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Adaptive Channel Allocation and Routing in Cognitive Radio Networks

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***Abstract*—One of the biggest challenges in multi-hop cognitive radio networking is the dynamic change of channel availability to secondary users which could cause the breaking of routes and thus communications. To address this challenge, we propose an adaptive channel allocation and routing scheme in this paper. Our scheme is flexible so that it can react to the dynamic change of channel availability, and it can maximize the throughput by exploiting network coding opportunities. First, we model the primary users' activity, channel availability and the interference among the secondary users in a cognitive radio network environment, and show how to implement a backpressure algorithm and a network coding scheme in multi-hop cognitive radio networks. Second, we formulate an optimization problem to maximize the throughput of the network. We consider the channel availability constraint, and make use of the network coding opportunity. In order to reduce the computing complexity, we propose a distributed channel allocation and route selection algorithm. Furthermore, we compare the performance of our scheme with existing schemes for different scenarios of channel availability and network load through simulations. Our work brings insights on how to make route selection and channel allocation in multi-hop cognitive radio networks.**

I. Introduction

Cognitive radio network (CRN) is a technology based on spectrum sensing and opportunistic spectrum access which can improve the spectrum efficiency of wireless networks [1]. According to Federal Communications Commission (FCC) [2], the secondary users would sense the activities of primary users periodically. When a channel is not occupied by a primary user, a secondary user can use the channel opportunistically. One major characteristic of cognitive radio is that the activities of primary users change dynamically and the secondary users have to adapt to the dynamic changes of the channel availability.

Multi-hop cognitive radio networks bring several new challenges compared to the single hop cognitive radio networks. First, users should choose an appropriate route dynamically to make good use of available channels. Second, besides the dynamic route selection problem, optimal channel allocation and link scheduling is also a complicated task. Third, there are many new transmission technologies that could be incorporated into multi-hop cognitive radio networks, but the effects of these technologies on the cognitive radio aspects have not been well-studied yet.

To address the challenges in multi-hop cognitive radio networks, we propose a joint adaptive channel allocation and routing scheme in this paper. After the secondary users obtain the instant channel availability information through spectrum sensing, channels can be allocated dynamically to the users in need. At the same time, the routes will be established according to the newest channel availability information.

Although CRN technology can help exploit much more spectrum resources, there are still situations where the demand is higher than the available spectrum resources. In this case, a channel needs to be shared by multiple communication links. To further improve the throughput of a cognitive radio network, we introduce both network coding [3] and backpressure routing [4] in our adaptive channel allocation and routing scheme.

The major contributions of this paper are as follows. First, we consider the activities of the primary users in a CRN model, and introduce a network coding scheme and a backpressure algorithm into multi-hop CRNs. Second, we formulate an optimization problem considering channel availability, link weight and network coding opportunities. Third, we propose a channel allocation and routing scheme to solve the problem in a distributed way with low complexity. We prove that our scheme can stabilize the network and achieve close to optimal performance. Finally, we compare the performance of our scheme with existing schemes through simulations. We demonstrate that our scheme has better throughput and lower delay than other existing schemes.

The rest of this paper is organized as follows. In Section II we overview the related work. In section III, we describe the CRN model and introduce network coding and backpressure scheduling into the CRN model. We formulate an optimization problem in Section IV and propose a distributed channel allocation and routing scheme in Section V. In Section VI, we present simulation results with detailed discussions. In Section VII, we conclude this paper.

II. Related Work

There are extensive studies on routing and channel allocation schemes in cognitive radio networks. In [5], the authors focused on the problem of designing efficient spectrum sharing techniques for multi-hop CRNs with multiple channels and multiple radios considered. However, a major difference of our work is that our scheme is distributed and can adapt to the dynamic change of channel availability in a better way.

