Reliable Channel Selection and Routing for Real-Time Services over Cognitive Radio Mesh Networks

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Abstract. In Cognitive Radio Mesh Networks (CogMesh), Secondary Mesh Routers (SMRs) can opportunistically utilize the licensed spectrums for the traffic of the Secondary Mesh Users (SMUs). How to guarantee Quality of Service (QoS) for real-time services over CogMesh is still an opening issue. In this paper, we present a discrete-time vacation queueing system to abstract the Primary User (PU) interruption to SMR data transmission. Moreover, we formulate the optimization problem of joint channel selection and routing, to achieve minimum end-to-end delay for SMR while guaranteeing the channel unavailability. A heuristic method is proposed to solve this problem and results show our proposed method performs the closest to the scheme using optimization tool, and outperforms the minimal unavailability scheme and minimal delay scheme in terms of end-to-end delay and solution rate.

Keywords: cognitive radio mesh networks, real-time services, vacation queueing, channel selection.

1 Introduction

Wireless mesh networks have emerged as a highly promising technology to extend the network access area in an economical and convenient way [1] [2]. To further improve the network flexibility and increase spectrum utilization, there is a strong motivation to utilize the unused spectrum to deliver the mesh network traffic flows [3]. Cognitive Radio (CR) [4], an agile technology enables Secondary Users (SUs) to intelligently access the spectrum bands licensed to Primary Users (PUs), is come forth for this critical requirement. Furthermore, the Cognitive Radio Mesh Networks (CogMesh), which combines CR and mesh technologies, is proposed to improve the spectrum utilization and expand the network access area simultaneously [3] [5] [6].

A significant challenge in CogMesh is the real-time service communication, which has strict Quality of Service (QoS) constraints on end-to-end delay, jitter, packet loss, etc. Channel selection and routing are two ever important mechanisms in the provision of QoS in CogMesh. The integration of channel selection

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in the establishment of end-to-end routes is of critical importance. However, it is still a tough problem.

There are some related works which focus on channel assignment and end-to-end delay guarantee for wireless mesh networks [7] [8]. However, the schemes for traditional wireless mesh networks cannot be applied directly to CogMesh scenario due to the channel unavailability caused by primary system. Therefore, some research devotes to channel selection and dynamic spectrum access in CR networks. Y. Hou *et al.* [9] studied the channel selection and routing in multi-hop CR networks, with the objective of minimizing the total bandwidth used in the network. Y. Song *et al.* [10] proposed a stochastic channel selection algorithm based on learning techniques. Each secondary node selects one channel with a probability which is recorded in a list and updated according to the result of each selection. And then a packet will be sent once the channel selected is available to use. M. Rehmani *et al.* [11] proposed a channel selection scheme to select the channel with the highest channel weight which is defined as $e^{-p}(1-p)$, where p is the occupancy rate of PUs.

However, these previous works do not consider the end-to-end service requirement. In this paper, we will address the problem of joint channel selection and routing, which is crucial in QoS guarantee for real-time services over CogMesh. The major contributions of this paper are threefold. First, we adopt a vacation queueing system to abstract the channel vacation due to PU interruption in CogMesh. The analytical results based on the vacation queueing system are used to derive the channel asymptotic unavailability and the expected end-to-end delay for SMR. Second, we formulate the optimization problem to minimize the end-to-end delay for SMR while guaranteeing the channel unavailability and propose the joint channel selection and routing scheme. Third, numerical results show our proposed scheme performs close to the scheme using optimization tool and outperforms two other greedy heuristic schemes, i.e., the minimal unavailability scheme and minimal delay scheme.

The rest of the paper is organized as follows. We introduce the system model in Section 2. In Section 3, we formulate and analyze the optimization problem. In Section 4, we describe our proposed scheme. In Section 5, we evaluate the performance of the proposed scheme. Finally, we draw the conclusions in Section 6.

