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Local Coordination Based Routing and Spectrum Assignment in Multi-hop Cognitive Radio Networks

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Abstract Although Cognitive Radio technology brings efficient spectrum usage and effective interference avoidance, it also brings new challenges to routing in multi-hop Cognitive Radio Networks. Firstly, spectrum assignment is required for each hop in routing; secondly, new delay is introduced during multi-frequency scheduling and frequency switching in each node; thirdly, the intersecting nodes serving multi-frequency traffic is easy to be bottleneck in neighborhood region. In this paper, we analysis and model the per-node delay and the path delay in multi-hop Cognitive Radio Network. Then we propose a framework of local coordination based routing and spectrum assignment to solve above problems, which consists of one protocol for routing path and one scheme for neighborhood region. A on-demand Routing and Spectrum Assignment Protocol is proposed to exchange the local spectrum information and interact with multi-frequency scheduling in each node. A local coordination scheme is presented to support flow redirection at an intersecting node and distribute heavy multi-frequency workload to its neighborhood. We prove the correctness and effectiveness of the protocol by thorough simulations, and find that the proposed solution provides good adaptability to varying spectrum distribution. The end-to-end delay when adaptive relay is cooperating with routing protocol outperforms traditional bare-routing solutions.

Keywords wireless multi-hop networks · cognitive radio networks · routing · spectrum assignment · local coordination

1 Introduction

Spectrum resources are pre-allocated and fixed in traditional wireless communications. This license based static spectrum policy results in poor utilization and spectrum holes [1]. One promising solution is Cognitive Radio (CR) technology [2], which enables unlicensed users to sense, identify and intelligently access the unused licensed radio resources. In Cognitive Radio Network (CRN), the legacy license holders (primary users) have priority in spectrum access, while unlicensed (secondary) users opportunistically utilize the currently unoccupied and available frequency bands. CRNs are expect to provide efficient spectrum usage and simplified deployment for new wireless applications. There are lots of new challenges in every layer of CRN architecture. In this paper, we focus on the network layer issues in wireless multi-hop CRN.

In wireless multi-hop network, If the destination node is out of the transmission range of the source node, the data packets will be relayed by the nodes

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along the route to destination. On-demand routing algorithms [3] were proposed to infrastructure-less multi-hop networks, such as Mobile Ad hoc network and sensor network. As to wireless multi-hop CRN, there are several new challenges in routing:

- At First, routing in multi-hop CRN will be jointly studied with spectrum assignment. In traditional wireless networks, nodes communicate in the same frequency band. The distances among nodes are the only parameters affecting the connectivity of network topology. In multi-hop CRN, the neighbor nodes may work on different frequency bands to avoid collisions with primary (authorized) users. Then the communication frequency band is an essential parameter for every hop record in route table. Thus, not only the nodes' location but also their communication frequency bands affect network connectivity.
- Secondly, there is a need to investigate the performance metrics of routing in multi-hop CRN. End-to-end delay along route is a traditional metric for routing algorithms, while it faces several different cases in multi-hop CRN. Two nodes are not able to communicate if they are on different frequency bands, resulting in 'deafness problem' [4]. If it occurs, communicating nodes would wait for a while and retransmit the packet, which brings unnecessarily increased delay. If a node changes frequency band, it will bring extra switching delay [5, 6]. When nodes are working on identical frequency band, the MAC protocols to solve hidden-terminal and exposed-terminal problems will result in backoff delay.
- Finally, the *intersecting nodes*, who provide forwarding service for the traversing flows with different communication frequency, are easy to be the performance bottleneck of multi-hop CRN. Additional switching delay will be introduced if the intersecting nodes serving flows with too many frequency. What's more, since the spectrum utilization is always related to the current status of radio resource occupation in specific region, it is hard to achieve high spectrum utilization just by separate spectrum assignment along different routes. New methods, such as local relay cooperation, are required to increase the spectrum utilization in the neighbor region of intersecting nodes.

Similar research works were done in the area of wireless multi-channel networks, which want to find efficient routes and assign channels. Some methods were proposed based on centralized algorithms aiming for overall optimal network performance (such as low interference, high throughput and fairness) [7–9]. Those methods assumed that global information, either the nodes' position or spectrum distribution, is known aforehand. But in the scenario of infrastructure-less multi-hop CRN, it is hard to obtain such information or keep it up-to-date. On-demand approaches were also proposed to reactively select routes and assign spectrum resources [4, 10, 11]. Those approaches assumed that the set of available channels is static and globally known by all. However, the spectrum resource adopt for communication in multi-hop CRN might be quite different from node to node, and the set of available channels might dynamically change as well.

In this paper, we focus on the scenario of infrastructure-less multi-hop CRN. As to the CR ability of each node, we assume that each node can individually detect its *Spectrum Opportunity* (SOP) [9], a set of frequency bands currently unoccupied and available for use. And each node can not only switch to different communication frequency, but also perform self-evaluation of workload. A general framework is proposed to achieve efficient routing and spectrum assignment in multi-hop CRN, which consists of two parts. One is a joint on-demand routing with frequency band selection, similar to our prior work [12], mitigating multiple delays. We evaluate the effectiveness of on-demand routing in multi-hop CRN, taking into account of the spectrum switching delay, backoff delay and intersecting node serving delay. The other is a local coordination scheme, in which the intersecting nodes perform data flow redirection based on the cost evaluation of frequency band switching and queueing.

The main contributions of this paper include:

- A joint on-demand routing algorithm with frequency band selection is proposed to achieve minimal end-to-end delay in multiple-hop CRN.
- A local coordination scheme is proposed for load balancing among multiple frequency traffic in the intersecting relay node.

The rest of this paper is organized as follows. First, we discuss the background scenario and state the problems in Section 2. Then, we describe the whole framework of Local Coordination based Routing and Spectrum Assignment in Section 3, and present the analytical model of workload on intersecting nodes in Section 4. The detailed implementation of proposed framework is discussed in Section 5. In Section 6, we evaluate the system performance by simulations. Relevant work in this area is reviewed in Section 7. Finally we conclude this paper in Section 8.

2 Problem statement and motivation

2.1 Problem statement

In multi-hop CRNs, the under-utilized licensed bands can be dynamically accessed and reused, and the interference can be alleviated by distributing interfering links to non-interfering frequency bands. However, it also brings several side effects on relaying nodes:

2.1.1 Inconsistency of SOPs

The spectrum agile transceiver in a CRN node actively senses the 'spectrum hole' [13] according to the presence of primary users, tunes within a wide range of spectrum and operates on any possible frequency band. As a result, the set of available frequency bands, known as the node's SOP, may vary with time, subject to the spectrum usage of primary users. The working frequency band of a node is selected from its SOPs, and the communication between two nodes in CRN depends on an agreement of utilizing the same band. So the inconsistency of SOPs may change the instantaneous neighboring relationship of corresponding nodes, and leads to changes of network topology. Therefore, an SOP exchanging and synchronization mechanism is required among nodes in multiple-hop CRN such that routes with communication potential can be found.

