A Joint Link and Channel Assignment Routing Scheme for Cognitive Radio Networks

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Abstract. *Cognitive radio (CR) is a promising technology that enables opportunistic utilization of the temporarily vacant spectrum to mitigate the spectrum scarcity in wireless communications. Since secondary users (SUs) should vacate the channel in use immediately after detecting the reappearances of primary users (PUs) in cognitive radio networks (CRNs), the route reliability is a distinctive challenge for routing in CRNs. Furthermore, the throughput requirement of an SU session should be satisfied and it is always preferable to select a route with less negative influence on other current or latish sessions. To account for the route reliability challenge, we study the joint link and channel assignment routing problem for CRNs. It is formulated in a form of integer nonlinear programming (INLP), which is NP-hard, with the objective of minimizing the interference of a new route to other routes while providing route reliability and throughput guarantee. An on-demand route discovery algorithm is proposed to find reliable candidate paths, while a joint link and channel assignment routing algorithm with sequentially-connected-link coordination is proposed to choose the near-optimal route for improving the route reliability and minimizing negative influence. Simulation results demonstrate that the proposed algorithm achieves considerable improvement over existing schemes in both route reliability and throughput.*

Keywords

Cognitive radio networks, joint link and channel assignment routing, route reliability, interference-impact ratio, integer nonlinear programming.

1. Introduction

Cognitive radio (CR) aims to mitigate the spectrum scarcity problem in wireless communication through opportunistic access to the radio spectrum. Based on the development of software defined radio technologies, secondary users (SUs) can dynamically detect the temporarily vacant spectrum and access the idle spectrum without unacceptable interference to the primary users (PUs). This flexible capability provides a great potential for enhancing the efficiency of spectrum utilization and improving the network capacity of cognitive radio networks (CRNs) [1] In the last decade, many efforts have been devoted to the physical layer and MAC layer issues in CRNs [1], [2]. Nevertheless, it is likely that single-hop optimization may become largely inefficient in end-to-end performance consideration. The channel and power assignment given by an optimized MAC protocol can be quite inefficient in the view of a multi-hop flow which may traverse several regions influenced by different PUs. As a result, the performance at high layers is another important aspect for CRN optimization, such as end-to-end performance and network performance on route reliability and throughput.

Routing in a CRN is to establish and maintain a multi-hop route through joint relay node selection and channel assignment, rather than choosing only relay node as in traditional wireless networks. The node selection is tightly coupled with channel selection [3]. According to the relationship between the scales of channel availability time and flow duration, different strategies should be investigated for a CRN [4]. We focus on a scenario in which the available channels on a route stay invariant during the routing process, but may change during the lifetime of the flows. Routing in such a context is expected to be prevalent in CR applications.

For SUs, the interference to PUs is prohibited or needs to be strictly controlled. Only the channels unused by PUs are regarded as usable for SUs. The assigned channels of an established route should be vacated immediately after detecting presence of PU activities and the on-going SUs session may be interrupted. Thus channel availability is dominated by the geographical distribution and real-time channel occupation of PUs, resulting in the dynamic heterogeneous channels in the network. For dynamic routing in a CRN, route performance is challenged by distributed multi-hop networks, dynamic network topology, diverse quality-of-service (QoS) requirements, and time and location dependent channel availability [6]. Yet frequent re-routing is prone to induce a broadcast storm, radio resource wastage, and severe degradation of end-to-end performance such as in throughput and delay [7]. Thus, it is desirable to choose the routes which are likely to have a greater longevity [8], [9]. In this paper, we use route reliability to evaluate the feature of a route to provide the greater longevity, high and stable throughput, less channel switching or re-routing, and less negative impact on other flows, in the dynamic heterogeneous channel environment. We focus on joint link and channel assignment routing with high reliability under an assumption that the probability of the channel availability for a finite time, the channel bandwidth, and the transmission range of SUs are known.

In addition to route reliability, another concern of dynamic routing is the influence of a new established route to other concurrent or latish routes in the network. For a session request, a joint link and channel assignment routing scheme should be based on the current channel availability and load information in the network. From the network layer perspective, it is desired to fulfill as many session requirements as possible to improve service performance as well as to improve network throughput. Yet it is impossible or impractical for the current flow to acquire the performance evaluation information of other concurrent or latish sessions. As a result, it is preferred to choose the route that satisfies the throughput demand of the session while having minimal negative influence on other sessions for the network throughput consideration.

In this paper, we study the joint link and channel assignment routing problem in the dynamic channel scenario of CRNs. A cross-layer optimization scheme is proposed to construct the near-optimal reliable route. Firstly, we define a new interference-impact metric to indicate the interference of a route on the adjacent routes, and then formulate the path stability and route reliability. Secondly, we formulate this joint optimization problem in the form of integer nonlinear programming (INLP), which is NP-hard in general, with the objective of minimizing the interference-impact ratio while providing route reliability and throughput guarantees. Thirdly, we propose a two-step method to obtain the near-optimal solutions of the joint optimization problem, based on the problem-specific feature of the formulation. An on-demand route discovery algorithm with expurgation of weak paths is used in the first step to obtain robust candidate paths. A joint routing and channel assignment algorithm through the sequentially-connected-link coordination is used in the second step to construct the route. It will provide throughput guarantee from these candidate paths with minimal interference-impact ratio. Finally, simulations results are presented, demonstrating that the proposed joint link and channel assignment routing scheme provides significant improvement in route performance over existing schemes.

The rest of this paper is organized as follows. Section 2 reviews related works, followed by the system model and routing problem formulation for a dynamic channel environment of CRNs in Section 3. The routing problem is transformed and the joint link and channel assignment routing algorithm is proposed in Section 4. In Section 5, the performance of the proposed scheme is evaluated through extensive simulations. Section 6 concludes the work.

2. Related Work

In a dynamic heterogeneous channel environment of CRNs, the main challenge in network layer performance comes from the uncertainty of the channel availability, which results from the variable PU activities in CRN.

