], most of the assigned spectrum bands (licensed bands) are under-utilized while unlicensed spectrum bands are always crowded. To solve the contradiction between the underutilized licensed bands and the limited available unlicensed bands, an efficient way is to allow unlicensed users to dynamically access the licensed bands without interfering with licensed users (primary users). Cognitive radio (CR) [2] is a promising technology that can support the flexible use of wireless radio spectrums [5]. In a typical CR network, nodes are equipped with a *spectrum-agile radio* which has the capabilities of sensing the available spectrum band, reconfiguring radio frequency, and switching to the selected band [4~7]. Based on the sensed radio information, CR users access the licensed band opportunistically when no primary users are using that band and vacate the band as soon as a primary user activity starts [8].

Routing in multi-hop CR networks faces several new challenges. A unique challenge is the collaboration between the route selection and the spectrum decision. Due to the dynamically changed and intermittent spectrum band, the spectrum information is required when selecting the route. Another major challenge is the lack of a fixed common control channel (CCC). Since a CR user has to vacate the spectrum band as soon as a primary user begins to use the network, the implementation of a fixed CCC becomes infeasible for CR networks. The third challenge is the spectrum-adaptive route recovery. In addition to node mobility, link failure in multi-hop CR networks may happen when primary user activities are detected. How to vacate the current spectrum band and to move to another available spectrum band quickly is still an unexplored problem.

There is a limited amount of work available for the routing problem in multi-hop CR networks. A spectrum-aware data-adaptive routing algorithm is proposed in [9]. A layered graph model is presented in [10] as well as routing and interface assignment algorithms. In [11], a joint approach of on-demand routing and spectrum scheduling is proposed. However, the work in [9~11] require a fixed CCC which is not easy for CR networks. The inter-dependence between route selection and spectrum management is investigated in [12]. A tree-based routing protocol is described in [13]. However, none of the above works consider route recovery when primary user activities are detected.

In this paper, we introduce a Spectrum-Tree based On-Demand routing protocol (STOD-RP) which simplifies the collaboration between spectrum decision and route selection by establishing a "*spectrum-tree*" in each spectrum band. The routing algorithm combines tree-based proactive routing and on-demand route discovery. Moreover, a new route metric which considers both CR user's QoS requirements and primary user activities is proposed. In addition, our work provides a fast and efficient spectrum-adaptive route recovery method for resuming communication in multi-hop CR networks.

The rest of the paper is organized as follows. In Section II, the STOD-RP protocol framework is described as well as the new route metric. Sections III describes the Spectrum-Tree based On-Demand Routing Algorithm (STOD-RA) and the spectrum-adaptive route recovery method in detail. Then, simulation results are illustrated in Section VI. Finally, we conclude this paper in Section V.

II. PROTOCOL OVERVIEW

A. Framework of STOD-RP

In our multi-hop CR network, each node is equipped with a *spectrum agile radio* which has the capabilities of spectrum awareness and reconfiguration. The nodes forward traffic for

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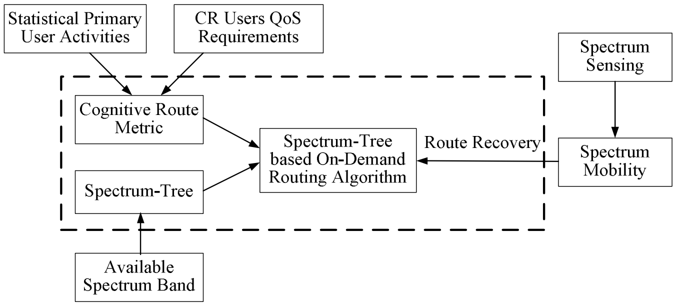

Fig. 1. Framework of STOD-RP.

each other in an ad-hoc manner. Unless stated otherwise, all nodes are fixed or move very slowly. The framework of STOD-RP is illustrated in Fig. 1. At first, we define a new cognitive route metric by using statistical primary user activities and CR user QoS requirements. Then, we form a spectrum-tree in each sensed available spectrum band. Based on the calculated route metric and formed spectrum-tree, the end-to-end route is selected by using the Spectrum-Tree based On-Demand Routing Algorithm (STOD-RA). When the available spectrum band between two CR users changes or vanishes, both *spectrum handoff* [5] and path rerouting methods will be used for route recovery. In our paper, we assume that the statistics of primary user activities and available spectrum band information can be obtained by existing spectrum sensing and sharing techniques. Therefore, we focus on the blocks encircled by dash line in Fig. 1.