In [6], the authors considered both the channel assignment and routing. They proposed to find a route at first and make channel assignment after that. In [7], the authors proposed a cross-layer opportunistic spectrum access and dynamic routing algorithm for CRNs. Spectrum resources are dynamically allocated to maximize the capacity of links without generating much interference to other users while guaranteeing the physical constraints for the receiver. However, the authors mainly focused on physical layer issues and the link capacity on a single-hop network. In [8], the authors introduced control and scheduling algorithms to maximize the throughput of secondary users and to stabilize the CRN. However, the schemes proposed would bring longer delay to the network and network coding issue was not considered there.

As an important aspect in cognitive radio networks, the activities of primary users have been well studied. One research method is to use the statistical information of primary users. In [9], the authors proposed an algorithm which uses the statistical information to select a suitable route. According to the activities of the primary users, the most stable end-to-end route could be selected. However, the algorithm did not take into account the real time activities of the primary users. In this paper, we use the instant information of primary users in multi-hop cognitive radio networks and we can make better use of the available channels to increase the throughput.

Network coding is a popular technique used for improving spectrum efficiency in a wireless network. The basic network coding scheme was first proposed in [3]. It showed that network coding can increase throughput in different kinds of networks [10]–[13]. In [14], the authors studied a tuple network coding scheme. They proposed a dynamic control policy for routing, scheduling, and k-tuple coding, and proved that their policy is throughput optimal subject to the k-tuple coding constraint. However, in their work, a practical routing scheme with low complexity was not considered and the delay performance was not studied. In [15], the authors compared the performance of traditional unicast routing and coding-aware routing on a variety of wireless networks. They showed that a route selection strategy that is aware of network coding opportunities can get a higher throughput than the shortest path routing. However, in all these work, they focused on a small wireless network where the throughput optimization problem can be solved using centralized algorithms with limited scalability and applications.

Besides network coding, the backpressure scheduling is widely used in wireless networks for improving the performance [4]. It adopted the maximum weight scheduling and differential backlog routing policy to maximize the throughput of the whole network. In [16], the authors used backpressure concept to forward a packet to its destination in order to maximize the differential backlog. However, backpressure scheduling may cause the packet to go in loops and the delay of the network could be high [17]. In order to avoid the loops and reduce the delay in backpressure scheduling, we propose an adaptive backpressure routing algorithm in this paper.

In summary, the previous work discussed above addressed important aspects of multi-hop cognitive radio networks. However, joint adaptive routing and channel allocation considering the activities of the primary users have not been thoroughly investigated so far. In this paper, we combine channel allocation, routing and network coding, and analyze the effects of the primary users' activities on the throughput.

III. The CRN Model with Network Coding and Backpressure Scheduling

TABLE I
The List of Notations

Symbol	Meaning
i, j, k, m, n	Node
c	Channel
s	Session
$X_c(t)$	Primary user activity on channel c at time t
(i, j)	Ordinary link (i, j)
(i, j, k)	Network coding link (i, j, k) and i is the transmitter
$d_{i,j}$	Distance between node i and j
d_p	Transmission range of a primary user
d_s	Transmission range of a secondary user
H	Channel availability matrix
I	Interference matrix
$U_a^s(t)$	Queue length at node a for session s at time t
$W_{ab}^s(t)$	Weight of link ab for session s at time t
$h_{i,j}^{s,c}$	Availability of channel c at link (i, j) for session s
$\mu_{i,j}^{s,c}$	Indicator of allocation of channel c at link (i, j) for session s
$\sum_i$	Summation over all the nodes in CRN
$\sum_c$	Summation over all the channels in CRN
$\sum_s$	Summation over all the sessions in CRN
μ_s^r	Indicator of allocation of route r for session s

In this paper, we consider a time-slotted (with slot duration normalized to 1) cognitive radio network with M primary users and N secondary users, where secondary users contend for the channels when the primary users are inactive [18]. Among the secondary users, there are a set of S unicast communication sessions. The source and destination nodes of session s are denoted as $O(s)$ and $D(s)$. The list of notations of the CRN model is given in Table I.