2.1.2 Various delays in CR nodes and routes

Figure 1 shows a typical case scenario of multiple-hop CRN. Suppose that $flow_{new}$ is currently being established from source node 1 to destination node 6. Node 2,3,4,5 are chosen as relaying nodes. In the figure, there already exist $flow_1$ and $flow_2$ that utilize node 2 and node 5, respectively. Node 2 relays $flow_1$ by receiving data on frequency band A and transmitting data on frequency band B, while Node 5 relays $flow_2$ using frequency band C for both receiving and transmitting. Suppose $flow_{new}$ needs node 2 to send and receive on frequency band D, then node 2 has to switch among frequency band A, B and D. On the other hand, if $flow_{new}$ wants node 5 to send and receive on frequency band C, then it doesn't switch at all. The delay at node 2 is dominated by switching delay, while the backoff delay is dominant in node 5. Due to the backoff policy in [14], it is of comparative order of magnitude with the switching delay, and thus is non-negligible.

In addition to the delays at nodes, there exists delay along a path as well. As the SOP varies from node to node, a multi-hop path may be assigned with identical frequency band, or totally distinct frequency bands, or a hybrid of the two. Different frequency assignments result in different path-long delay. Typically, the more frequency bands a route employs, the larger switching delay it brings, thus the routing protocol need to be flexible enough to accommodate a range of switching delays. On the other hand, routes with fewer switching utilize fewer frequency band, resulting in not only the decrease of spectrum utilization, but also the increase of interference and collision in certain frequency bands (say, the famous hidden/exposed terminal problem), which also brings time delay.

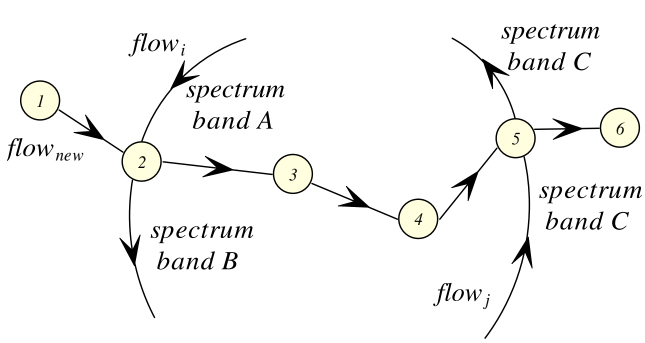

Figure 1 Impact of other flows

2.1.3 Multi-frequency traffic on intersecting nodes

In addition to the various delays, relaying nodes at intersections of multiple data flows are facing special problem of multi-frequency-band serving. For heavily loaded multi-hop CRN, intersecting node like node 2 and 5 (see Fig. 1) is commonly seen. Different flows may require the intersecting node working in different frequency bands. As a result, intersecting nodes will keep switching among a set of bands for its own traffic and forwarding traffic. In Fig. 1, suppose $flow_{new}$ needs node 2 to receive and send on frequency band C, then node 2 has to switch among frequency band A, B and C to serve $flow_{new}$ and $flow_1$.

According to existing proposals on routing and frequency band assignment, nodes in multi-hop CRN have no other option but to accommodate the incoming flow, no matter whether to change frequency bands or not. Therefore, the intersecting nodes will serve for multiple data flows and thus switch among a lot of frequency bands. This surely results in severe degradation of network relaying performance, introducing unnecessary switch delay to traffic flows and decreasing the spectrum utilization in the neighbor region of intersecting node. This problem can not be solved by centralized or reactive routing algorithms. For centralized routing schemes, it is hard and infeasible to calculate optimal routes and frequency band assignment between all possible node pairs. In the case of reactive solutions, route calculation and frequency band assignment is invoked upon every randomly initiated flow. Although it brings efficiency, the distributed manner keeps the nodes from knowing the impact of other existing data flows.

2.2 Motivation

To overcome the inconsistency of SOPs among nodes, we propose an on-demand routing protocol for SOP information exchanging and synchronization [12]. What's more, a kind of multi-flow multi-frequency scheduling scheme is proposed to select frequency band to restrain various delays. In the case of Multi-frequency traffic impact at intersecting nodes, we notice that neighboring secondary nodes usually sense and avoid the same primary user, thus nodes in proximity are sharing with similar wireless environment most of the time. To overcome the potential performance degradation due to overflowed serving at intersecting nodes, we propose to offer intersecting nodes another option of redirecting the data flow to other neighboring nodes, and therefore, a local coordination scheme is motivated for those intersecting nodes to make decisions locally and adaptively.

Figure 2 shows the motivation of Local Coordination in multi-hop CRNs. Once the incoming flow is brought by the routing and frequency assignment protocol, the intersecting node decides whether to accommodate the flow or redirect it to its neighbors. In the figure, $flow_1$ is being established, node 1 and 2 are selected for relaying. However, node 1 is already serving for $flow_2$ and $flow_3$, and node 2 is serving for $flow_4$. These two intersecting nodes perform Local Coordination to find appropriate neighbor for redirecting the flow, and in this way relief the local heavy workload. In the example, $flow_1$ and $flow_3$ are redirected via neighboring node M and N of node 1, respectively, while $flow_4$ is redirected via neighboring node Q of node 2. Consequently, the workload at the intersecting nodes are fairly distributed onto their neighborhood.

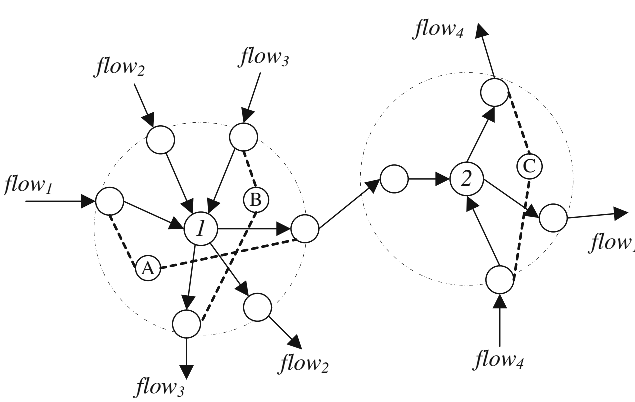

Figure 2 Motivation of local coordination

3 Framework of local coordination based routing and spectrum assignment

Following the motivation stated in Section 2, we present the framework of our Local Coordination based Routing and Spectrum Assignment. It consists of two main parts, one is Routing and Spectrum Assignment protocol, the other is local coordination scheme. As shown in Fig. 2, routing and spectrum assignment protocol establishes the multi-hop path $flow_1$, assigning appropriate frequency band to each hop. The intersecting nodes on the path initiate local coordination to achieve possible flow redirections, aiming for load balance in multi-frequency traffic.