B. *Cognitive Route Metric Computation*

The routing metric used in multi-hop CR networks should reflect the route quality and the spectrum availability, i.e., the routing metric should consider CR users QoS requirements and primary user activities as well. In this paper, we use cognitive route cost as the routing metric, which is based on resource consumption and route stability. In the following, we calculate the link cost on each pairwise link at first, and then get the cumulative routing cost.

We use the airtime cost to evaluate the resource consumption of a link l_i, which can be calculated as [14]:

$$C_i = \left[O_{ca} + O_p + \frac{P_{kt}}{r_i} \right] \frac{1}{1-e_{pti}} \qquad (1)$$

where O_{ca}, O_p and P_{kt} are constants for specific access technology. O_{ca} is the channel access overhead, O_p is the protocol overhead and P_{kt} is the size of a packet. Their values for IEEE 802.11a/b are listed in [14]. r_i and e_{pti} are the link rate in Mbps and the packet error rate, respectively.

The link stability is evaluated by the time duration of a link, i.e., the available time of the spectrum band used by the link. The available time of a spectrum band can be predicted from the statistical history of primary user activities. Finally, the link cost for a link l_i can be calculated as:

$$C_i = \left[O_{ca} + O_p + \frac{P_{kt}}{r_i} \right] \frac{1}{1-e_{pti}} \bullet \frac{1}{T_{l_i}} \qquad (2)$$

where T_{li} is the time duration during which a spectrum band is available to the link l_i.

Furthermore, the cost of an end-to-end route can be calculated as follows:

$$C = \sum_{i=1}^{k} C_i + M \bullet D_{switch} \qquad (3)$$

where k is the link number along a specific route, M is the number of spectrum band switches along the route and D_{switch} is the switch delay caused by a CR user switches between two different bands. In [15], D_{switch} may range from $150\mu s$ to $200\mu s$ for real devices.

C. *Spectrum-Tree Formation*

CR users form a tree in each available spectrum band, called *spectrum-tree*. Each spectrum-tree has only one root (e.g., node A in Fig. 2(a)), which keeps the basic information about the spectrum-tree topology, such as the routes to other non-root nodes. Some nodes may belong to multiple spectrum-trees, we call them *overlapping nodes* (e.g., node B in Fig. 2(c)). The *overlapping nodes* are equipped with multiple spectrum-agile radios and work in multiple spectrum-trees simultaneously.

1) *CR User ID (CRID) Assignment*

Each node has its unique CR user ID (CRID) in one spectrum-tree. The CRID of node X is $\text{CRID}_X = \{A_0 A_1 \ldots A_n\}$, where A_0 is the spectrum band in which the spectrum-tree is formed, and it is also the CRID of the root in this spectrum-tree. n is the hop number away from the root. $\{A_0 A_1 \ldots A_{n-1}\}$ is the CRID of node X's parent node. In this way, CRID indicates the proactive route to the root node easily.

The *overlapping node* who works in multiple spectrum bands has multiple CRIDs (e.g., $\text{CRID}_A = \{1, 2\}$ in Fig. 2(c)).

2) *Root Selection*

The root selection procedure ensures that there is only one root in each spectrum-tree. At the initiation of a CR network, each node assumes itself as the root and sends a *Root Request* $<N, T_i>$ message to its neighboring nodes in the detected available spectrum band, where $<N>$ is the number of available spectrum bands detected by the node and $<T_i>$ is the available time of the spectrum band i in which the node sends the *Root Request* message. After receiving the *Root Request* message, each node compares the N and T_i with its current root record and selects new root according to the root select algorithm (Fig. 3). At last, the node which has the largest N or has the longest T_i will be selected as the root. The spectrum-tree formation procedure is converging and is implemented only one time in each spectrum band. Therefore, the cost is acceptable.