The secondary users form a secondary user network. We assume that all the secondary users have an equal transmission range. If the distance between nodes i and j is less than the transmission range, they are said to be neighbors and (i, j) is one link of the secondary user network. We also introduce network coding into the CRN, which needs the participation of more than two nodes. If node i transmits to nodes j and k using network coding, then (i, j, k) is called a network coding link of the secondary user network.

We assume that all the primary users are independent from each other and each primary user transmits on a different channel.

The primary user activity on channel c at each time slot t can be denoted as $X_c(t)$, $(1 \leq c \leq C)$, where C is the number of channels. When $X_c(t) = 1$, primary user is OFF, which means that the channel is available to secondary users; when $X_c(t) = 0$, primary user is ON, which means that the channel is not available. We assume that at each time slot, the channel availability information would be sensed by secondary

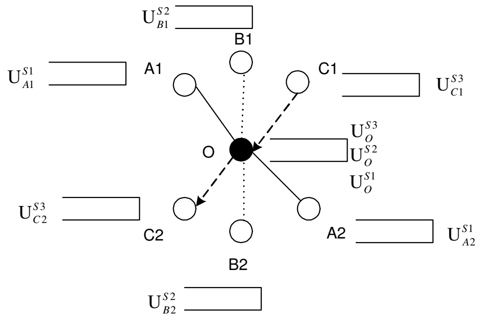


Fig. 1. Network coding with backpressure.

users without error. If channel c is available ($X_c(t) = 1$) or secondary user i is outside the transmission range d_p of the primary user, then the secondary user i can transmit on channel c.

In this paper, we use a special interference model in [19]. If secondary user i transmits to secondary user j and secondary user k transmits to secondary user l, then the transmission will be successful in two cases: (a) node i and node k transmit on two different channels. In this case, they do not have any interference. (b) node i and node k transmit on the same channel and if $d_{i,j} < d_s$, $d_{k,j} > d_s$ and $d_{i,l} > d_s$. This means that node i is the neighbor of j and k is the neighbor of l. However, k is not the neighbor of j and i is not the neighbor of l.

In order to represent the channel availability and the interference of the links in a cognitive radio network, we set up a channel availability matrix and a link interference matrix for each link on every channel [20].

Fig. 1 shows an example of an XOR-based network coding scheme with a backpressure algorithm. When A1 transmits packet p_1 to A2, B2 and C2 can overhear and get packet p_1 from A1. When B1 transmits packet p_2 to B2, A2 and C2 can overhear B1. When C1 transmits packet p_3 to C2, A2 and B2 can overhear C1. The relay node O can encode three packets together by doing $p_1 \oplus p_2 \oplus p_3$ and then transmits the encoded packet to A2, B2 and C2 using one channel. This means that we only need four channels to transmit with this network coding scheme. In contrast, without network coding, the number of channels needed should be six. As a result, the coding gain is 6/4 which is the proportion of the channel usage without network coding over that with network coding.

Lemma 1. *The XOR-based network coding gain of a network which consists of Ns pairs of sessions and one relay node O is 2Ns/(Ns+1), where Ns is the number of sessions which will perform network coding at O.*

Proof: O can encode Ns packets together by doing $p_1 \oplus p_2 \oplus p_3 \oplus ... \oplus p_{Ns}$ and then transmit the encoded packet to all the destinations using one channel. This means that we only need (Ns+1) channels to transmit with the network coding scheme with opportunistic listening. In contrast, without the network coding, we need 2Ns channels. As a result, the coding gain is 2Ns/(Ns+1). ■

Next, we discuss the construction of queues and subqueues. In a traditional way, each node has one queue. However, in order to support network coding, we set up subqueues at every node and each subqueue corresponds to one session s. We consider unicast transmission, while wireless broadcast is used only for the transmission of network coded packets. For simplicity we assume that the links transmit at unit rate and packets have fixed size so that one packet will be transmitted per time slot. We also assume that packet arrivals follow a stochastic process with finite second moment.

We extend the backpressure algorithm from Tassiulas and Ephremides [4] to jointly optimize for channel allocation, routing and network coding in cognitive radio networks.