3.1 Scenario description and assumption

To ensure that routing protocol messages are received by network nodes despite of the inconsistency between their frequency bands, we assume that each node is equipped with a traditional wireless interface in addition to the CR transceiver, following the suggestion in [15]. A common control channel is then formed by those traditional interfaces, such that all nodes' SOPs can be shared among network. Although there are other possible solutions such as broadcasting on all frequency bands, implementing with off-the-shelf wireless equipments is more practical. Additionally, we assume that every node is able to provide the routing module with its SOP information. This can be achieved by applying cross-layer design, sharing spectrum sensing result between network layer and MAC layer.

3.2 Routing and spectrum assignment protocol

The proposed protocol, similar to our previous approach [12], consists of the following modules:

3.2.1 Multi-flow multi-frequency scheduling

For nodes in multi-hop CRN that serving for multiple data flows, only part of the frequency bands from their SOPs are used, we call them *active* frequency bands. For such intersecting nodes, serving flow by flow introduces unnecessary switching delay if some flows are utilizing identical frequency bands. Therefore we propose a scheduling scheme that nodes perform polling

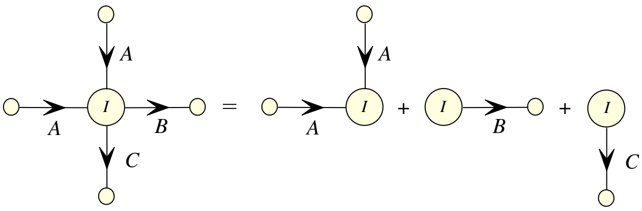

Figure 3 Decomposition for frequency band polling

among the *active* frequency bands, and the spectrum agile transceiver on each node tunes to a specific frequency band once within a polling cycle, processing all correlated flows (see Fig. 3).

3.2.2 On-demand routing

To smooth away the inconsistency of SOP, we modified AODV [3] to form a mechanism on the control channel for exchanging SOP information among network nodes. The protocol should also identify traversing flows at each node and calculate the *active* frequency bands taken, which are used for multi-flow multi-frequency scheduling. The switching and backoff delay along the path or at the intersecting nodes are represented as PATH-delay(DP) and NODE-delay(DN), respectively. They are the judging basis for evaluating the cumulative delay of the path.

We further apply interaction between on-demand routing and scheduling: scheduling module adaptively selects appropriate frequency band, and the selection result is piggybacked by the routing module for exchanging. On the other hand, routing module provides SOP information of other nodes, based on which the scheduling module could establish queueing system at the intersecting nodes. In this way, the delay of nodes along the path are collected and reused as feedback to calculate the path-long cumulative delay.

3.3 Local coordination scheme

The scheme of Local Coordination is applied to every node in multi-hop CRN. Once it becomes intersecting node for multiple data flows, the Local Coordination process is invoked. The scheme helps nodes decide whether to perform flow accommodation or flow redirection, the former follows the basic procedure of routing and spectrum assignment protocol described above, the latter is based on interaction within the neighborhood of the intersecting node. Moreover, the criteria of the decision is based on workload evaluation on intersecting nodes.

3.4 Summary

The routing and spectrum assignment protocol is the basis of multi-hop transmission in CRNs, in which route computing is reactively initiated whenever there is need to establish an end-to-end path, and SOP information is disseminated while frequency band of each hop is selected to minimize the cumulative delay [12]. The local coordination is an enhancement scheme for intersecting nodes on a path. These nodes begin the local coordination while evaluating the workload (or the potential cost) of both accommodating the flow and redirecting it. Based on the evaluation results and neighborhood interaction, the nodes then choose either *Flow Accommodation* or *Flow Redirection* to deal with the incoming data flow.

4 Workload analysis and evaluation at intersecting nodes

In this section, we analyze the performance of intersecting nodes in multi-hop CRNs. As assumed earlier, a node has only one spectrum-agile transceiver. Under such situation, node can send and receive data packets on one frequency band at a time. We also assume that each possible frequency band has similar throughput capacity. This is because band quality fluctuates due to fading, shadowing and environmental factors, making it impractical to collect instantaneous band quality in real time. Hence, a reasonable approach is to assume all frequency bands result in a similar average throughput in this respect.

Intersecting nodes in such scenario is facing multiple flow relaying requests, however, such relaying nodes with single radio are able to handle only one relaying request at a time, while other flows have to wait. This is similar with the nature that nodes are contending for access to the wireless medium, where the medium is allocated to one communicating pair following some typical policies [14, 16], while in this paper, several flows are contending for the same relaying node. Therefore, we set up an analytical system model that captures the essential of the problem (Fig. 4): a 2-hop network consisting of n nodes (representing n incoming flows), and a relaying node I that forwards the traffic to whatever destinations.

4.1 Queueing system model

We model the analytical system described above as a multi-flow queueing system. Suppose the system capacity is C, as n nodes are sending traffic via the

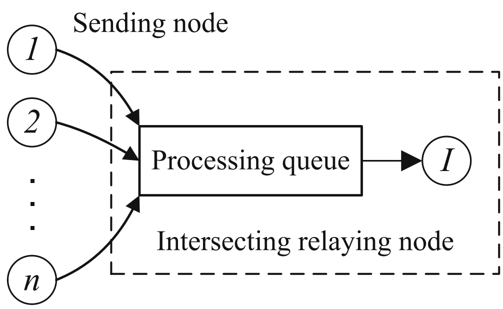

Figure 4 Analytical model of intersecting relaying node

same relaying node I, then due to the sharing policy, the relaying node obtains just the same share of the medium capacity as each of the 'sending nodes'. In other words, as soon as $n \geq 1$, the relaying node's input load exceeds its output rate, and hence the excess traffic accumulates in the node's buffer; only when $n = 0$ does the queue drain. As the consequence, these relaying nodes become bottlenecks, and will strongly affect the performance of the flow relaying through the whole multi-hop CRN.

We assume that the incoming flows are arriving according to a Poisson process with the arrival rate λ, requesting that they be forwarded via the same intersecting node. In Fig. 4, the sending nodes $1 \sim n$ (representing the incoming flows) and the relaying node I equally share the system capacity C. Therefore, with n sending nodes bringing traffic into its *processing queue* at the rate $C/(n+1)$, the relaying node serves the buffer at the same rate. A sending node leaves this system as soon as it finishes the last data packet for the corresponding flow.

It is claimed that flow sizes F are independently and identically distributed random variables with finite mean f and second moment f_2, and the load of the system is defined by $\rho = \frac{\lambda f}{C}$ [17].

Our interest lies in the evaluation of the service time required to serve the queue related to the service rate C, thus in the following part, we investigate the performance of this queueing system in terms of queueing delay.