2 System Model and Assumptions

Each SMR and SMG are equipped with one CR transceiver and one normal radio transceiver with a dedicated control channel. Several secondary mesh users (SMUs) access their nearby SMRs to communicate with the users in not only the CogMesh but also the Internet through the SMG. In this paper, we use pre-computed paths for each source-destination pair to guarantee the QoS for each service session. $\mathcal{R}$ is the route set from source SMR to the gateway SMG. For each link l on one route r, the available channels consist a subset $\mathcal{M}_{r,l}$ of $\mathcal{M}$.

Different channels at the same link may have different quality metrics, such as channel fading parameters, interference, channel bandwidth, and so on. We

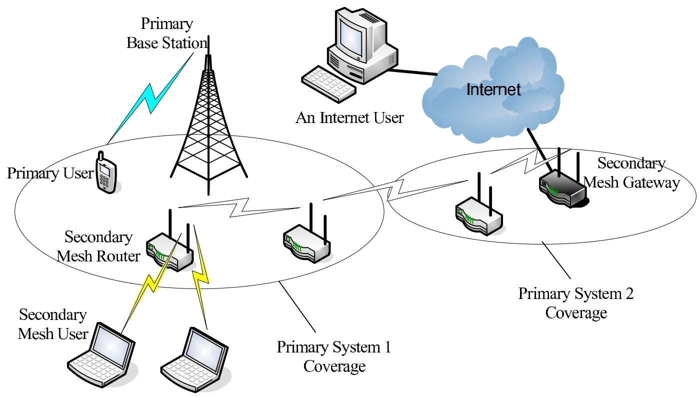

Fig. 1. An example of Cognitive Radio Mesh Network

use the Finite-State Markov Channel (FSMC) model [12] to represent the time- and frequency-selective slow fading Channels. Assume that all channels have S states. In each state, the received Signal to Interference plus Noise Ratio (SINR) is different. We define Γ_s $(s = 1, ..., S)$ as the lower bound threshold of the state s, where $0 < \Gamma_1 < ... < \Gamma_S < \infty$. We say link e_i is in state s, if the SINR is between Γ_s and Γ_{s+1}. Adaptive Modulation Coding (AMC) technique is used in our system model. Where, channel's quality can be estimated by the SINR measured on the receiving node. Different modulation schemes can bring out different data transmission rates.

The mode of access mechanism in this paper is 802.11 distributed coordination function (DCF) medium access control (MAC) protocol. Each SMR maintains a separate queue for real-time data packets on the network layer. We consider a time-slotted packet transmission scenario, where the slot length is fixed as T_{slot}.

Table 1. List of Notations

Symbol	Meaning
$\mathcal{R}$	the set of routes
$\mathcal{N}$	the set of SMRs
$\mathcal{L}$	the set of links
$\mathcal{M}$	the set of channels
$\mathcal{N}_r$	the set of SMRs in route r
$\mathcal{L}_r$	the set of links in route r
$\mathcal{M}_l$	the set of channels of link l on route r
r	a route
l	a link
n	a SMR
m	a channel
C	the average packet length
x_{rlm}	the binary indicator of channel m at link i in route r

The basic slot structure consists of sensing, data transmission, and acknowledge periods, as illustrated in Fig. 3. At the beginning of a slot, the SMR senses the channel. If the channel is identified idle, the SMR transmits data. At the end of the slot, the receiver acknowledges a successful transmission. For the sake of simplicity, the transmission of acknowledgement is assumed to be error-free. It is natural for us to model the PUs interruption as a discrete-time queueing system. For this reason we devote the next section to the PU interruption modeling. Table 1 describes the main notations used in this paper.

3 Problem Formulation and Analysis

In this section, the optimal joint channel selection and routing for real-time services in CogMesh is formulated as an optimization problem. We will first introduce the PU interruption model and discuss end-to-end delay. Afterwards, we formulate the optimization problem and solve it.

Note our further discussion will take the example case of channel m at link l in route r. For description simplicity, we employ a binary variable x_{rlm} ($x_{rlm} \in \{0,1\}, \forall r \in \mathcal{R}; \forall l \in \mathcal{L}; \forall m \in \mathcal{M}$) to indicate whether channel m is selected for the link l or not. If x_{rlm} is equal to 1, channel m is selected for the link l, 0 otherwise.