After the root selection procedure, the selected root i broadcasts a *Root Announcement* message which contains its CRID in spectrum band i. Nodes hearing the *Root Announcement* message reply with a *connection request* message and make the root as their parent node. The root then assigns CRID to its child nodes. Its child nodes add their new CRID in the *Root Announcement* message and then forward it to their neighboring nodes. In this way, *Root Announcement* message is transmitted further down until every node gets CRID. A node may hear more than one *Root Announcement* messages sent by different nodes in the same spectrum-tree. In this situation, the node will choose its parent node by using the route metric described in Section II.B.

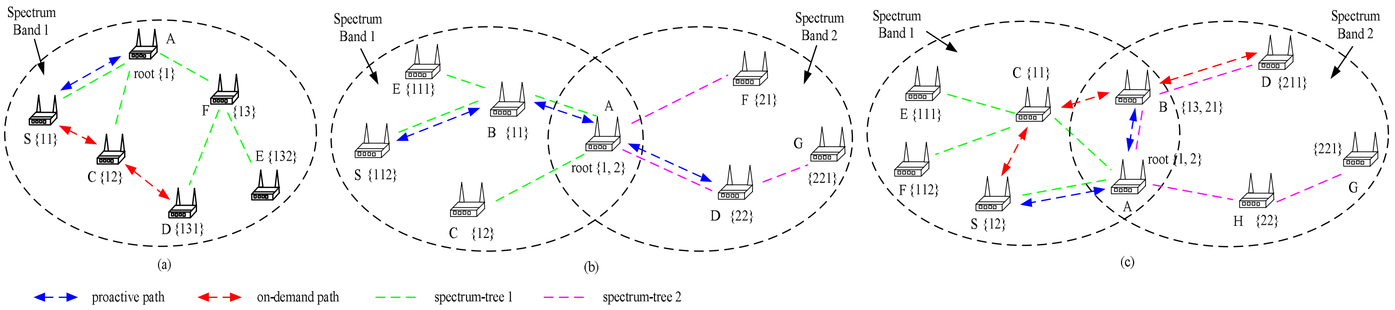

Fig. 2. Examples of spectrum-tree. (a) A single spectrum-tree. (b) Two spectrum-trees with only one overlapping node. (c) Two spectrum-trees with multiple overlapping nodes.

```
begin
root$_i$ = $X$; //At the beginning, node $X$ assumes itself as the root in spectrum band $i$.
recvRootRequest<$N_Y$, $T_{iY}$> //$X$ receives Root Request message from node $Y$ in spectrum band $i$.
if ($N_Y > N_X$) then
    $X$ sets (root$_i$ = $Y$) and records <$N_Y$, $T_{iY}$>, and then forwards the message to other nodes;
end if
if ($N_Y < N_X$) then
    $X$ discards the message;
end if
if ($N_Y = N_X$) then
    if ($T_{iY} > T_{iX}$) then
        $X$ sets (root$_i$ = $X$) and records <$N_X$, $T_{iY}$>, and then forwards the message to other nodes;
        else $X$ discards the message;
    end if
end if
end
```

Fig. 3. Root selection at node *X*.

Every node must notify its CRID to the root. Each root keeps an *inter-spectrum nodes list* which contains the information (e.g. the CRIDs and the current queuing size) of the overlapping nodes in its spectrum-tree.

III. SPECTRUM-TREE BASED ON-DEMAND ROUTING ALGORITHM (STOD-RA)

A. *Route Discovery*

The proposed Spectrum-Tree based On-Demand Routing Algorithm (STOD-RA) combines tree-based proactive routing with on-demand route discovery. The proactive route between non-root nodes and the root node is indicated by node's CRID. The on-demand routing in STOD-RA is an extension of the original Ad-hoc On-demand Distance Vector (AODV) protocol [16]. We classify the routing in multi-hop CR networks as intra-spectrum routing and inter-spectrum routing. Intra-spectrum routing occurs in a single spectrum-tree, while inter-spectrum routing occurs in multiple spectrum-trees.