To accommodate the dynamic channel environment, several heuristic reactive approaches have been proposed. In [10], links with more usable channels are regarded as more robust and the weighted sum of hop counts and valid channel numbers are taken as the path cost. In [11], the channel number of a link, which is weighted by the usable probability, is regarded as the link reliability, and links whose reliability is higher than a threshold are taken as potential usable links to compose a robust route.

Compared to the connectivity analysis based on current PU activities, PUs activity modeling has a potential to increase spectrum opportunities and has attracted much attention in the spectrum sensing and access [8], [12]. There have been several reliability concerned routing approaches based on PU activity modeling in literatures. Shih et al. [13] take the presence behavior of PUs on each link-channel pair with an arrival rate following a Poisson distribution. The probability that no PU appears on a channel of a link is taken as the link-channel robustness. The maximum link-channel robustness is regarded as the link robustness while the product of the link robustness over a route denotes the route robustness. It has the same meaning as route reliability in the terms of longevity of routes, and the maximal link-channel valid probability (MLCVP) based robustness metric is used. However the usable channel number of a link is not considered in the robustness computation. It keeps the route robustness from precisely reflecting the real robustness of a route only based on the probability of no PU appearance.

Other researchers focus on the channel switching schemes in dealing with PU activities to avoid frequently re-routing. A joint spectrum handoff scheduling and routing optimization scheme is proposed in [14], based on the prediction of PU activities to improve the route throughput. In [15], the maintenance cost is considered in routing process, and the total cost of route establishment and route maintenance is minimal in the route selection phase. Guan et al. [16] estimate the link available period in a CRN and multiply a re-routing penalty factor to the routing metric for reducing the re-routing frequency. But this approach requires network-wide knowledge, collection of which is a complex task.

For the joint link and channel assignment optimization, many efforts have been made to construct a multi-path route [17], [18], [19]. While multi-path routes have shown to be preferable in throughput, the implementation of multi-path route in wireless networks is complex, with the problems such as complicated routing table and packet reordering. These efforts differ from ours in this paper, which focuses on minimizing the influence of the selected route on other concurrent route or intending flows on the constraint of throughput and route reliability. Moreover, in conventional networks, application-level flows generally use single-path routing [20]. This is another reason that only single-path route optimization is investigated in this paper.

The problem of link and channel assignment with maximal session throughput is a challenging issue for routing in CRNs. In [21], we propose a heuristic algorithm for high probability of feasible solutions to address practical multi-hop routing problems in a cognitive radio ad hoc network. We focus on obtaining solutions for multi-hop routing in a distributed and dynamic network. In this paper, we deal with how to obtain the reliable route from multi-link and multi link-channel pairs, based on the joint link and channel assignment routing scheme. These two papers deal with the similar problem but in different respects.

3. Assumption System Model and Problem Formulation

3.1 Network Architecture

We consider a CRN consisting of a set of N SU nodes. The radio spectrum in the network is divided into a set $\mathbf{M}=\{m|m=1,2,\cdots,M_{ch}\}$ of non-overlapping channels, where m is the channel index and M_{ch} is the number of channels in the CRN. The bandwidth of channel m is denoted by b_m, which can be different for different channels. Each node is capable of transmitting on a channel while receiving on another channel at the same time. The underlay approach is considered in this study, where the SUs access a licensed channel only when no PU is using it. Node $i(i\in\mathbf{N})$ determines its available channel set $\mathbf{C}_i=\{c_1,c_2,\cdots,c_{k_i}\}(\mathbf{C}_i\in\mathbf{M})$ through individual or collaborative spectrum sensing, where $c_1,c_2,\cdots,c_{k_i}$ are the channel indexes, and k_i is the number of the available channels for node i. The channel sets for different nodes may be different and change over time due to the distribution and variation of PU activities. The path longevity for a candidate path in a route is defined as the interval from the instant that the path is established to the instant that there is a link invalid on the path. We adopt a common assumption that the channel sets are invariant during the route discovery and establishment process, and a common control channel is provided through a dynamic topology management scheme such as that proposed in [22], [23].

3.2 Transmission and Link Interference Model

Following the widely-used propagation model proposed in [24], the propagation gain g_{ij} is given by

$$g_{ij}=\beta d_{ij}^{-\eta} \tag{1}$$

where β is an antenna related constant, η denotes the path loss exponent, and d_{ij} is the distance between neighboring nodes i and j. All SUs transmit at the same power p and have the same detection power threshold α. Then, the transmission range of every SU is

$$r_T=\left(\frac{\beta}{\alpha}p\right)^{1/\eta}. \tag{2}$$

A link between two neighboring nodes i and j is denoted by $<i,j>$. When routing, a new link may be set up for a new route in the CRN only if the two nodes locate in the transmission range r_T of each other and have at least one common usable channel, i.e. $\mathbf{C}_i\cap\mathbf{C}_j\neq\varnothing$. We consider bidirectional rather than unidirectional links because link-level acknowledgements are necessary in the dynamic heterogeneous channel environment of CRNs.

For inter-link interference control, we adopt the protocol model [25], in which both the transmitter and receiver of a link need to be free of interference to sustain bidirectional links. The interference range is denoted by

$$R_I=(1+\Delta)r_T \tag{3}$$

where Δ is an interference guard parameter. We use $\Delta=0.5$ in this study while the analysis and algorithms are equally applicable to other value of Δ. For link $<i,j>$ using channel m, the link set $\mathbf{I}_{ij}^m$, which may interfere with link $<i,j>$ when using channel m concurrently, is given by

$$I_{ij}^m=\{<x,y>|\, d_{ab}\le R_I, ab=xi,yi,xj,yj\} \tag{4}$$

where d_{ab} denotes the distance between node a and node b. We assume that the neighboring nodes i and j can obtain the information of interference set $\mathbf{I}_{ij}^m$ for each channel m within the common channel set $\mathbf{C}_{ij}=\mathbf{C}_i\cap\mathbf{C}_j$ through local beacon message exchange.