According to [17], the workload and the queueing delay are derived from two different situations:

1. **Arbitrary Epoch**:
This is an ordinary transfer epoch at which a sending node brings flow data. It is called an Arbitrary Epoch. In this epoch, the total amount of work consists of two parts: the amount of work present at the sending nodes and the amount of work present in the queue of the relaying node. Therefore, the mean queueing delay of an ordinary flow transmission ($\mathrm{E}D_{queueing}$) in the queue of the relaying node can be stated as follows [17]:

$$\mathrm{E}D_{queueing} = \frac{2\rho f_2}{f \cdot C(1-2\rho)(1-\rho)} \tag{1}$$

2. **Last-Particle Epoch**:
This is the epoch when the last particle of a flow arrives at the relaying node. It is denoted as Last-Particle Epoch. In this epoch, the queue depth of a particular flow (denoted by $Q^*_{relaying}$ [17]) is the queue occupancy at arrival of the flow plus the increase during its flow transfer time $D_{sending}$, and thus the queueing delay ($\mathrm{E}D^*_{queueing}$) is equal to the time required by the relaying node for serving the queue content. Following the approximation given in [17], we have:

$$\begin{aligned}\mathrm{E}D^*_{queueing} &\approx \sum_{n=0}^{\infty} \pi_n \mathrm{E}\left(\frac{Q^*_{relaying}}{C}\right) \\ &= \sum_{n=0}^{\infty} \frac{\pi_n}{C}\left(\frac{2\rho^2 f_2}{f(1-2\rho)(1-\rho)} + \frac{2f\rho}{1-\rho}\right)\end{aligned} \tag{2}$$

where π_n is the distribution $\mathrm{P}(N=n)$ of the number of sending nodes in the system [17]:

$$\mathrm{P}(N=n) = (n+1)(1-\rho)^2\rho^n \tag{3}$$

4.2 Integrated cost evaluation

In the scenario of multi-hop CRN, there are other impacts on the transmission cost evaluation in such 'Relaying-node Sharing System'.

As stated in Section 2, there exist switching delay between frequency bands ($D_{switching}$) and backoff delay within identical frequency band ($D_{backoff}$). Our prior work [12] proposed a routing and spectrum assignment protocol for multi-hop CRN, and gave out routing and frequency band selection metric which is aware of the two kinds of delay. Their impacts on the route selection was measured by cumulative delay, which was investigated from the following two different parts:

1. Switching delay and backoff delay caused by existing flows at relaying node. It is called NODE-delay (DN), which depends on the number and the frequency bands of traversing flows. According to [12], $DN = D_{switching} + D_{backoff}$. The switching delay $D_{switching}$ is formulated as:

$$D_{switching} = 2k \cdot |Band_M - Band_1| \tag{4}$$

where k is a positive constant (suggested as $\frac{10ms}{10MHz}$ in [6]) and $Band_i$ is the frequency band from node's *active* band set, which has M active bands. The backoff delay $D_{backoff}$ is obtained by the following expression:

$$D_{backoff}(Num_i) = \frac{1}{(1-p_c)\left(1-(1-p_c)^{\frac{1}{Num_i-1}}\right)} W_0 \tag{5}$$

where Num_i is the number of contending nodes, p_c denotes the probability that a contending node experiences collision, and W_0 represents the minimum contention window size [14].

2. Switching delay and backoff delay caused by the path itself. It is called PATH-delay (DP), which depends on frequency bands assigned to all the nodes along the path. The PATH-delay at node i is $DP_i = D_{switching,i} + D_{backoff,i}$. The switching delay along the path is derived as [12]:

$$D_{switching,i} = \sum_{j=i}^{H} k \left| Band_j - Band_{j+1} \right| \tag{6}$$

where H is the number of hops between node i and the destination. On the other hand, let p_o be the probability that a node observes the channel available, p_c be the probability that node M observes the channel available given that its neighbor N observes the channel available, and q_c be the probability that M observes the channel available given that N does not, we also have the backoff delay along the path as [12]:

$$D_{backoff,i} = \frac{S_{data}}{B} \left(\frac{\left\lfloor \frac{h_X+1}{2} \right\rfloor - U(h_X)}{U(h_X)} \right) \tag{7}$$

where S_{data} is packet size, B is the bandwidth under current frequency band, h_X is the number of consecutive nodes who are sharing an identical frequency band X, and:

$$U(h_X) = \begin{cases} \sum\limits_{j \text{ is even}}^{h_X} \left((1-p_o) q_c \frac{1-p_c^j}{1-p_c^2} \right) \\ \sum\limits_{j \text{ is odd}}^{h_X} \left((1-p_o) q_c \frac{1-p_c^{j-1}}{1-p_c^2} + p_o p_c^{j-1} \right) \end{cases} \tag{8}$$

As we can see, for a relaying node i who is running routing and spectrum assignment protocol [12], the metric of cumulative delay along a candidate route is derived as:

$$D_{route,i} = DP_i + \sum_{i}^{M} DN_q \tag{9}$$

However, $D_{switching}$ and $D_{backoff}$ are used to evaluate the effectiveness of next-hop and frequency band selection in the routing protocol, while the queueing delay derived in Section 4.2 is an objective evaluation on the workload at intersecting node. Therefore, we propose to integrate $D_{switching}$, $D_{backoff}$ and queueing delay together as the 'Generalized Cost' (denoted by $C_{generalized}$) for choosing the current intersecting node:

$$C_{generalized} = D_{route,i} + D_{queueing} \tag{10}$$

4.3 Summary and discussion

In this section, we analysis the queueing system at relaying nodes. However, the queueing delay is not the only factor that affects the performance of relaying nodes. While utilizing multiple frequency bands, they are suffering both switching delay and backoff delay [12], therefore we make an integration to take a joint consideration of these three kinds of delay at relaying nodes. The integration results in a generalized cost $C_{generalized}$, which objectively tells the effectiveness of route selection.

We further formulate the generalized cost as:

$$C_{generalized} = F_{protocol}(D_{switching}, D_{backoff}) + D_{queueing} \tag{11}$$

where $F_{protocol}(\cdot)$ is a function of $D_{switching}$ and $D_{backoff}$, corresponding to any particular routing protocols in CRN, and $D_{queueing}$ varies with different epochs according to the queueing system.

5 Implementation of local coordination based routing and spectrum assignment

We implement the routing and spectrum assignment protocol based on on-demand routing protocol AODV [12]. Incoming flows are described as 2-tuples {*source-side band, destination-side band*}, indicating the frequency bands a flow claims when traversing the node. The detailed procedures for handling both RREQ and RREP are illustrated in Fig. 5. Every node in multi-hop CRN follows this procedure to exchange their SOPs and frequency band selection result, based on which route selection is made.