3.1 PU Interruption Model

In CogMesh, SMR's data transmission process is error-prone since data packets are transmitted over unreliable wireless channels and PUs may interrupt SMRs data transmission randomly. How to abstract the PU interruption process? Our choice is to use a discrete-time queueing model subjected to vacations. Before we proceed with the model, it is clear that we should understand why we do in this fashion. First, the discrete-time scale reflects the nature of the underlying wireless communication, i.e., time-slotted data transmission. Moreover, "vacation" refers to the process that PU interruption such that channel becomes unavailable for SMR, and "random" refers to the fact that vacation occurs independently of the system state. Without loss of generality, we consider "continue after vacation" operation mode, which means a packet continues to transmit after vacation times. It can be easily extended to other operation modes in vacation queueing system, such as "repeat after interruption", "repeat after interruption with resampling" [13]. The concepts of vacation queueing system will be found useful throughout the remainder analysis.

As noted above, one of the most important factors causing the channel unavailable is PU behavior, which is modelled as a Markovian ON-OFF process as illustrated in Fig. 2. The ON-OFF process is used most frequently to model the PU behaviors, slots during which the channel is available for SMRs are called ON slots, and analogously, slots during which the channel takes a vacation for SMRs due to PU interruption are called OFF slots. Let α_{rlm} and β_{rlm} denote the probabilities that the channel m remains in ON and OFF state, respectively,

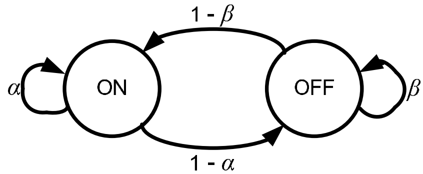

Fig. 2. Transition diagram of the channel vacation

in addition, μ_{rlm}^{ON} and μ_{rlm}^{OFF} represent the mean time in the ON and OFF state, respectively. Accordingly, the fraction of ON slots A_{rlm} is calculated by Eq. (1)

$$A_{rlm} = \frac{\mu_{rlm}^{ON}}{\mu_{rlm}^{ON} + \mu_{rlm}^{OFF}} = \frac{1 - \beta_{rlm}}{2 - \alpha_{rlm} - \beta_{rlm}} \tag{1}$$

We have considerable freedom in constructing a large number of vacation models through the choice of α_{rlm} and β_{rlm} corresponding to different PU behaviors. In a similar fashion, we obatin the fraction of OFF slots

$$U_{rlm} = \frac{\mu_{rlm}^{OFF}}{\mu_{rlm}^{ON} + \mu_{rlm}^{OFF}} = \frac{1 - \alpha_{rlm}}{2 - \alpha_{rlm} - \beta_{rlm}} \tag{2}$$

In the view of dependability engineering, Eq. (2) matches the definition of asymptotic unavailability. For this reason we immediately obatin the channel asymptotic unavailability due to PU interruption for the link l

$$U_{rl} = \sum_{m \in \mathcal{M}_l} U_{rlm} x_{rlm}, \quad \forall l \in \mathcal{L}_r. \tag{3}$$

Furthermore, let U_r denote the channel asymptotic unavailability for PU interruption over route r. Since all the links over the route consist a series system and channels on each link fail independently, we can obtain

$$U_r = 1 - \prod_{l \in \mathcal{L}_r} (1 - \sum_{m \in \mathcal{M}_l} U_{rlm} x_{rlm}), \quad \forall r \in \mathcal{R}. \tag{4}$$

3.2 End-to-End Delay

End-to-end delay is one important element of the network performance experienced by a user. In particular, it is of concern to the real-time service. The end-to-end delay over one route is the summation of delays of all links along the route. In our study we shall only consider access delay and transmission delay, for the sake of simplicity.