To avoid interference to the existing neighboring links, only the channels, which do not interfere with the already existing neighboring links, can be used by a new link. Thus, the usable channel set for the new link $<i,j>$ is

$$\mathbf{C}_{ij}^{if}=\{m\mid m\in\mathbf{C}_{ij},\mathbf{I}_{ij}^m=\varnothing\}. \tag{5}$$

For link $<i,j>$, the link-channel Shannon capacity when using channel $m\left(m\in\mathbf{C}_{ij}^{if}\right)$ for transmission is given by

$$B_{ij}^m=b_m\log_2(1+\frac{g_{ij}p}{\sigma^2}) \tag{6}$$

where σ^2 is the noise power, and b_m is the bandwidth of channel m. The interference item for capacity calculation in

(6) includes only noise power, because the channel usage that may interfere with PUs and neighboring assigned links are prohibited.

3.3 Link-channel Interference Impact Ratio

To derive the interference-impact ratio [26], the influence of an existing neighboring link $< i, j >$ with channel m on its potential neighboring links is investigated.

Let
$$\delta_{ij}^{m} = \frac{B_{ij}^{m}}{\sum_{n \in \mathbf{C}_{ij}^{if}} B_{ij}^{n}} \quad (7)$$

denote the importance of channel m for link $< i, j >$ in capacity. A larger value of δ_{ij}^{m} means that channel m is more important for the link in terms of the link-channel capacity. The interference-impact ratio of link $< i, j >$ using channel m is defined as

$$\phi_{ij}^{m} = \sum_{<h,k> \in \mathbf{I}_{ij}^{m}} \delta_{hk}^{m} \,. \quad (8)$$

A higher value of ϕ_{ij}^{m} indicates that channel m is a less preferable channel for neighboring links, i.e., if link $< i, j >$ selects channel m, its neighboring links have to accept less flows using the same channel. To minimize its negative influence on the neighboring links, a link should choose a channel with a minimal interference-impact ratio.

3.4 Path-valid Probability and Route Reliability

For a session request in the network, it is desirable to construct a robust route that can still be usable even when PUs are present on some of its assigned channels, so as to maintain end-to-end performance with less route restoration overhead and fewer re-routing times. In this subsection, we define a link-valid probability (LVP) metric for routing in CRNs.

Let $p_{ij}^{m}(t)$ denote the probability of no PU working on channel m for link $< i, j >$ over a time interval t. For simplicity, assume that $p_{ij}^{m}(t)$ is independent among all usable channels [13]. Link $< i, j >$ is regarded to be valid as long as there is at least one channel that can be used for the link. Let $p_{ij}(t)$ denote the LVP of link $< i, j >$. Then

$$p_{ij}(t) = 1 - \prod_{m \in \mathbf{C}_{ij}^{if}} [1 - p_{ij}^{m}(t)] \,. \quad (9)$$

It can be inferred from (9) that a link is more stable with more usable channels and higher probability of channel availability. The function, $p_{ij}^{m}(t)$, is likely different for different PU applications and can be obtained through PU activity modeling or runtime prediction. In this study, we assume that $p_{ij}^{m}(t)$ has been obtained [13] and its computation or prediction is out of the scope of this work.

Let $\theta_l = (l_0, l_1, l_2, \cdots, l_n)$ denote a candidate path for a new route, where $l_0, l_1, l_2, \cdots, l_n$ are the indexes of the nodes on path l. A path can be regarded as valid only if all the links on the path are valid. The path-valid probability (PVP) of a path over a time interval t is

$$p_{\theta_l}(t) = \prod_{k=1}^{n} p_{l_{k-1}l_k}(t) = \prod_{k=1}^{n} [1 - \prod_{m \in \mathbf{C}_{l_{k-1}l_k}^{if}} [1 - p_{l_{k-1}l_k}^{m}(t)]] \,. \quad (10)$$

From (10), it is preferred to choose paths with more available link-channel pairs along the path, higher LVPs, and less hops.

3.5 Problem Formulation

A dynamic traffic model, with the random network-layer session arrival, is considered in this study. A session request is characterized by the source node s, destination node d, throughput demand b_0, and session duration requirement t_0. For implementation simplicity (as explained in Section 2), only single-path routing is considered. We aim to investigate a joint link and channel assignment routing scheme which minimizes the interference to other flows, satisfies the throughput requirement, and keeps the route valid at a given probability p_0 ($0 < p_0 \le 1$) over the session interval t_0.

To facilitate the relay node and channel assignment, two variables are defined as

$$x_{ij} = \begin{cases} 1, & \text{if } < i, j > \text{ is selected} \\ 0, & \text{otherwise} \end{cases} \quad (11)$$

$$y_{ij}^{m} = \begin{cases} 1, & \text{if } m \text{ is selected by } < i, j > \\ 0, & \text{otherwise} \end{cases} \,. \quad (12)$$

A relationship between them is given by

$$\sum_{m \in \mathbf{C}_{ij}^{if}} y_{ij}^{m} \le x_{ij} \,. \quad (13)$$

Mathematically, the problem of selecting a single-path route with the minimal interference-impact ratio, guaranteed throughput and reliability is formulated in *Problem 0.*

- **Problem 0.** Single-path routing:

$$\min \sum_{x_{ij}=1} y_{ij}^{m} \phi_{ij}^{m} \quad (14)$$

subject to
$$y_{ij}^{m} \le x_{ij} \,, \quad (15)$$

$$\sum_{<s,p> \in \mathbf{L}_{\mathrm{s}}^{\mathrm{out}}} x_{\mathrm{sp}} = 1 \,, \quad (16)$$

$$\sum_{<p,i> \in \mathbf{L}_{\mathrm{i}}^{\mathrm{in}}} x_{\mathrm{pi}} - \sum_{<i,q> \in \mathbf{L}_{\mathrm{i}}^{\mathrm{out}}} x_{\mathrm{iq}} = 0, \ \forall i \in \mathbf{N} \left| \{s, d\} \right. , \quad (17)$$

$$y_{ij}^{m} + \sum_{<p,q>\in \mathbf{I}_{ij}^{m}} y_{pq}^{m} \le 1 \ , \tag{18}$$

$$\min\{B_{ij}^{m} \mid x_{ij} y_{ij}^{m} = 1\} \ge b_0 \ , \tag{19}$$

$$\prod_{<i,j>\in\{<i,j>|x_{ij}=1\}} p_{ij}(t_0) \ge p_0 \ , \tag{20}$$

$$x_{ij}, y_{ij}^{m} \in \{0,1\},\ t_0 > 0, b_0 > 0, p_0 > 0$$

where $\mathbf{L}_i^{in}$ and $\mathbf{L}_i^{out}$ denote the incoming and outgoing link sets of node i respectively.