In Fig. 1, the backpressure from O to A_2 for session s_1 is:

$$U_O^{s_1} - U_{A_2}^{s_1} \quad (1)$$

where $U_O^{s_1}$ and $U_{A_2}^{s_1}$ are the queue lengths of the subqueue for session s_1 at node O and at node A_2 respectively. Similarly, the backpressure from O to B_2 for session s_2 and the backpressure from O to C_2 for session s_3 are $U_O^{s_2} - U_{B_2}^{s_2}$ and $U_O^{s_3} - U_{C_2}^{s_3}$.

The backpressure at node O is defined as $min\{U_O^{s_1} - U_{A_2}^{s_1}, U_O^{s_2} - U_{B_2}^{s_2}, U_O^{s_3} - U_{C_2}^{s_3}\}$.

For every link (a, b) without network coding, let $U_a^s(t), U_b^s(t)$ be the backpressure (backlog) at node a and b at time t for session s. Let $W_{ab}^s(t)$ be the link weight at link (a, b) for session s. Then the weight can be calculated as the following:

$$W_{ab}^s(t) = max(U_a^s(t) - U_b^s(t), 0) \quad (2)$$

For network coding link (O, D_1, D_2,...D_k) with k sessions, calculate the weight as follows:

$$W_{O,D_1,D_2,...D_k}^{s_1,s_2,..s_k}(t) = max \\ (\frac{2k}{k+1} \cdot min\{U_O^{s_1} - U_{D_1}^{s_1}, U_O^{s_2} - U_{D_2}^{s_2}, ..., U_O^{s_k} - U_{D_k}^{s_k}\}, 0), \quad (3)$$

where $\frac{2k}{k+1}$ is the coding gain of the network coding link (O, D_1, D_2,...D_k) given by Lemma 1, and $min\{U_O^{s_1} - U_{D_1}^{s_1}, U_O^{s_2} - U_{D_2}^{s_2}, ..., U_O^{s_k} - U_{D_k}^{s_k}\}$ is the backpressure at node O.

In CRNs, since the activities of primary users change dynamically, sometimes the number of channels might become limited. As a result, the queue length at an intermediate node could build up quickly, which makes the node a bottleneck of the network. With backpressure scheduling applied, however, these bottleneck nodes would have a higher weight and get more chances to transmit. Moreover, with network coding, the bottleneck nodes can encode the packets from different sessions using XOR-based network coding and transmit to the next hop using one transmission. Thus, the whole network can clear up the bottleneck more easily and the throughput will increase. In this paper, we assume that nodes will decode the network coded packets hop by hop and we only consider the network coding between different sessions.

IV. Problem Formulation

Our objective is to maximize the aggregated throughput of all sessions while ensuring the stability of all the queues. Therefore, we have the following objective function:

$$\text{maximize} \sum_{s\in S} \lambda_s \tag{4}$$

where λ_s denotes the packet arrival rate of session s, and S is the set of all the sessions in the network. The constraints that need to be considered are discussed in the following.

First, we model queue dynamics and network constraints in the CRN. Let $U_{sn}(t)$ be the backlog of the total number of session s packets at node n at time slot t. If n is the destination of session s, we have $U_{sn}(t) = 0$. If the destination of session s is not n, we have:

$$\begin{aligned} U_{sn}(t+1) \quad \leq \quad & \max\{U_{sn}(t) - \sum_k \sum_s \sum_c \mu^{s,c}_{n,k}, 0\} \\ + \quad & \sum_m \sum_s \sum_c \mu^{s,c}_{m,n} + \lambda_{sn} \end{aligned} \tag{5}$$

where λ_{sn} is the packet arrival rate at node n for session s. The term $\sum_{k,s,c} \mu^{s,c}_{n,k}$ stands for the number of packets which can be transmitted by node n and $\sum_{m,s,c} \mu^{s,c}_{m,n}$ stands for the number of packets which are received by node n. The inequality comes from the fact that the packet arrival rate should be less than $\sum_{k,s,c} \mu^{s,c}_{n,k}$.