The STOD-RA uses Spectrum Route REQuest (SRREQ) and Spectrum Route REPly (SRREP) to discover paths between nodes. These two messages are defined as follows:

- Spectrum Route REQuest (SRREQ) which extends RREQ with the fields <$CRID_S$, $CRID_D$, metric, intra/inter>. <$CRID_S$> and < $CRID_D$ > are the CRIDs of source node and destination node, respectively. <metric> is the cumulative cognitive route cost (See Section II.B) from source to the node processing the SRREQ. <intra/inter> indicates whether the destination node is in the same spectrum-tree as source node or not.
- Spectrum Route REPly (SRREP) which extends RREP with the fields <$CRID_S$, $CRID_D$, intra/inter>.

1) *Intra-Spectrum Routing*

Fig. 2(a) illustrates the intra-spectrum routing. Source node *S* wants to communicate with destination node *D*. Both of them work in spectrum band 1. *S* first sends a SRREQ to root 1 (node *A*) by using proactive path. In this SRREQ, the <intra/inter> and <$CRID_D$> fields are empty. When root 1 receives the SRREQ, it checks destination address and finds that *D* is also in spectrum-tree 1. Root 1 adds $CRID_D$ in the SRREQ and marks the <intra/inter> field as "intra-spectrum". Then, root 1 sends the marked SRREQ back to *S* along the spectrum-tree. After receiving the message, *S* checks the <intra/inter> field and knows that *D* is in the same spectrum-tree. Then, *S* broadcast the SRREQ in spectrum band 1 as AODV does. Intermediate nodes calculate the cumulative route metric (See Section II.B) and put it in the <metric> field of SRREQ. When node *D* receives the SRREQ, it chooses the route which has the best route metric and sends back a SRREP to *S*. The best route between nodes *S* and *D* is established when node *S* receives SRREP.

2) *Inter-Spectrum Routing*

Fig. 2(b) and Fig. 2(c) illustrates the inter-spectrum routing. According to the route selection algorithm, node *A* is selected as root in both spectrum-trees 1 and 2. As in intra-spectrum routing, *S* sends SRREQ to root *A* at first. When root *A* receives the SRREQ, it finds that *D* is in spectrum-tree 2. Root *A* adds $CRID_D$ in the SRREQ and marks the <intra/inter> field as "inter-spectrum". *A* then checks its *inter-spectrum nodes list* to find an overlapping node between spectrum-trees 1 and 2.

If there is no other overlapping node (Fig. 2(b)), root *A* sends a SRREP along the spectrum-tree 1 to *S* directly. After receiving data packet from *S*, root *A* forwards it to *D* along the spectrum-tree 2. In this case, the route between nodes *S* and *D* is established through root *A* by using the proactive route, no on-demand routing discovery procedure is initiated.

```
if spectrum band 2 is available to node $S$
    then 1. node $S$ joins spectrum-tree 2;
         2. node $S$ initiates on-demand route discovery in
            spectrum-tree 2 to find the best route to $D$.
    else 1. node $S$ joins an available spectrum-tree (e.g.,
            spectrum-tree 3);
         2. node $S$ asks root 3 to find a gateway node to
            spectrum band 2;
            if a gateway node to spectrum band 2 is available
                then root 3 informs the gateway node to find
                     the best routes to nodes $S$ and $D$,
                     respectively;
                else node $S$ initiates inter-spectrum routing
                     discovery to find a route to $D$.
            end if
end if
```

Fig. 4. Inter-spectrum routing recovery algorithm at node *S*.