In *Problem 0*, x_{ij} and y_{ij}^{m} are optimization variables. The objective function (14) is to minimize the interference-impact of the selected route. Constraints (15) - (17) establish a single-path route from the source node to the destination node with one channel assigned to each link; constraint (18) is for prohibiting the inter-link interference; constraint (19) guarantees that the required flow rate, which is the minimal link throughput on the path, is satisfied; constraint (20) guarantees the life time of the chosen route no less than t_0 with a possibility p_0. The problem is in a form of INLP, which is NP-hard in general and cannot be solved in polynomial time[27].

4. Problem Analysis and Proposed Solutions

In this section, we first investigate the specific features of the original problem. Then an on-demand route discovery protocol is proposed to obtain robust candidate paths as well as the channel availability information along these paths. Based on the information, a joint link and channel assignment routing algorithm is proposed to determine a desired route.

4.1 Problem Analysis and Transformation

The formulation of *Problem 0* is in an INLP form, for which the possible solutions or near-optimal solutions are difficult to be obtained. We now take a close look at *Problem 0* to investigate its specific features.

- **Linear objective function:** Since we assume that all SUs can obtain current channel usage information of neighboring links, the interference-impact ratio ϕ_{ij}^{m} of each link-channel pair can be calculated and the objective function is a weighted linear summation of binary variables.
- **Linear constraints:** Constraints (16)-(20) are linear flow constraints which guarantee that a single-path route satisfying throughput requirement is chosen without intra-flow interference. The binary variables make the problem fall into the classification of integer programming. However, it is noticed that the determination of the binary variables is only related to the adjoining or interfering links, following these constraints.
- **Nonlinear constraint:** Route reliability constraint (20) is in the form of product and the constraint can only be verified for each specific path. It makes the development of a near-optimal solution very complex.

From the preceding analysis, it can be concluded that the complexity of *Problem 0* optimization arises mainly from the binary variables and the product form of constraint (20). Now we take it as a practical cross-layer designing problem in CRNs rather than a sole optimization problem. It is costly or even unaffordable for SUs to have the entire network information through proactive routing strategies. A practical routing strategy is to discover the route with an on-demand mode. Thus it is possible to expurgate the poor paths in the route discovery process rather than through the optimization at the destination node. Furthermore, although the determination of x_{ij} and y_{ij}^{m} is interrelated, i.e., the interactional relationship between the link selection and channel selection, y_{ij}^{m} can be determined according to the value of x_{ij} since a channel may be selected only if a link is selected. Based on these characteristics, *Problem 0* can be transformed into the following two problems:

- **Problem 1.** Robust paths discovery:

Find $$\theta_l = (l_0, l_1, \cdots, l_n) \tag{21}$$

subject to $$l_0 = s, l_n = d \tag{22}$$

$$\prod_{k=0,1,\cdots,n-1} p_{l_k l_{k+1}}(t_0) \ge p_0 \ , \quad p_0 > 0 \tag{23}$$

- **Problem 2.** Channel assignment optimization:

$$\min \sum_{x_{ij}=1} y_{ij}^{m} \phi_{ij}^{m} \tag{24}$$

subject to $$y_{ij}^{m} \le x_{ij} \tag{25}$$

$$y_{ij}^{m} + \sum_{<p,q>\in \mathbf{I}_{ij}^{m}} y_{pq}^{m} \le 1 \tag{26}$$

$$\min\{B_{ij}^{m} \mid y_{ij}^{m} = 1\} \ge \eta b_0 \tag{27}$$

$$y_{ij}^{m} \in \{0,1\},\ x_{ij} \ge 0,\ t_0 > 0,\ b_0 > 0,\ \eta > 0 \ .$$

Problem 1 is to find all candidate paths for a route which satisfy the reliability requirement, while *Problem 2* is to generate a route with channels assigned to its candidate paths. It is easy to conclude that there is no optimality loss in the problem transformation. Although the first constraint of *Problem 2* is formally the same as that of *Problem 0*, x_{ij} has been determined in *Problem 1* and can be taken as a given input in the optimization of *Problem 2*.

For the former problem, an on-demand robust path discovery algorithm is proposed, with weak path expurgation, to acquire the candidate robust paths and the channel availability information along the paths. For the latter problem, a near-optimal joint link and channel assignment routing algorithm is proposed.

4.2 On-demand Path Discovery with Expurgation of Weak Paths

To solve *Problem 1* as well as to collect channel availability and interference information for the later cross-layer optimization, an on-demand path discovery algorithm is proposed, which is derived from a dynamic source routing (DSR) protocol [28]. The pseudo code of the algorithm is presented in *Algorithm 1* and is explained in the following.

Algorithm 1

Input: $\langle s, d, p_0, b_0 \rangle$

1. The source node *s*: broadcasts an RREQ.
2. Intermediate node $j \in \mathbf{N} | \{s,d\}, j \neq s,d$ that receives an RREQ from the neighbor node $i \in \mathbf{N} | \{s,d\}, i \neq d$

   if j has processed this RREQ or $\mathbf{C}_{ij}^{if} = \varnothing$

   discard the RREQ

   else

   append link $< i, j >$ to the path

   check $p_{\theta_l}(t)$, $\theta_l = \{(l_0, l_1, \cdots, l_{n-1}, l_n) | l_0 = s, l_{n-1} = i, l_n = j\}$

   if $p_{\theta_l}(t) < p_0$,

   discard the RREQ

   else

   append $\mathbf{C}_{ij}^{if}$ and $\mathbf{I}_{ij}^{m} (m \in \mathbf{C}_{ij})$ to the RREQ and rebroadcast it

   end

   end
3. The destination node d :

   if destination node d receives an RREQ

   start a timer and collect all RREQs of the session

   decode the stability-eligible path set $\mathbf{\Theta}_{s,d}$

   end

When a session request comes with destination node *d*, the throughput requirement b_0, the session interval t_0, and a sequence number n_{seq} (since rebroadcast may be necessary), the source node *s* embedded these information in the route request message (RREQ) and broadcast it on the common control channel. The content of the RREQ is illustrated in Tab. 1.