However, if two sessions applied network coding, the expression above would be:

$$\begin{aligned} U_{sn}(t+1) \quad \leq \quad & \max\Bigg\{U_{sn}(t) - \Bigg(\sum_k \sum_s \sum_c \mu^{s,c}_{n,k} \\ + \quad & \sum_k \sum_l \sum_s \sum_c 2 \times \mu^{s,c}_{n,k,l}\Bigg), 0\Bigg\} \\ + \quad & \sum_m \sum_s \sum_c \mu^{s,c}_{m,n} + \lambda_{sn} \end{aligned} \tag{6}$$

Let $\mu^{s,c}_{i,j}$ denote the indication variable on whether we assign the channel c to link (i, j) for session s or not. If we assign the channel c, then $\mu^{s,c}_{i,j} = 1$; otherwise, $\mu^{s,c}_{i,j} = 0$. Therefore, we have

$$\mu^{s,c}_{i,j} = 0 \quad \text{or} \quad 1 \tag{7}$$

From the channel availability information, we know that channel c can be assigned to link (i, j) for session s only when it is available. Thus, we have

$$\mu^{s,c}_{i,j} \leq h^{s,c}_{i,j} \tag{8}$$

From the CRN model, we know that a channel c is either available or unavailable. If channel is available, $h^{s,c}_{i,j} = 1$; otherwise, $h^{s,c}_{i,j} = 0$. So we have

$$h^{s,c}_{i,j} = 0 \quad \text{or} \quad 1 \tag{9}$$

One link can use only one channel to transmit for one session

$$\sum_c \mu^{s,c}_{m,n} \leq 1 \quad \forall m, n \tag{10}$$

From the interference matrix, we know that if link (m, n) and link (j, k) interfere with each other, they can not transmit simultaneously using the same channel c. If they do not interfere with each other, they can share the same channel. As a result, we have

$$\sum_{s_1} \mu^{s_1,c}_{m,n} + \sum_{s_2} \mu^{s_2,c}_{j,k} \leq I_{(m,n),(j,k)} \tag{11}$$

Now, we consider the case with network coding. Let $\mu^{s,c}_{i,j,k}$ denote the indication variable which indicates whether we assign the channel c to both link (i, j) and link (i, k) for session s. If we assign the channel c, then $\mu^{s,c}_{i,j,k} = 1$; otherwise, $\mu^{s,c}_{i,j,k} = 0$. Therefore, we have

$$\mu^{s,c}_{i,j,k} = 0 \quad \text{or} \quad 1 \tag{12}$$

Only when both links (i, j) and (i, k) are available, network coding link (i, j, k) is available. Thus, we have

$$h^{s,c}_{i,j,k} = h^{s,c}_{i,j} \cdot h^{s,c}_{i,k} \tag{13}$$

Similar to the case of without network coding, when channel c is available on the network coding link, $\mu^{s,c}_{i,j,k}$ has the chance to use the channel; otherwise, $\mu^{s,c}_{i,j,k} = 0$.

$$\mu^{s,c}_{i,j,k} \leq h^{s,c}_{i,j,k} \tag{14}$$

One link can use only one channel to transmit one session

$$\sum_s \sum_c \mu^{s,c}_{m,n} + \sum_s \sum_c \mu^{s,c}_{m,n,k} \leq 1 \quad \forall m, n \tag{15}$$

Similarly, the link interference constraint with network coding is:

$$\begin{aligned} & \sum_s \mu^{s,c}_{m,n,l} + \sum_s \mu^{s,c}_{i,j,k} \leq \\ & \quad I_{(m,n),(i,j)} \cdot I_{(m,l),(i,j)} \cdot I_{(m,n),(i,k)} \cdot I_{(m,l),(i,k)} \end{aligned} \tag{16}$$

The objective function (4) is hard to solve. In order to solve it in an easier way, after knowing the weight of all the links for the network, the channel allocation problem can be formulated as in the following:

$$\text{maximize} \quad \sum_c \sum_s \sum_l \mu^{sc}_l(t) \cdot w_l(t). \tag{17}$$

Constraints: from (7) to (16).