Since the 802.11 DCF MAC protocol is adopted as our distributed access scheme, the access delay is mainly caused by SMR packets transmission backoff. Let K denote the maximum number of transmission retries, and W_j denote the contention window at the jth ($1 \leq j \leq K+1$) backoff stage. According to the 802.11 standard, the set of contention window W_j shall be sequentially ascending integer powers of 2, minus 1, ranging from the specified minimum value W_{min} to the maximal value W_{max}, that is, $W_j = 2^{j-1}(W_{min}+1) - 1$. Based on the contention window parameter, SMR backoff time T_j^Q in jth backoff stage can be calculated as below

$$T_j^Q = W_j^{'} \times T_{slot} \tag{5}$$

where $W_j^{'}$ is a random integer drawn from a uniform distribution over the interval $[0, W_j]$, and T_{slot} is the slot length. For the sake of simplicity, we set $T_{slot} = 1$. Then, the mean value of jth backoff time can be expressed $E[T_j^Q] = \frac{W_j}{2}$.

Now it satisfies the condition to calculate the mean backoff access delay. We still take the channel m at link l over route r for example. Let p_{rlm} represent the transmission failure probability which remains the same at all backoff stages. To guarantee the selected channel quality, we consider a predefined threshold value I for p_{rlm}, that is p_{rlm} of the selected channel should not exceed the upper bound I. Note, each SMR needs to measure the transmission failure probability periodically. Then, the mean backoff access delay

$$\begin{aligned} D_{rlm}^Q &= \sum_{i=1}^{K} p_{rlm}^{i-1}(1-p_{rlm}) \sum_{j=1}^{i} E[T_j^Q] + p_{rlm}^K \sum_{j=1}^{K+1} E[T_j^Q] \\ &= \frac{1-(2p_{rlm})^{K+1}}{2(1-2p_{rlm})}(W_{min}+1) \end{aligned} \tag{6}$$

Similar results on access delay can be found in [8], we extend the related work on transmission delay to take the PU interruption into account. In fact, the transmission delay can also be interpreted as the packet effective service time, which is defined as the number of slots between the beginning of the slot where the packet enters the channel and the end of the slot where the packet leaves the channel as illustrated in Fig. 3. Based on this definition, the transmission delay for one packet should include the actual transmission time and the channel vacation time.

In the "continue after vacation" operation mode, a packet's transmission continues after PU interruption. The unfinished part can be seen as a new packet with length equals to the remaining transmission time. Therefore, we can derive the mean transmission delay D_{rlm}^T per packet for SMR as follows

$$D_{rlm}^T = \frac{C}{B_{rlm}A_{rlm}} \tag{7}$$

here C represents the mean packet length including MAC control overhead, in bits, B_{rlm} is the link transmission capacity, in bits per sec, and A_{rlm} is the fraction of ON slots calculated from Eq. (1).

As noted above, the delay over one link D_{rlm} consists of access delay D_{rlm}^Q and transmission delay D_{rlm}^T. From Eq. (6) and (7) it is apparent that the end-to-end delay D_r in one route r can be expressed as the sum of mean delay of all links in route r

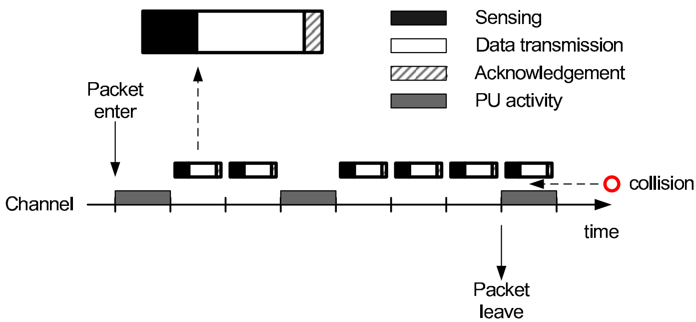

Fig. 3. Transmission scenario

$$D_{rlm} = D^{Q}_{rlm} + D^{T}_{rlm} \tag{8}$$

$$D_r = \sum_{l \in \mathcal{L}_r} \sum_{m \in \mathcal{M}} (Q_{rl} + 1) D_{rlm} x_{rlm} \tag{9}$$

where Q_{rl} is the number of packets buffered on link l. It should be monitored by SMR in each transmission.