All the necessary local channel availability information is assumed to have been acquired through individual or collaborative spectrum sensing system when the RREQ is received. When an intermediate node $j\,(j \notin \{s,d\})$ receives an RREQ from a neighbor node i, it checks $\mathbf{C}_{ij}^{if}$ to determine whether there is at least one usable channel for link $< i, j >$. If $\mathbf{C}_{ij}^{if} = \varnothing$, it means that no channel can be used and node j just discards the RREQ. Otherwise, node j appends link $< i, j >$ to the path embedded into the RREQ and executes a reliability examination for the renewed path following equation (10). If $p_{\theta_l}(t_0) < p_0(\theta_l = \{(l_0, l_1, l_2, \cdots, l_{n-1}, l_n) | l_0 = s, l_{n-1} = i, l_n = j\})$, node j concludes that the current path is not eligible in reliability and discards the RREQ. Otherwise, node j embeds $\mathbf{C}_{ij}^{if}$ and $\mathbf{I}_{ij}^{m}$ into the RREQ and rebroadcasts it on the common control channel.

RREQ	S	D	t_0	b_0	n_{seq}
l_1	$\mathbf{C}_{sl_1}^{if}$			$\mathbf{I}_{sl_1}^{m}$	
l_2	$\mathbf{C}_{l_1 l_2}^{if}$			$\mathbf{I}_{l_1 l_2}^{m}$	
……					
l_k	$\mathbf{C}_{l_{k-1} l_k}^{if}$			$\mathbf{I}_{l_{k-1} l_k}^{m}$	
i	$\mathbf{C}_{l_k i}^{if}$			$\mathbf{I}_{l_k i}^{m}$	
j	$\mathbf{C}_{ij}^{if}$			$\mathbf{I}_{ij}^{m}$	

Tab. 1. Content of the RREQ for $\theta_l = \{(l_0, l_1, \cdots, l_{n-1}, l_n) | l_0 = s, l_{n-1} = i, l_n = j\}$

Through the reliability examination, the unqualified paths are eliminated in the discovery process. Thus the complexity of the route discovery and the cross-layer optimization for the destination node is reduced. To avoid vain forwarding and route looping, each intermediate node only processes the RREQ from a specific neighbor one time and will drop all subsequences.

When the destination node d receives the first RREQ from the source node s, it starts a timer and collects all the RREQ of the source node s until the timer expires. The destination node d also executes the reliability examination and reserves only the reliable ones. The stability-eligible path set is denoted by

$$\mathbf{\Theta}_{s,d} = \{\theta_l = (l_0, l_1, \cdots, l_n) \mid l_0 = s, l_n = d, \prod_{k=0,\cdots,n-1} p_{l_k l_{k+1}}(t_0) \geq p_0\} \quad (28)$$

Meanwhile, the channel availability and link inference information along the candidate paths, i.e. $\mathbf{C}_{ij}^{if}$ and $\phi_{ij}^{m} (m \in \mathbf{C}_{ij})$ for each link $< i, j > \in \{\theta_l | l_0 = s, l_n = d\} \in \mathbf{\Theta}_{s,d}$, are also obtained.

4.3 Joint Link and Channel Assignment Routing

Based on the eligible candidate paths and channel availability information attained from the path discovery, the destination node d constructs the desired route to solve *Problem 2*. The aim of the proposed joint link and channel assignment routing (JLCAR) algorithm through sequentially-connected-link coordination is to construct a route that has minimal interference-impact ratio and satisfies the throughput requirement.

Problem 2 is in the form of binary programming and is still NP-hard in general. The main complexity arises from the constraint (26) which requires a channel not to be assigned to two or more interfering links. As we take $\Delta = 0.5$ in this study, three sequentially-connected links on a path are sure to interfere with each other if they use the same channel. The basic idea of JLCAR is to coordinate the channel assignment within the three sequentially-connected links rather than the whole path, in order to avoid the exponential complexity. The complete pseudo code of the algorithm is given in *Algorithm 2*, where m_{01}, m_{12}, m_{23} are the usable channel indexes of the three sequentially-connected links on the path $\theta_l \in \mathbf{\Theta}_{sd}$, link $< i_0, i_1 >$, link $< i_1, i_2 >$, and link $< i_2, i_3 >$, respectively. The selected channel for link $< i_{-2}, i_{-1} >$, which is the two-hop neighbor link of link $< i_0, i_1 >$ towards the source node s, is denoted as m'_{-2-1}, when node i_0 is a multi-hop neighbor ($\geq 3\,hops$) of source node s.

In *Algorithm 2*, for candidate path $\theta_l = (s, l_1, l_2, ..., l_{n-1}, d) \in \mathbf{\Theta}_{s,d}$, the algorithm starts from the channel assignment of the first link $< i_0, i_1 >$. It chooses a channel m that satisfies

$$\begin{aligned} &\min \phi^m_{i_0 i_1} \\ s.t.\quad & B^m_{i_0 i_1} \geq b_0 \\ & y^m_{i_0 i_1} + \sum_{<p,q> \in \mathbf{I}^m_{i_0 i_1}} y^m_{pq} \leq 1 \end{aligned} \quad . \qquad (29)$$

If there is no satisfied channel, it can be concluded that no satisfied route can be constructed on this path and the next candidate path is considered subsequently. Otherwise, it turns to the subsequent link $< i_1, i_2 >$, which chooses a channel following a similar equation as (29). If no satisfied channel can be used for link $< i_1, i_2 >$, the channel assignment of link $< i_0, i_1 >$ is backtracked. The selected channel of link $< i_0, i_1 >$ is deleted from the candidate usable channel set and another channel is selected following (29). Then link $< i_1, i_2 >$ executes channel assignment again. It is the same as link $< i_2, i_3 >$ except that the channel assignment of link $< i_0, i_1 >$ can be backtracked if no feasible assignment can be obtained after backtracking link $< i_1, i_2 >$.