If there are other overlapping nodes, root *A* chooses the one which has the shortest queuing size (e.g., node *B* in Fig. 2(c)) as the gateway node between two spectrum-trees. Then, root *A* sends the SRREQ to node *B*. After receiving the SRREQ, node *B* checks the <$CRID_S$, $CRID_D$> fields and knows that the route between nodes *S* and *D* will be established through itself. *B* then broadcast a SRREQ in spectrum band 1 to find the best path to *S* and broadcast a SRREQ in spectrum band 2 to find the best path to *D*, respectively. In the SRREQ broadcasting in spectrum band 1, the source and destination addresses are nodes *B* and *S*, respectively. But the <$CRID_S$, $CRID_D$, intra/inter> fields indicate that the on-demand routing discovery is initiated for nodes *S* and *D*. When node *S* receives the SRREQ, it chooses the route which has the best route metric and sends a SRREP back to overlapping node *B*. Similarly, in the SRREQ broadcasting in spectrum band 2, the source and destination addresses are nodes *B* and *D*, respectively. But the <$CRID_S$, $CRID_D$, intra/inter> fields are the same as the SRREQ sent in spectrum band 1. At last, the best route between nodes *S* and *D* is established through node *B*.

B. Spectrum-Adaptive Route Recovery

Generally, link failures in multi-hop communication result from node mobility. However, in CR networks, the link failures may arise when primary user activities are detected. In our paper, link failure is defined as "the available spectrum band between two CR users changed or vanished as primary users begin to use the network". But our proposed route recovery method also can be used to recover a failed link caused by node mobility. In our solution, according to the radio environments and CR users' QoS requirements, both spectrum handoff and path rerouting methods can be used for route recovery.

1) Intra-Spectrum Routing Recovery

We assume that both nodes *S* and *D* work in spectrum-trees 1 (see Fig. 2(a)). When primary user starts using spectrum band 1, root 1 dismisses the spectrum-tree 1 by sending a *dismiss* message along the spectrum-tree. If there is an empty spectrum band (e.g., spectrum band 2), root 1 notifies the empty spectrum band information to other node before sending the *dismiss* message. Then all the nodes in the spectrum-tree 1 handoff to spectrum band 2. After that, they change their CRIDs automatically (only change A_0 in the CRID), and inform root their new CRIDs. In this case, the spectrum-tree does not need to be re-formed and the route between nodes *S* and *D* does not need to be re-established. Therefore, the control message is reduced significantly. In this case, spectrum handoff is used for route recovery.

If there is no empty spectrum band, then all the nodes re-join other spectrum-trees based on their sensed information after receiving the *dismiss* message. After re-joining the new spectrum-tree, node *S* re-establishes the route to *D* by using the STOD-RA.

2) Inter-Spectrum Routing Recovery

We assume that nodes *S* and *D* work in spectrum-trees 1 and 2, respectively (see Fig. 2(c)). When the primary user starts using spectrum band 1, root 1 dismisses the spectrum-tree 1 by sending a *dismiss* message along the spectrum-tree. Based on CRID, *S* knows that *D* works in spectrum-tree 2. The route recovery algorithm performed by *S* is described in Fig. 4. Similarly, when primary user starts using spectrum band 2, root 2 dismisses the spectrum-tree 2 by sending a *dismiss* message along the spectrum-tree. Then, *D* re-establishes the route to *S* by using the similar algorithm shown in Fig. 4.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed route protocol by carrying out various simulation results. The simulation model was built in NS-2 [17] with multi-radio multi-channel extensions [18]. Simulations are performed in IEEE 802.11-based multi-hop networks, in which nodes are distributed in an area of $500\times500m^2$. Two-ray ground propagation model is used at the radio layer. The bit rate for each channel is 2Mbps. The transmission range of each node is 250*m*. Each source node generates and transmits constant bit rate (CBR) traffic and each data packet size is taken as 512 bytes. The transmission interval for each node is set to 100*ms*. Each simulation is run for 150 seconds of simulation time. Unless otherwise specified, we assume source and destination nodes work in different spectrum bands. The parameters we vary are: number of nodes in the network, number of flows, number of gateway nodes, and number of spectrum bands.