In addition to the above-mentioned protocol, we propose local coordination in multi-hop CRN to offer intersecting nodes another option of redirecting the data flows. The intersecting node should invoke the

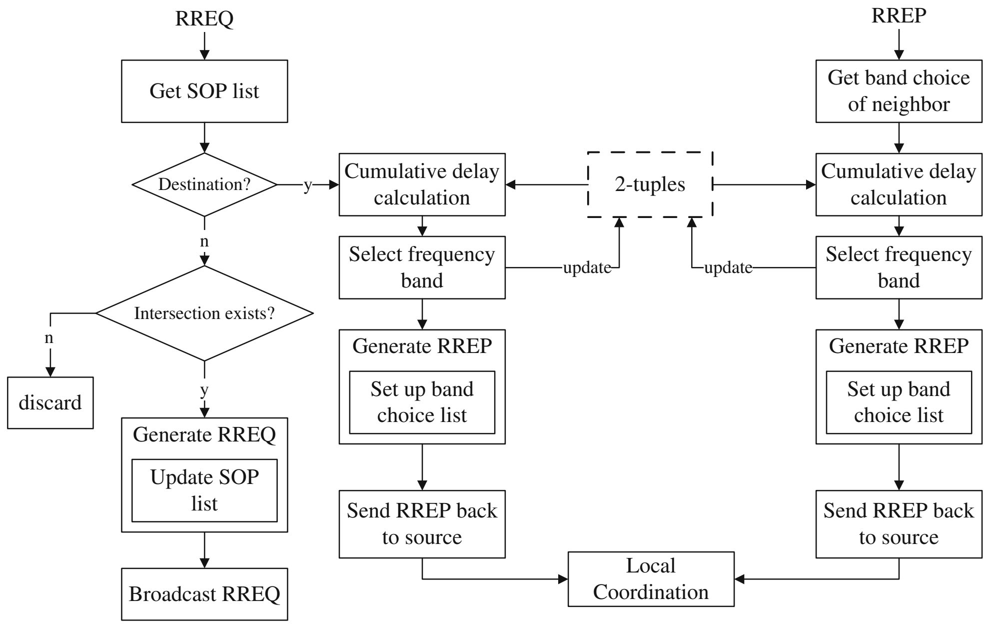

Figure 5 Implementation of routing and spectrum assignment protocol

mechanism of Local Coordination upon receiving flow packets directed by routing protocol.

Figure 6 shows the implementation flowchart of local coordination, which includes operations of Cost Evaluation, Neighborhood Interaction and Flow Redirection. Cost Evaluation is done at every nodes in the proximity, and the evaluation results are synchronized using Neighborhood Interaction such that every relaying node has a clear view if there exists any neighbor that can provide better service of relaying. If the intersecting node decides to redirect the incoming flow, it again uses Neighborhood Interaction for messaging and negotiation. Note that both Flow Redirection and Cost Evaluation are implemented based on Neighborhood Interaction, Flow Redirection is done only by intersecting nodes while Cost Evaluation happens on every node, in that every node in proximity has the potential to relay data flows.

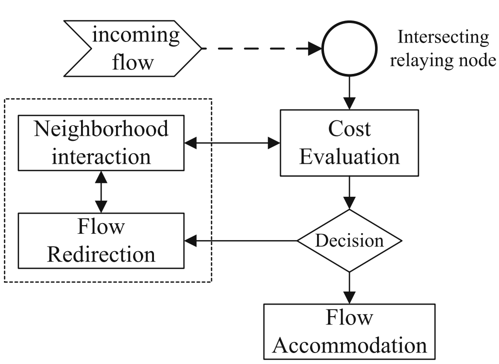

Figure 6 Implementation of local coordination

5.1 Neighborhood initialization

The first step of Neighborhood Interaction is neighborhood initialization or neighbor discovery, which is done through channel scanning and beacon broadcast. With the help of common control channel, node discovery process may be shorter than those need to broadcast beacons rotating through available frequency bands.

In multi-hop CRN, neighboring secondary nodes usually sense and avoid the same primary user. Thus they are sharing with similar wireless environment most of the time, which would result in faster neighborhood establishment and less complicated maintenance.

After neighborhood initialization, each node in the proximity has a list of its neighbors and their available channels. This allows the nodes to send messages to all of its neighbors.

5.2 Cost evaluation exchanging and flow redirection

When confronting multiple incoming flows, the intersecting relaying nodes start the operation of exchanging cost evaluation information within neighborhood. We suppose that every relaying node has the intention to find better substitutions by doing so.

Figure 7 shows the complete process of the interaction among sending node, intersecting node and the neighboring nodes. Once the intersecting node receives ‘Relaying Request’ (Fig. 8) from a new incoming flow, it initiates the process of Cost Evaluation Exchanging. Intuitively, the information of the incoming flow

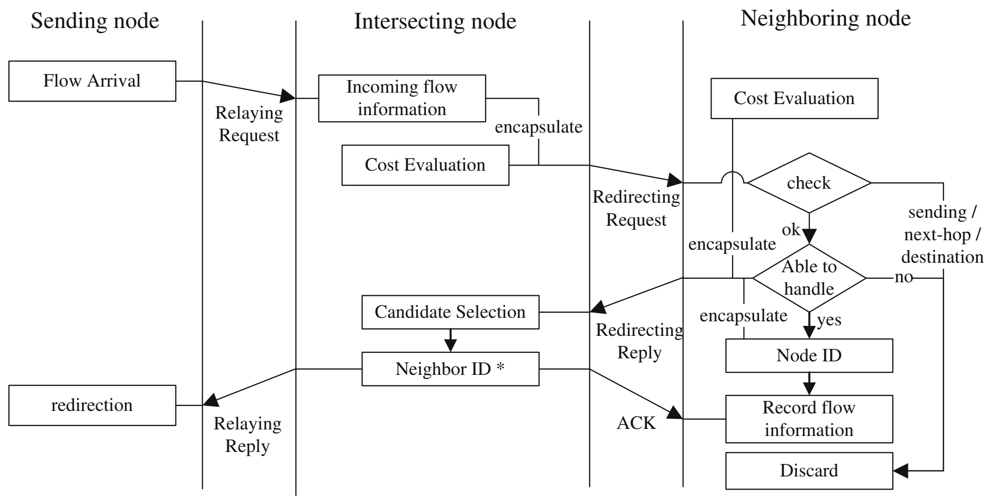

Figure 7 Flow redirection

is brought to the intersecting node by routing protocol. It is then directly broadcasted by the intersecting node, along with its value of 'Generalized Cost'. Those information is encapsulated as 'Redirecting Request' (Fig. 8).

From a neighboring node's point of view, once a 'Redirecting Request' is received, it checks its validity with the corresponding flow, ensuring that it is not the source/destination node or next-hop node of that flow. Then the neighboring node initiates the process of Cost Evaluation, making comparison between its 'Generalized Cost' and the one extracted from the 'Redirecting Request'. If the Generalized Cost in the neighboring node outperforms that of the relaying node, it generates a message named 'Redirecting Reply' (Fig. 8), piggybacking the cost evaluation result and its node ID back to the relaying node.

On receiving 'Redirecting Reply' from several of its neighbors, the intersecting node then begins candidate selection, during which the intersecting node extracts the Generalized Cost value from each 'Redirecting Reply' to find an optimal one. Then it generates a 'Relaying Reply' (Fig. 8) with optimal node ID in it, and sent to the sending node. As soon as the 'Relaying Reply' is sent, the intersecting node sends out another acknowledgement message to the selected neighbor, informing that it is chosen to handle the flow.