Algorithm 2.

Input: $\mathbf{\Theta}_{s,d}$, $\mathbf{C}^{if}_{ij}$, B^m_{ij} and ϕ^m_{ij} $(m \in \mathbf{C}^{if}_{ij})$

for each path $\theta_l \in \mathbf{\Theta}_{s,d}$
    if $i_0 \neq s, l_1, l_2$,
        $m_{01} \in \mathbf{C}^{if}_{01}, m_{01} \neq m'_{-2-1}$
    else
        $m_{01} \in \mathbf{C}^{if}_{01}$
    end
    for link $< i_0, i_1 >$
        select channel m_{01} with $\min \phi^m_{i_0 i_1}$, s.t. $B^m_{i_0 i_1} \geq b_0$, $y^m_{i_0 i_1} + \sum_{<p,q> \in \mathbf{I}^m_{i_0 i_1}} y^m_{pq} \leq 1$
        if no satisfied m_{01} exists,
            delete path $\theta_l = (s, l_1, l_2, ..., l_{n-1}, d)$ and go to next path.
        end
    end
    for link $< i_1, i_2 >$
        select channel m_{12} with $\min \phi^m_{i_1 i_2}$, s.t. $B^m_{i_1 i_2} \geq b_0$, $y^m_{i_1 i_2} + \sum_{<p,q> \in \mathbf{I}^m_{i_1 i_2}} y^m_{pq} \leq 1$
        if no satisfied m_{12} exists,
            delete the selected m_{01} of link $< i_0, i_1 >$ from $\mathbf{C}^{if}_{i_0 i_1}$ and reselect channels for the two links.
            if no satisfied channels for the two links
                delete path $\theta_l = (s, l_1, l_2, ..., l_{n-1}, d)$ and skip for next path.
            end
        end
    end
    for link $< i_2, i_3 >$
        select channel m_{23} with $\min \phi^m_{i_2 i_3}$, s.t. $B^m_{i_2 i_3} \geq b_0$, $y^m_{i_2 i_3} + \sum_{<p,q> \in \mathbf{I}^m_{i_2 i_3}} y^m_{pq} \leq 1$
        if no satisfied m_{23} exists,
            delete the selected channel m_{12} of link $< i_1, i_2 >$ from $\mathbf{C}^{if}_{i_1 i_2}$ and reselect channels for the two links.
            if no satisfied channels for the two links
                delete the selected channel m_{12} of $< i_1, i_2 >$ from $\mathbf{C}^{if}_{i_1 i_2}$ and reselect channels for the three links.
                if no satisfied channel assignment scheme
                    delete path $\theta_l = (s, l_1, l_2, ..., l_{n-1}, d)$ and skip for next path.
                end
            end
        end
    end
    Choose a channel for each following link similar to link $< i_2, i_3 >$
    Calculate the interference-impact for the route.
end
Return the route with minimal interference-impact ratio.

If the backtracking can be executed for all links ahead, optimal solution of *Problem 2* can be found, yet the complexity is exponential. In this algorithm, we restrict the backtracking within the former two links. This channel assignment operation is executed for each subsequent link on this path. It is easy to conclude that the channel assignment of a link can be determined without further changes after the channel assignment of the subsequent two links.

After the channel assignment of each candidate path, the interference-impact ratio of the route is computed. At the end of the algorithm, the route with minimal interference-impact ratio is selected. Then the destination node d embeds the selected route in a route reply (RREP) message and sends it back to the source node s along the reverse route for route construction. Note that it is also possible that no satisfied route can be found, for which case a failure message is sent to the source node s.

5. Performance Evaluation

In this section, we evaluate the performance of the proposed joint link and channel assignment routing scheme via simulations based on Matlab.

5.1 Route Reliability

Firstly, we compare the proposed reliability metric LVP with MLCVP [13] and the shortest path route (SPR) metric used in DSR [28]. The simulation topology is illustrated in Fig. 1.

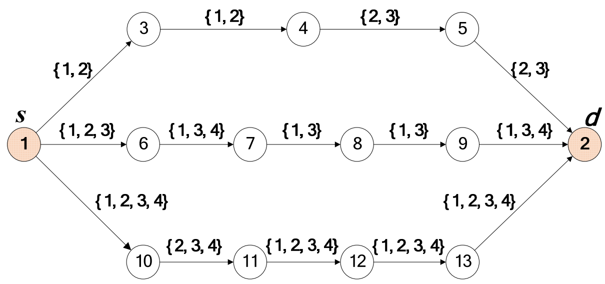

Fig. 1. The simulation topology.

The global channel set **M** = (1,2,3,4) and the presence of PUs on the channels is assumed to follow Poisson distributions with parameters {λ, 2λ, 3λ, 4λ}. In Fig. 1, a number in a circle "○" denotes the SU node index and a number in braces "{ }" above a link sign "→" denotes as available channel for the link. There are three candidate paths from the source node 1 to the destination node 2, which are $\theta_1 = (1,3,4,5,2)$, $\theta_2 = (1,6,7,8,9,2)$ and $\theta_3 = (1,10,11,12,13,2)$.

We vary the value of λ to compare the path longevity on different channel variation scenarios. The simulation results are given in Fig. 2. Different paths are regarded as the most preferable path by different reliability metrics. Because a link with more channels indicates the link with higher LVP, a link with the most number of available channels is selected by the LVP scheme. The MLCVP scheme focuses only on the maximum valid probability of a link-channel pair and ignores the number of channels a link has. The SPR scheme tends to select the shortest path. Three different paths, θ_3, θ_2, θ_1, are chosen by LVP, MLCVP and SPR, respectively. It is observed that the longevity of θ_3 is longer than that of θ_2 and θ_1 by 28%~36% and 12%~20% respectively. The results indicate that choosing a robust route following LVP can be much more preferable than the two counterparts. Combining consideration of link selection and channel assignment can help to obtain a reliable route.