3.3 Formulation of Channel Selection for Each Route

The problem we study is how to enable every link choose an optimal channel for data transmission. The route selection is based on the result of the optimization formulation. Here, the objective function is to minimize the expected end-to-end delay of real-time service. We assume that each link has at least one channel that can be used. For each route, we select channels to minimize the objective function while guaranteeing the channel asymptotic unavailability due to PU interruption not exceed the threshold, i.e.,

P1

$$\text{Minimize } D_r = \sum_{l \in \mathcal{L}_r} \sum_{m \in \mathcal{M}_l} (Q_{rl} + 1) D_{rlm} x_{rlm} \tag{10}$$

Subject to:

$$U_r \leq U \tag{11}$$

$$p_{rlm} x_{rlm} \leq I \tag{12}$$

$$\sum_{m \in \mathcal{M}_l} x_{rlm} = 1, \quad \forall l \in \mathcal{L}_r \tag{13}$$

$$x_{rim} + x_{rjm} \leq 1, \quad \forall m \in \mathcal{M}_l; i, j \in \mathcal{L}_r; j \in \mathcal{L}_{I,i} \tag{14}$$

$$x_{rlm} \in \{0, 1\}, \quad \forall l \in \mathcal{L}_r; m \in \mathcal{M}_l. \tag{15}$$

where U is the route channel unavailability threshold, I is the required transmission failure probability threshold. Constraint (11) represents the route channel unavailability in Eq. (2) can not exceed the threshold U. Constraint (12) represents the transmission failure probability in Eq. (6) can not exceed the threshold I. Constraint (13) indicates that each link should work on one and only one data channel. Constraint (14) means the link in interference range area can not work on the same channel, thus there is no additional delay in the data channel. The solution is to find out every x_{rim}, so that all the constraints are satisfied and the objective function is minimized. Obviously, this is a nonlinear integer problem.

3.4 Transformation

According to (11) and (4), we have

$$
\begin{aligned}
& 1-\prod_{l\in\mathcal{L}_r}(1-\sum_{m\in\mathcal{M}_l}U_{rlm}x_{rlm})\leq U \\
\Leftrightarrow & \prod_{l\in\mathcal{L}_r}(1-\sum_{m\in\mathcal{M}_l}U_{rlm}x_{rlm})\geq 1-U \\
\Leftrightarrow & \ln\left(\prod_{l\in\mathcal{L}_r}(1-\sum_{m\in\mathcal{M}_l}U_{rlm}x_{rlm})\right)\geq\ln(1-U) \\
\Leftrightarrow & \sum_{l\in\mathcal{L}_r}\ln(1-\sum_{m\in\mathcal{M}_l}U_{rlm}x_{rlm})\geq\ln(1-U) \\
\Leftrightarrow & \sum_{l\in\mathcal{L}_r}\sum_{m\in\mathcal{M}_l}\ln(1-U_{rlm})x_{rlm}\geq\ln(1-U)
\end{aligned}
$$

The last transformation is ture since x_{rlm} is either 0 or 1, and only one channel for each link is selected. Moreover, since U is less than 1, $\ln(1-U)$ is negative, the above inequality can be transformed to the following inequality by deviding $\ln(1-U)$ on both sides.

$$
\begin{aligned}
& \sum_{l\in\mathcal{L}_r}\sum_{m\in\mathcal{M}_l}\ln(1-U_{rlm})x_{rlm}\geq\ln(1-U) \\
\Leftrightarrow & \sum_{l\in\mathcal{L}_r}\sum_{m\in\mathcal{M}_l}\frac{\ln(1-U_{rlm})}{\ln(1-U)}x_{rlm}\leq 1 \\
\Leftrightarrow & \sum_{l\in\mathcal{L}_r}\sum_{m\in\mathcal{M}_l}\log_{(1-U)}(1-U_{rlm})x_{rlm}\leq 1
\end{aligned}
$$

From (11) and (12), the number of binary varialbles can be reduced for each link by removing any channel m where $U_{rlm}\geq U$ or $p_{rlm}>I$. Assume the new channel set for each link l is $\mathcal{M}'_L$.