On the side of sending node, once receiving the 'Relaying Reply', it extracts out the node ID, and slightly changes the next-hop node for the current flow.

Please see detailed procedure in Algorithms Eqs. 1, 2, 3 and 4.

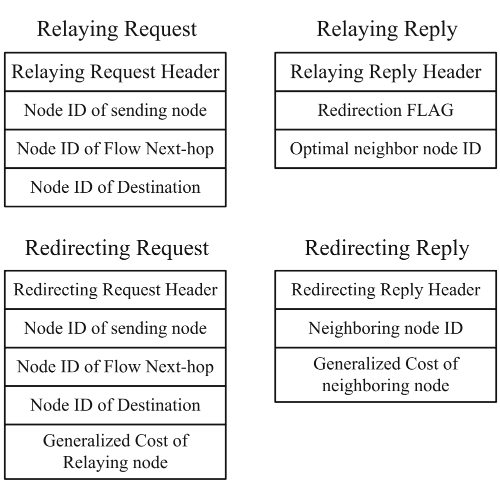

Figure 8 Format of adaptive relay messages

Algorithm 1 Handling Relaying Request at Relaying node

1. calculate Generalized Cost GC_R;
2. generate and broadcast Redirect Request;

Algorithm 2 Handling Redirecting Request at neighboring node *m*

1. Redirecting Request message parsing, get flow information and GC_R from relaying node;
2. **If** $m = sending\ node \,||\, nex\text{-}hop\ node \,||\, destination$ **then**
   | discard message;

end
else calculate Generalized Cost GC_m;
if $GC_m > GC$ **then**
| discard message;
end
else generate and send Redirecting Reply

Algorithm 3 Handling Redirecting Reply at relaying node

1. Redirecting Reply message parsing, get node ID and GC_m;
2. $GC_{min} \longleftarrow GC_R$;
3. **while** $GC < GC_{min}$ **do**
   | $GC_{min} \longleftarrow GC_m$;

end

4. $nodeID^* \longleftarrow m, args_m(GC_{min})$;
5. generate and send Relaying Reply to sending node;
6. generate and send ACK to neighboring node m;

5.3 Discussions

The mechanism of Local Coordination aims to alleviate the service load of intersecting nodes. The comparisons between relaying node's Generalized Cost and those of neighboring nodes' are distributed to every neighboring node to introduce minimum impact on the intersecting node's current multi-flow processing. In addition, we eliminate neighboring nodes which are originally on the path of the incoming flow, otherwise the Redirecting Requests are sent to nodes without redirecting potential. Furthermore, we conduct loop-free operation by recording negotiated flow information, such that the neighboring node, which is chosen for flow redirecting, will not generate its own Redirecting Request for this just-assigned flow. As a result, the Local Coordination scheme is a light-weight, and robust scheme. The relationship between Routing and Spectrum Assignment Protocol and Local Coordination is shown in Fig. 5, where Local Coordination is invoked after an intersecting node sends out RREP message back to source node. That is the moment the intersecting node is preparing for accommodating the new flow, as routing protocol told it to do so.

6 Simulation and analysis

6.1 Numerical results for queueing system modeling

In this section, we present numerical results of the exact and approximate results of the previous Queueing System Modeling (Section 4.1).

Algorithm 4 Handling Relaying Reply at sending node

1. Relaying Reply message parsing, get node ID $nodeID^*$;
2. next-hop ID $\longleftarrow nodeID^*$;
3. transmit flow;

The simulations are conducted using Matlab, a queueing system is set up with one server and one queue. According to the model in Section 4.1, we simulated the system using $C = 1$ and $f = 1$. As the performance measures are linear in f, the performance measures for different flow sizes f can be directly obtained from $f = 1$. For flow-size distributions we used Deterministic, Erlang-4 and Exponential distributions. The load ρ is varied from 0.05 to 0.45 to observe the system under different loads.

Figure 9 presents the results for the mean queueing delay for both arbitrary epoch (Fig. 9a) and the last particle epoch. The queueing delay of the last particle in Fig. 9b is an approximation, but it captures the behavior very well, not only for exponential flow sizes (for which the approximation is originally designed), but also for other flow-size distributions. An interesting observation is that queueing delay corresponding to an arbitrary particle is higher than the queueing delay of the last particle (see Fig. 9c, where prefix 'L-' stands for last particle epoch and prefix 'A-' stands for arbitrary epoch). This effect can be explained that as with high probability an arbitrary particle belongs to a large flow. It has two negative effects: first, before the particle enters the queue the sending node has been transmitting for a long period, so the queue depth will be high; second, when the particle has entered the queue, the sending node will remain active (in the system) for a long period resulting in a low rate for the relaying node.

6.2 Queueing system cost evaluation

We conduct experimental simulations to quantify the performance of Adaptive Relay mechanism. We carry out simulations on several random scenarios with distinct source-destination pairs. Up to 100 wireless nodes are randomly distributed over a 1800 by 1800 m area, the two-ray ground path loss model is used and the radio range is assumed to be 372.214 m (see Fig. 10). Each network node is equipped with single transceiver that actively switches working frequency band.

We let each node randomly pick 6 accessible frequency bands out of 8, in order to simulate the situation that neighboring secondary nodes share with similar wireless environment most of the time.

To establish a queueing system with heavy load at the intersecting relaying node, we set up 8 source-destination pairs crossing the whole simulation topology. As the mechanism under evaluation is routing-protocol independent, we manually set every source-destination pair to ask for a particular node in the center of the topology for relaying service (say the