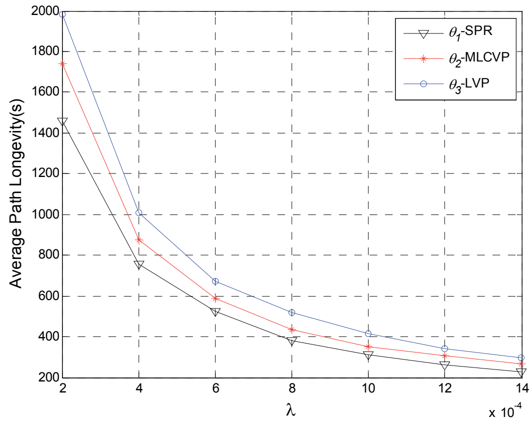

Fig. 2. Path longevity vs. λ .

5.2 Route Throughput

In the second simulation, we compare the throughput of the generated routes following JLCAR and the minimum accumulated spectrum temperature routing algorithm (MAST) proposed in [29]. The simulated CRN locates in a 200 m × 200 m square, consisting of 60 SU nodes. There are 10 channels in the network, bandwidths of which are randomly selected from 1 Mbps to 4 Mbps. The initial usable probability of each channel is $p_{ij}^m(0) = 0.3 \sim 0.75$ and the parameter λ is $\lambda = 0.2\times10^{-4} \sim 2.0\times10^{-4}$. The presence of PUs on the channels is assumed to follow Poisson distributions with parameters {λ, 2λ, 3λ, 4λ} again. The route requirements under consideration are the route throughput b_0 of 2 Mbps and the session duration t_0 of 120 s.

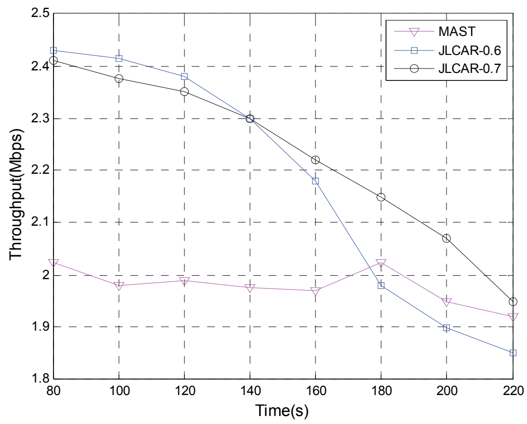

Fig. 3. Throughput vs. time.

First, we assign the source node and the destination node at (40 m, 40 m) and (160 m, 160 m) respectively. The throughputs of the routes generated by JLCAR and MAST with p_0 = 0.6 and 0.7 are shown in Fig. 3, each data point of which is an average of 50 randomly generated topologies. It can be observed that JLCAR with $p_0 = 0.6$ (JLCAR-0.6) and JLCAR with $p_0 = 0.7$ (JLCAR-0.7) can both guarantee the throughput in the demand session time ($t_0 = 120$ s). On the other hand, the route throughput by MAST cannot be guaranteed to be at least b_0.

Next, we compare the end-to-end performance of ten nodes at randomly generated locations, routes of which are selected successively. The average throughput comparison for different SU transmission ranges is presented in Fig. 4.

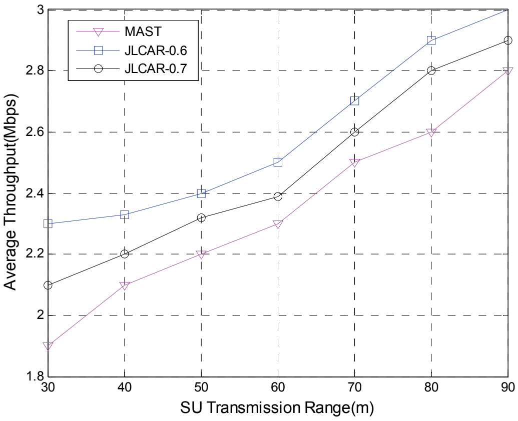

Fig. 4. Throughput with $t_0 = 120$ s vs. SU transmission range.

It can be seen that the average route throughput increases with the increase of the transmission range, and the JLCAR scheme gives a higher throughput than MAST by 11% and 6% when the route valid probability is $p_0 = 0.6$ and 0.7 respectively. Moreover, the throughput of JLCAR-0.6 is higher than that of JLCAR-0.7. This is because higher p_0 will expurgate more candidate paths which may provide bigger throughput. The phenomenon indicates that higher reliability requirement may reduce the maximal obtained route throughput.

6. Conclusions

In this paper, the joint link and channel assignment routing problem is studied for a dynamic heterogeneous channel environment of CRNs. The path-valid probability and route reliability are formulated based on the link-valid probability, and the interference-impact ratio is introduced to capture the influence of a route on its adjacent routes. Based on the measures, we propose a two-step method to obtain the near-optimal solutions of the joint link and channel assignment routing problem, which is a NP-hard problem. An on-demand path discovery with expurgation of weak paths algorithm is proposed to find reliable candidate paths in the first step. A joint link and channel assignment routing algorithm through sequentially-connected-link coordination is proposed to assign the links and channels with high reliability and throughput to satisfy the session demand in the second step. Simulation results demonstrate that the proposed algorithm can improve the path longevity, while improving whole network throughput. It not only guarantees the throughput, but also enhances the route reliability.

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References

[1] HAYKIN, S. Cognitive radio: brain-empowered wireless communications. *IEEE Journal on Selected Areas of Communications*, 2005, vol. 23, no. 2, p. 201 - 220.

[2] YUCEK, T., ARSLAN, H. A survey of spectrum sensing algorithms for cognitive radio applications. *IEEE Communications Surveys & Tutorials*, 2009, vol. 11, no. 1, p. 116 - 130.

[3] CORMIL, C., CHOWDHURY, K. R. A survey on MAC protocols for cognitive radio networks. *Ad Hoc Networks*, 2009, vol. 7, no. 7, p. 1315 - 1329.

[4] CESANA, M., CUOMO, F., ERICI, E. Routing in cognitive radio networks: challenges and solutions. *Ad Hoc Networks*, 2011, vol. 9, no. 3, p. 228 - 248.