Let $\hat{D}$ denote the maximum link delay. The objective function in (10) can be transformed as follows.

$$Minimize \sum_{l\in\mathcal{L}_r}\sum_{m\in\mathcal{M}'_l}(Q_{rl}+1)D_{rlm}x_{rlm}$$
$$\Leftrightarrow Maximize \sum_{l\in\mathcal{L}_r}\sum_{m\in\mathcal{M}'_l}\left(\hat{D}-(Q_{rl}+1)D_{rlm}\right)x_{rlm}$$

We introduce positive variable v_{rlm} and w_{rlm} to denote the coefficience in the modified objective function and constraint function as follows

$$v_{rlm} = \hat{D} - (Q_{rl}+1)D_{rlm}, \forall l \in \mathcal{L}_r; m \in \mathcal{M}'_l \tag{16}$$

$$w_{rlm} = \log_{(1-U)}(1-U_{rlm}), \forall l \in \mathcal{L}_r; m \in \mathcal{M}'_l \tag{17}$$

For any channel m in link l on route r, the analog meaning of v_{rlm} is the value (profit), while the meaning of w_{rlm} is the weight (cost). The retransformed problem can be defined as follows *P2*

$$\text{Maximize} \sum_{l\in\mathcal{L}_r}\sum_{m\in\mathcal{M}'_l} v_{rlm}x_{rlm} \tag{18}$$

Subject to:

$$\sum_{l\in\mathcal{L}_r}\sum_{m\in\mathcal{M}'_l} w_{rlm}x_{rlm} \leq 1 \tag{19}$$

$$\sum_{m\in\mathcal{M}'_l} x_{rlm} = 1, \quad \forall l \in \mathcal{L}_r \tag{20}$$

$$x_{rim} + x_{rlm} \leq 1, \quad \forall l \in \mathcal{L}_r; m \in \mathcal{M}'_l; i \in \mathcal{L}_{I,l} \tag{21}$$

$$x_{rlm} \in \{0,1\}, \quad \forall l \in \mathcal{L}_r; m \in \mathcal{M}'_l. \tag{22}$$

This is a $0-1$ integer linear problem, which is in general NP-complete [14]. Moreover, without constraint (21), this problem can be viewed as an instance of Multiple-Choice Knapsack Problem, where we have $|\mathcal{L}_r|$ mutually disjoint classes (links) of items (channels) to be packed into a knapsack of capacity 1. Each item m ($m \in \mathcal{M}_l$) has a profit v_{rlm} and a cost w_{rlm}. The problem is to choose exactly one item from each class such that the total profit is maximized without exceeding the capacity. In addition, the item in interfered classes should be varied from each other.

Using optimization tools such as MOSEK [15] and CPLEX [16], we can get the optimal solution for the above problem. In this paper, we are interested in finding a heuristic method to get an accepted result within affordable time complexity.

4 Proposed Channel Selection and Routing Schemes

In this section, we propose a heuristic channel selection scheme for each route, and then choose the route with minimum end-to-end delay D_r.

For any link l, we sort the channels according to increasing weights w_{rlm}, and derive R_l. Therefore, the index of channels in $\mathcal{R}_l$ is different from that in $\mathcal{M}_l$. We then construct an instance of knapsack by setting

$$\tilde{v}_{rlm} = v_{rlm} - v_{rl,m-1}, \forall l \in \mathcal{L}_r, m = 2, 3, ..., |\mathcal{M}_l^{'}|.$$

and

$$\tilde{w}_{rlm} = w_{rlm} - w_{rl,m-1}, \forall l \in \mathcal{L}_r, m = 2, 3, ..., |\mathcal{M}_l^{'}|.$$

and the residual capacity is

$$\bar{c} = 1 - \sum_{l \in \mathcal{L}_r} w_{rl1}$$

Algorithm 1. Channel selection algorithm

Input: $\{\mathcal{N}_i\}$, $\{\mathcal{M}_i\}$, $\{Q_{rlm}\}$, α, β.
Output: $\{x_{ijc}\}$.