Here l stands for the links in the network including both standard links and network coding links.

The problem above is a Mixed Integer Linear Programming (MILP) problem, which is NP hard and may be solved using C-PLEX for small size networks. However, when the network size is large, the problem would be unscalable. In [21], the authors proposed a heuristic algorithm to solve their MILP model and the solution could be obtained in a timely manner for moderately sized networks. In the next section, we propose a distributed algorithm that is easy to implement and can achieve good performance in both throughput and delay with low complexity.

V. A Distributed Algorithm

There are two steps in the proposed channel allocation scheme as described in the following. First, choose the link which has the maximum weight and assign a channel for this link. Second, exclude the links which may have interference with the chosen link, and select a link with the highest weight which does not have interference with chosen links and assign a channel for it. The process continues till all the channels have been allocated.

Besides the channel availability issue, another important aspect is routing. Our goal is to choose a route which not only considers the channel availability but also considers network coding opportunity.

Let μ_s^r denote whether we use the route for session s, when we use route r, $\mu_s^r = 1$; otherwise, $\mu_s^r = 0$.

Since we only choose one route for each session, we have $\sum_{r \in R} \mu_s^r = 1$, where R is the set of all the possible routes for session s.

We know that, only after we choose route r, we can assign channel c to link (i, j) for session s. Thus, we have $\mu_{i,j}^{s,c} \leq \mu_s^r$. This constraint can be used for channel allocation after route selection.

The route selection problem can be formulated as following.

$$\text{maximize} \quad \frac{\sum_{i,j,c,s} h_{i,j}^c \cdot \mu_s^r}{\sum_s \text{hops of route of session } s} \cdot G \tag{18}$$

where $G = \prod_{i=1}^{N} CG(i)$ and $CG(i)$ is the coding gain at one secondary user i given by Lemma 1.

Constraints:

$$\begin{cases} (i, j) \quad \text{is on route } r \\ \sum_{r \in R} \mu_s^r = 1 \\ \mu_s^r = 0 \quad \text{or} \quad 1 \end{cases} \tag{19}$$

Our route selection scheme includes two steps: 1) Initiate a route of a session which maximizes the channel availability in terms of (No. of available channels/No. of hops). 2) Choose a route of a session which maximizes both channel availability and network coding opportunity until all the sessions find their routes.

We can actually combine routing, channel allocation and link scheduling schemes in cognitive radio networks. According to the channel availability, we can first choose the best route for all the sessions to maximize the channel usage and coding opportunity. Second, we use backpressure algorithm to calculate the link weights, based on which we use channel allocation schemes to assign channels to suitable links which have higher weight to make full use of available channels.

The complexity of our distributed algorithms is reduced in two aspects: 1) we choose the routes first for the sessions, which reduces many calculation of the weight of the links not on the route. 2) when we implement our channel allocation schemes, we exclude those links that have conflicts with the links that have been allocated channels. Thus, we do not need to consider the channel allocation of those links, which again reduces the complexity.

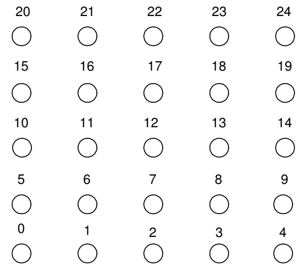
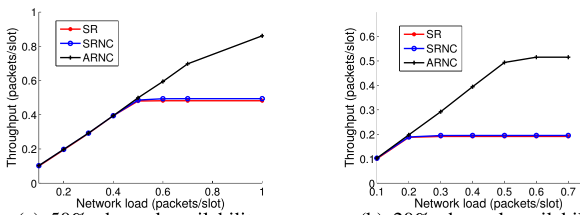


Fig. 2. A 25-node wireless network.