We first compare the end-to-end delay of STOD-RP with that of Cognitive Tree-based Routing (CTBR) protocol [13]. As we mentioned before, source and destination nodes work in different spectrum bands, thus gateway nodes are required for establishing the route between them. Since a packet has to wait to use the gateway nodes when traffic load is high, the average end-to-end delays of both CTBR and STOD-RP increase with the number of flows. Then, we vary the number of overlapping nodes between two spectrum bands. For the CTBR protocol, only the root node can forward data traffic between two trees. When the number of flows increases, the root becomes the bottleneck and the end-to-end delay increases significantly. In contrast, for the proposed STOD-RP, the root node chooses the overlapping node which has the shortest queuing size as the gateway node, thus the traffic is balanced among several

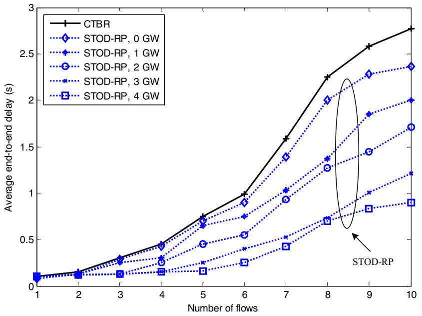

Fig. 5. Average end-to-end delay vs. number of flows.

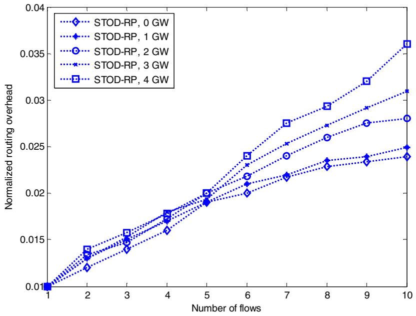

Fig. 6. Normalized routing overhead vs. number of flows.

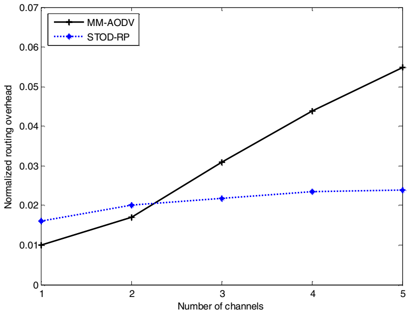

Fig. 7. Normalized routing overhead vs. number of channels.

gateway nodes. When we add the number of gateway nodes, the average end-to-end delay reduces accordingly. Fig. 5 shows the average end-to-end delay of these two protocols as the number of flows increases.

The normalized routing overhead of the proposed routing protocol is illustrated in Fig. 6. Here, the normalized routing overhead can be obtained as follows:

$$Overhead = \frac{N_{control}}{\left(N_{control} + N_{data}\right) \bullet N_{flow}} \tag{4}$$

where $N_{control}$ is the number of control packets transmitted, N_{data} is the number of data packets received, and N_{flow} is the number of flows. The results show that the control overhead is the lowest when there is no other overlapping node, i.e., the root is the gateway node between two spectrum-trees. This is because no on-demand routing discovery procedure is initiated when there is no other overlapping node between two spectrum-trees.

Then, we compare the normalized routing overhead of STOP-RP with that of multi-radio multi-channel AODV (MM-AODV) [18]. We assume there are 5 channels (i.e., spectrum bands) in the network. Since MM-AODV broadcasts Route REQuest (RREQ) in each channel during the route discovery procedure, our proposed protocol reduces control overhead as channel number increases, as shown in Fig. 7.

V. CONCLUSIONS

In this paper we introduce the Spectrum-Tree based On-Demand Routing Protocol (STOD-RP) for multi-hop CR networks. The STOD-RP combines tree-based proactive routing and on-demand route discovery. The key concept in this protocol is to establish a spectrum-tree in each spectrum band, by which the collaboration between spectrum decision and route selection is simplified. Moreover, a new cognitive route metric is proposed in this paper as well as a fast and efficient spectrum-adaptive route recovery method. Simulation results show that the average end-to-end delay decreases as the number of gateway nodes increases. Compared with MM-AODV, our proposed STOD-RP reduces the control overhead significantly.

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