Initialization: $\bar{c} \leftarrow 1$
Calculate w_{rlm}, v_{rlm}, μ_{rlm} for all route link and channels.
for $l \in \mathcal{L}_r$ **do**
  Remove the channels where $U_{rlm} \geq U$ or $p_{rlm} > I$.
  Sort the channels according to increasing w_{rlm} and derive $\mathcal{M}_l^*$.
  for $i = 2; i \leq |\mathcal{M}_l^*|; i++$ **do**
    $\tilde{v}_{rli} \leftarrow v_{rli} - v_{rl,i-1}$
    $\tilde{w}_{rli} \leftarrow w_{rli} - w_{rl,i-1}$
  end for
  $\bar{c} \leftarrow \bar{c} - w_{rl1}$
end for
Sort the link-channel pairs according to decreasing incremental efficiencies $\tilde{\eta}$
while 1 **do**
  Get the index of link-channel pair $\{i, j\}$ with the maximal $\tilde{\eta}$: $\{i, j\} \leftarrow \arg \max_{l \in \mathcal{L}_r, m \in \mathcal{M}_l^*} \tilde{\eta}_{rlm}$
  $\bar{c} \leftarrow \bar{c} - \tilde{w}_{ri1}$
  if $\bar{c} < 0$ **then**
    Break;
  else
    Record the channel index as m' for link i in the knapsack.
    Mark channel m' for all the interfering links as active.
    $x_{rim'} \leftarrow 0$
    Mark channel j for all the interfering links as inactive.
    $x_{rij} \leftarrow 1$
  end if
end while

Then, we sort all the link-channel pair according to decreasing incremental efficiencies defined as follows

$$\tilde{\eta}_{rlm} = \frac{\tilde{v}_{rlm}}{\tilde{w}_{rlm}}$$

We then fill the knapsack up to capacity $\bar{c}$ according to the order of the link-channel pair sorting in terms of incremental efficiencies $\tilde{\eta}_{rlm}$. Capacity constraint is checked before adding a link-channel pair. After adding a link-channel pair, the channel m used in this link l is marked as inactive from any interfering links $\mathcal{I}_l$, and the previous channel m' from the same link l in the knapsack is taken out, which means $x_{rlm'} = 0$, and channel m' in interfering links $\mathcal{I}_l$ is marked to be active. The residual capacity $\bar{c}$ will updated by

$$\bar{c} = \bar{c} - \tilde{w}_{rlm}$$

Following this approach until the capacity constraints break, the channel selection for all links in route r is finished. The details of this scheme is shown in Algorithm 1.

We shall select the route with the minimum end-to-end delay, while the other constraints are guaranteed.

$$r^* = \arg\min_{r \in \mathcal{R}} D_r \tag{23}$$

5 Numerical Results and Analysis

We have implemented the algorithms in MATLAB and evaluated the performance. We consider a grid topology similar to the topology used in [8], where SMRs are uniformly placed. The interference range of any SMR is one neighbouring hop. The number of available routes is 10. For each route, the number of hops changes from 1 to 10. For each link, the number of available channels changes from 2 to 10. Each channel on every link selects a data rate from {11, 5.5, 2, 1} Mbps according to the quality of that channel. The ON-OFF changing rate for each channel is randomly generated between 0 and 1. We assume the traffic follows the constant bit rate with the packet size of 128 bytes. The minimum contention window size W_{min} is 0.02ms, and the maximum number of retransmissions K is 4. The transmission failure probability p_{rlm} is randomly generated in [0,0.1]. The threashold of transmission failure probability for each link is 0.1. The threashold of channel asymptotic unavailability for PU interruption over any route is set as 0.9. For each study we randomly generated for 100 times (seeds).

We present the results of solution rate and end-to-end delay. Solution rate is defined as the rate of seeds with valid solutions from all the 100 seeds. End-to-end delay only with valid solution is presented. To make the discussion more concrete, a series of comparative performance evaluation between the proposed scheme and other schemes, including optimization tool based channel selection, minimal unavailability channel selection, and minimal delay channel selection are carried out.

5.1 Solution Rate

We study the solution rates for all the schemes. Figure 4, 5, 6, and 7 show the solution rate for channel selection schemes, MOSEK, proposed, minimal unavailability and minimal delay, respectively. Then, we can see for all schemes, when the number of available channels is less than 6, the MOSEK solution has the highest solution rate among others.