VI. Numerical Results

Our simulation setup is based on a 25-node wireless network shown in Fig. 2. We set up a 5 by 5 grid with two symmetrical unicast flows: node 0 to node 24 (flow 1), and node 20 to node 4 (flow 2). The packet arrival follows Poisson process. The transmission range of secondary users is set to be 2. Two different channels with availability of 50% and 20% are considered. The link capacity is set to be 1. We conduct simulations using C++. In all the figures, SR, $SRNC$, AR, and $ARNC$ represent shortest path routing, shortest path routing with network coding, adaptive channel allocation and routing without network coding, and our proposed adaptive channel allocation and routing scheme with network coding, respectively. Network load and throughput are average values on the number of flows.



(a) 50% channel availability (b) 20% channel availability

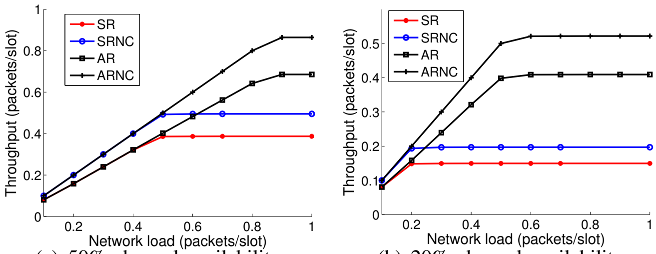
Fig. 3. Throughput of CRNs v.s. different network load with different channel availability

In Fig. 3(a), we illustrate the throughput of CRN as a function of different network load when the number of channels is 2. When the channel availability is 0.5, the route selection scheme with network coding performs the best while the shortest path routing without network coding performs the worst. The performance of shortest path routing with network coding lies in between. We can see that the route selection scheme with network coding performs better than other two schemes especially when the network load is greater than 0.5. The results show that our joint channel allocation and routing scheme can help achieve better performance.

In Fig. 3(b), we change the channel availability to 0.2 by keeping other configurations the same. Similar to Fig. 3(a), route selection scheme with network coding still performs the best. Compared with Fig. 3(a), the throughput of all three cases achieve much less throughput than the scenario of Fig. 3(a). This is mainly because now the channel availability is only

40% of that in Fig. 3(a). The results show that our scheme can still achieve good performance when the network load is high.

Next, we increase the number of flows to 5: node 0 to node 24, node 20 to node 4, node 21 to node 1, node 23 to node 3, and node 10 to 14. We investigate the throughput of our schemes in this case.



(a) 50% channel availability (b) 20% channel availability

Fig. 4. Throughput of CRNs v.s. different network load with 5 sessions with different channel availability

In Fig. 4(a), we illustrate the throughput of network with four schemes for different network load when the number of channels is 2. When the channel availability is 0.5, we can see that the route selection scheme and the shortest path routing with network coding performs much better than those schemes without network coding. Network coding can improve the throughput significantly in this scenario. This is because we have 5 sessions in the network, which provides more network coding opportunities and increases the throughput. The results show that our joint channel allocation and routing scheme still has the best performance.

In Fig. 4(b), we illustrate the throughput of the network when the channel availability is 0.2. Similar to Fig. 4(a), our scheme performs the best and network coding can also improve the throughput significantly in this scenario. However, the throughput in this case is lower than that in Fig. 4(a). This is because the low channel availability decreases the connectivity, and thus the throughput of the network.

VII. Conclusion

In this paper, we presented an adaptive channel allocation and routing scheme for multi-hop CRNs. First, we considered the activities of the primary users and the interference among the secondary users in a CRN model. We showed how back-pressure scheduling and network coding can be incorporated into multi-hop CRNs. Second, we formulated an optimization problem jointly considering the link weight, the network coding opportunities and channel availability in order to maximize the throughput of the network. The proposed scheme determines how to allocate channels and choose different routes in different channel availability scenarios. Finally, we studied the performance of our scheme in different situations of channel availability and showed how channel availability, channel allocation and route selection techniques influence the throughput and delay in CRNs.

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