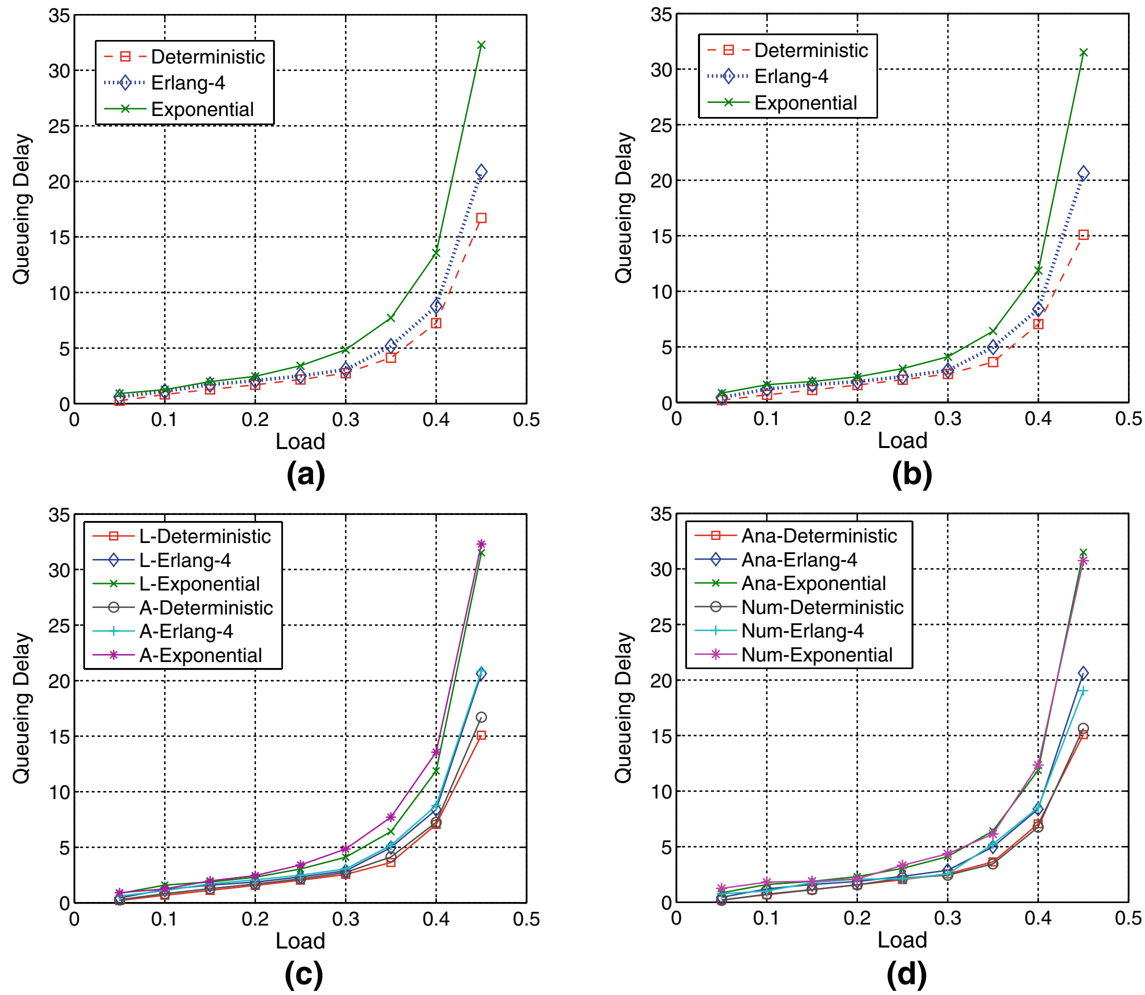

Figure 9 Mean queueing delay. **a** Analytical result in arbitrary epoch. **b** Analytical result in last particle epoch. **c** Arbitrary epoch vs. last particle epoch **d** Analytical result vs. numerical result

node in the center of a one-hop circle). To test the effectiveness of the Cost Evaluation, we let the source-destination pair be active one by one, set the flow size with deterministic distribution, and the Generalized Cost (see Eq. 11) derived at the relaying node increases.

From the curve in Fig. 11, it is obvious that the Generalized Cost increases more and more rapidly with the growing number of node-pairs. This matches the theoretical analysis well, is can be explained that the increasing number of incoming flows results in greater queue depth, and therefore incurs larger queueing delay. On the other hand, the Generalized Cost also has aspects such as frequency band switching delay $D_{switching}$ and backoff delay $D_{backoff}$. As band switching and backoff are is likely to happen in our simulation scenario, these kinds of delay is not negligible, yet makes the curve less smooth compared to the analytical result (Fig. 9b) where only queueing delay is considered.

6.3 Adaptability to varying spectrum distribution

To illustrate the proposed schemes' adaptability to varying spectrum distribution and their transmission performance, we employ the metric 'sparsity of spectrum distribution' (SSD) [12], which describes the average difference between two consecutive frequency bands in SOP. Apparently, higher SSD represents higher switching costs. In order to have thorough comparison, we introduce two other typical schemes. Scheme that aware of the side-effect of switching delay cares for the number of channel switches and the frequency of channel switching. On the other hand, another assignment scheme pointed out that spectrum assignment should be K-hop distinct to reduce interference and achieve high utilization. We implemented the two kinds of schemes in our simulation, called 'Switch-aware' [4, 15] and 'K-hop distinct' [10] respectively. We

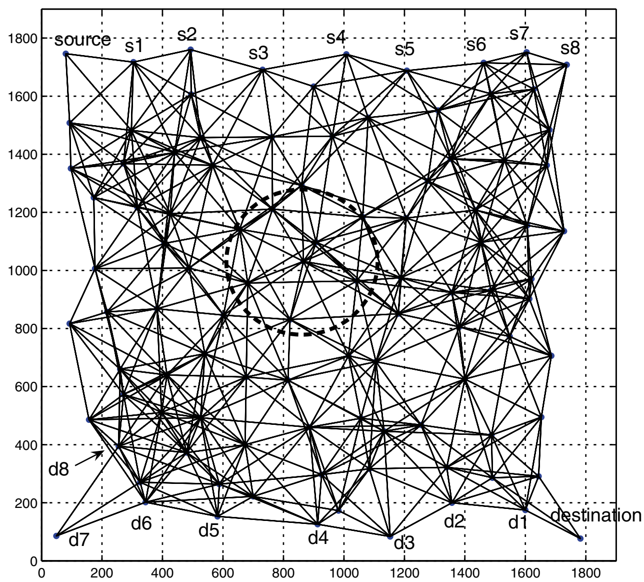

Figure 10 Evaluation topology

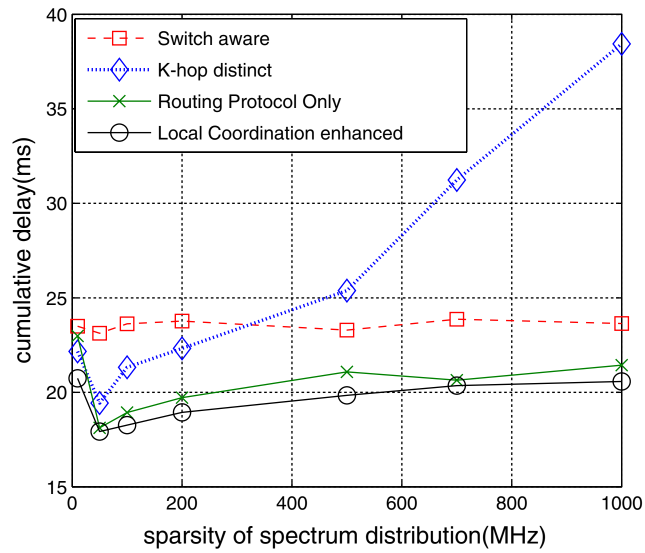

Figure 12 Cumulative delay with varying spectrum distribution sparsity

measured the cumulative delay along the route, and explore its behavior as SSD increases.

We use the topology shown in Fig. 10 to test the ability of adapting to various switching cost both on routing-protocol-only scheme and Local Coordination based protocol. In such a scenario, source node would discover multiple candidate routes to the destination, the difference among those routes are caused by the nodes' different SOPs. We start a CBR traffic from the source to the destination with 10000 packets sized 512 bytes each at the interval 0.1 s.