[5] KHALIFE, H., MALOUCH, N., FDIDA, S. Multihop cognitive ratio networks: to route or not route. *IEEE Network*, 2009, vol. 23, no. 4, p. 20 - 25.

[6] AKYILDIZ, I. F., LEE, W. Y., CHOWDHURY, K. R. CRAHNs: cognitive radio ad hoc networks. *Ad Hoc Networks*, 2009, vol. 7, no. 5, p. 810 - 836.

[7] TSENG, Y. C., NI, S. Y., CHEN, Y. S., SHEU, J. P. The broadcast storm problem in a mobile ad hoc network. *Wireless Networks*, 2002, vol. 8, no. 2/3, p. 153 - 167.

[8] CANBERK, B., AKYILDIZ, I. F., OKTUG, S. Primary user activity modeling using first-difference filter clustering and correlation in cognitive radio networks. *IEEE/ACM Transactions on Networking*, 2011, vol. 19, no. 1, p. 170 - 183.

[9] SHIN, K. G., KIM, H., MIN, A. W., KUMAR A. Cognitive radio for dynamic spectrum access: from concept to reality. *IEEE Wireless Communications*, 2010, vol. 17, no. 12, p. 64 - 74.

[10] WANG, L., WU, W. Channels intersection weight based routing in cognitive radio networks. In *Proceedings of the 2nd International Conference on Wireless and Mobile Networks*. Ankara (Turkey), 2010, p. 190 - 201.

[11] HAN, R., HUANG, X. X. Reliable link routing in cognitive radio networks. In *Proceedings of 2nd International Asia Conference on Informatics in Control, Automation and Robotics (CAR)*. Wuhan (China), 2010, p. 55 - 58.

[12] ZHAO, Q., TONG, L., SWAMI, A., CHEN, Y. Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: a POMDP framework. *IEEE .Journal on Selected Areas in Communications*, 2007, vol. 25, no. 3, p. 589 - 600.

[13] SHIH, C. F., LIAO, W., CHAO, H. L. Joint routing and spectrum allocation for multi-hop cognitive radio networks with route robustness consideration. *IEEE Transactions on Wireless Communications*, 2010, vol. 10, no. 9, p. 2940 - 2949.

[14] FENG, W., CAO, J., ZHANG, C., LIU, C. Joint optimization of spectrum handoff scheduling and routing in multi-hop multi-radio cognitive networks. In *Proceedings of IEEE ICDCS09*. Montrail (Canada), 2009, p. 85–92.

[15] FILIPPINI, I., EKICI, E., CESANA, M. Minimum maintenance cost routing in cognitive radio networks. In *Proceeding of IEEE MASS'09*. Macao (China), 2009, p. 284 - 293.

[16] GUAN, Q. S., YU, F. R., JIANG, S. G. Prediction-based topology control and routing in cognitive radio mobile ad hoc networks. *IEEE Transactions on Vehicular Technology*, 2010, vol. 59, no. 9, p. 4443 - 4452.

[17] PAN, M., ZHANG, C., LIT, P., FANG, Y. G. Joint routing and link scheduling for cognitive radio networks under uncertain spectrum supply. In *Proceedings of IEEE INFOCOM 2011*. Shanghai (China), 2011, p. 2237 - 2245.

[18] HOU, Y. T., SHI, Y., SHERALI, H. D. Spectrum sharing for multi-hop networking with cognitive radios. *IEEE Journal on Selected Areas in Communications*, 2008, vol. 26, no. 1, p. 146 - 155.

[19] SHI, Y., HOU, T., KOMPELLA, S., SHERALI, H. D. Maximizing capacity in multihop cognitive radio networks under the SINR model. *IEEE Transactions on Mobile Computing*, 2011, vol. 10, no. 7, p. 954 – 967.

[20] AYYOUB, M. A., GUPTA, H. Joint routing, channel assignment and scheduling for throughput maximization in general interference models. *IEEE Transactions on Mobile Computing*, 2010, vol. 9, no. 4, p. 553-565.

[21] ZHAO, H. S., ZHANG, J. Z., LIANG, H., ZHUANG, W. H. A practical multi-hop channel allocation algorithm for cognitive radio ad hoc networks. In *Proceedings of IEEE ICWITS2012*. Grand Wailea (USA), 2012, p. 605 – 608.

[22] ZHANG, J. Z., YAO, F. Q., ZHAO, H. S., WANG, F. Cluster-based dynamic topology management in cognitive radio ad hoc networks. *Frequenz*, 2011, vol. 65, no. 3/4, p. 109 – 119.

[23] ZHANG, J. Z., YAO, F. Q., ZHAO, H. S. Distributed clustering in cognitive radio ad hoc networks using soft-constraint affinity propagation. *Radioengineering*, 2012, vol. 21, no. 3, p. 785 - 794.

[24] GOLDSMITH, A. *Wireless Communications*. Cambridge University Press, Cambridge: New York, 2005.

[25] GUPTA, P., KUMAR, P. R. The capacity of wireless networks. *IEEE Transactions on Information Theory*, 2000, vol. 46, no. 2, p. 388 - 404.

[26] HINCAPIE, R., TANG, J., XUE, G. L., BUSTAMANTE, R. QoS routing in wireless mesh networks with cognitive radios. In *Proceedings of IEEE GlobeCom 2008*. New Orleans (USA), 2008, p. 1 - 5.

[27] GAREY, M. R., JOHNSON, D. S. *Computers and Intractability: A Guide to the Theory of NP-completeness*. New York, NY: W.H. Freeman and Company, 1979, p. 245–248.

[28] HOHNSON, D., HU, Y., MALTZ, D. The dynamic source routing protocol (DSR) for mobile Ad Hoc networks for IPv4. *IETF RFC 4728*, 2007.

[29] HUANG, X. X., LU, D. J., LI, P., FANG, Y. G. Coolest path: spectrum mobility aware routing metrics in cognitive ad hoc networks. In *Proceedings of 2011 31st Internationl Conference on Distributed Computing Systems*. Minneapolis (USA), 2011, p. 182-191.

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