Figure 12 shows the simulation result. The horizontal axis indicates the SSD and the vertical axis indicates the cumulative delay along the route. The 'Switch-aware' scheme takes switching delay as dominant factor and tries its best to avoid switching regardless of SSD, therefore the cumulative delay remains at a certain level

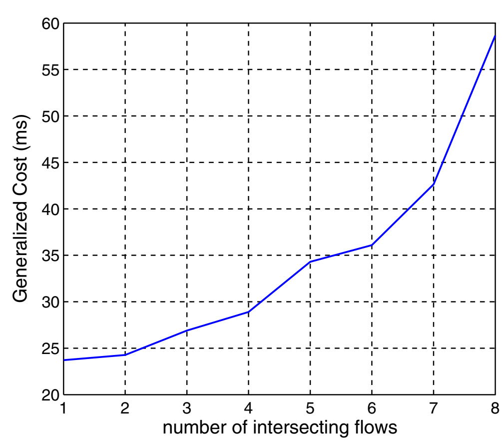

Figure 11 Generalized cost evaluation

(representing the traditional single-channel delay). On the other hand, the 'K-hop distinct' scheme tries its best to switch between channels, thus the cumulative delay rises sharply when SSD is above $500 MHz$, because of the sharp rise of switching delay. The 'Routing-protocol-only' scheme takes joint consideration of co-spectrum-band backoff delay and inter-spectrum-band switching delay, the cumulative delay incurred is fairly lower, however, when Local Coordination is employed, the workload ar intersecting nodes are distributed among several neighboring nodes, thus incurs lower cumulative delay. As SSD grows larger, the cost of switching delay on intersecting nodes increases, which results in the rise of the curve of 'Local Coordination Enhanced'.

6.4 End-to-end performance

We then evaluate the system end-to-end performance. We keep the basic scenario in the last subsection, but make the network nodes empowered solely by routing protocol, and by Local Coordination based Routing and Spectrum Assignment Protocol. We follow the procedure of Local Coordination presented in Section 5.2 and make every node be able to initiate flow redirection negotiation. We simply run the simulation and collect the end-to-end delay archived by the two schemes: one is barely routing, the other is Local Coordination enhanced routing.

Figure 13 shows the simulation result and the performance comparison. It is clear that when routing protocol incorporates with Local Coordination, heavy service load is distributed to the proximity around

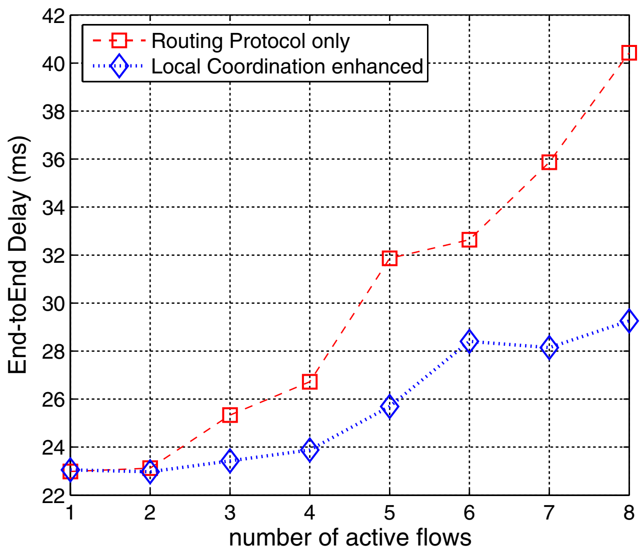

Figure 13 End-to-end performance

every relaying node. Note that when the number active flows in the network is small, Local Coordination didn't show much advantage, because queueing system is just formed or the load is not heavy enough to launch the flow redirection. However, when the number of active flows exceeds 3, intersecting nodes begin to suffer the accumulating queue, and from then on the flow redirection become necessary. It's also evident that the end-to-end delay increases sharply with 4 active flows even if Local Coordination is initiated, that is because the Local Coordination introduces certain amount of traffic and needs some time to make the negotiation work. After the flow number exceeds 6, the end-to-end delay become smooth, in that the negotiation traffic is negligible when compared to the large amount of data flow transmission in the network.

7 Related work

Many research have been presented in multi-channel network and CRNs to clarify the theoretical benefits of using multiple channels and multiple interfaces, together with centralized algorithms for achieving them [8, 18, 19].

There are also extensive proposals dealing with reactive routing protocol to exploit the high spectrum utilization and interference-free transmission brought by CR Technology [4, 10, 11]. They have investigated analytical or adaptive ways for improving transmission performance, many metrics are derived for protocol control.

Bahl et al. [20] have proposed SSCH, a link layer solution that uses a single interface. It can be extended to utilize multiple interfaces as well, requiring individual nodes to hop among channels based on a well published schedule. A key requirement for achieving good performance with SSCH is to use short slot times, which in turn requires fast interface switching. However, switching between different frequency bands causes at least milliseconds of switch delay, which is an order of magnitude higher than what SSCH assumes. The key design goal of our solution is to alleviate queueing at intersecting node via self-modeling and evaluation and network interaction.

There are a few routing proposals specifically designed for multi-channel and multi-interface wireless networks. Kyasanur and Vaidya [21] proposes routing and interface assignment algorithms for static networks, it also considers the scenario wherein the number of available interfaces is less than the number of available channels. However, the solution is designed specifically for use in networks that have already been assigned with frequency bands to all nodes.

Draves et al. [5] have proposed a new routing metric, called WCETT, for multi-channel ad hoc networks that routes with ensures distinct channels are selected. WCETT has been designed with the assumption that the number of interfaces per node is equal to the number of channels used by the network. Kyasanur and Vaidya [21] further modified this metric to handle the more general scenario where the number of available interfaces may be smaller than the number of available channels, but they took interface switching as a MUST, which neglect the fact of SOP inconsistency in CRNs. Therefore, we propose a Local Coordination based Routing and Spectrum Assignment scheme which focus on the criteria of queueing delay at intersecting node, and with joint respect of both switching delay and backoff delay in multi-hop Cogitative Radio Networks.

8 Conclusions

We proposed an complete solution of route computing and spectrum assignment for multi-hop CRNs, considering the situation at flow-intersection nodes with heavy relaying load. We further present a neighborhood interaction mechanism that enables negotiation among sending nodes, intersecting node and neighborhood nodes. We also implement novel mechanism of flow redirection as a effective solution to the queueing delay at the relaying node. The neighboring interaction, Generalized Cost evaluation, flow redirection, together with the On-demand Routing and frequency band selection forms a Local Coordination based Routing and Spectrum Assignment protocol.

We prove the correctness and effectiveness of the protocol by thorough simulations, and find that the proposed solution provides good adaptability to varying spectrum distribution. The queueing delay evaluation is fairly accurate while the end-to-end delay when adaptive relay is cooperating with routing protocol outperforms traditional bare-routing solutions.

Our future work focuses on spectrum assignment schemes with more complicated multi-flow scheduling and nodes' cooperation to achieve higher performance transmission, taking different traffic load and various priorities into consideration.

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