As the number of links increases, some cases will reduce the solution rate. For example in the MOSEK results, the solution rate for 2-channel case starts reduction from 4 hops, 3-channel case starts reduction from 5, 4-channel case starts reduction from 7, and 5-channel case starts reduction from 9. Other schemes have similar results. The reason behind it is that when the number of hops grows, more channels are required to avoid the interference.

Figure 8 compares the solution rate with different schemes in the case of 3 channels per link. The minimal delay scheme always achieves the lowest solution rate since it doesn't consider the unavailability constraints for the route which may cause invalid solutions.

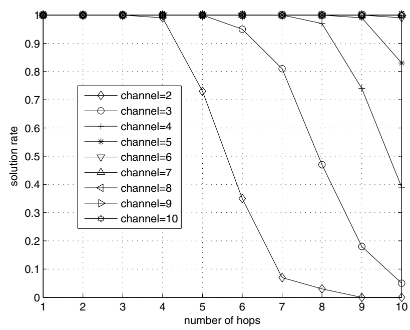

Fig. 4. Solution rate for MOSEK solution

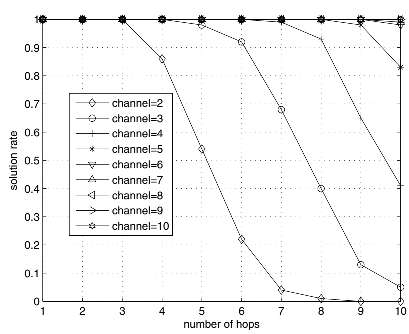

Fig. 5. Solution rate for proposed channel selection

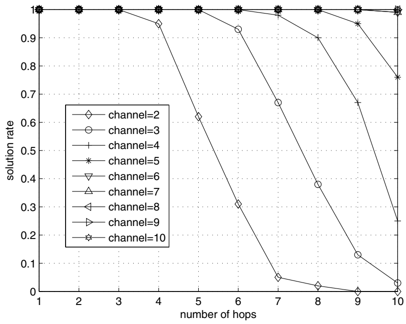

Fig. 6. Solution rate for channel selection based on minimal unavailability

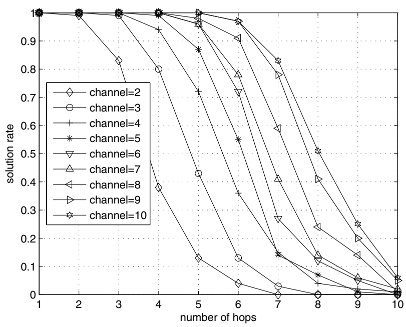

Fig. 7. Solution rate for channel selection based on minimal delay

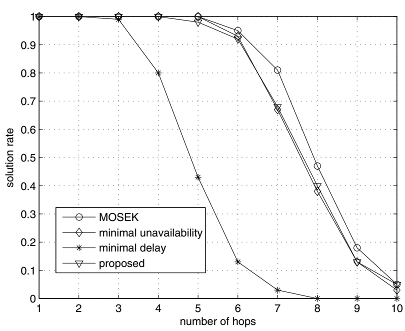

Fig. 8. Solution rate comparison for different channel selection schemes (when the number of available channel is 3)

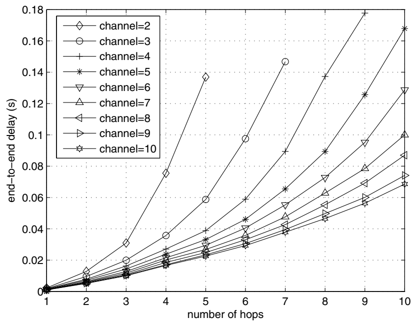

Fig. 9. End-to-end delay for MOSEK solution

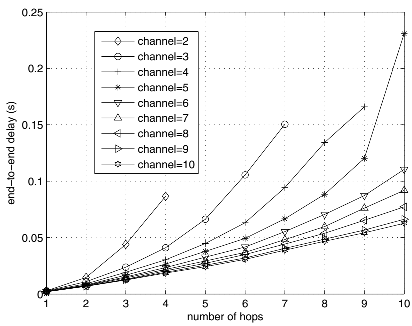

Fig. 10. End-to-end delay for proposed channel selection

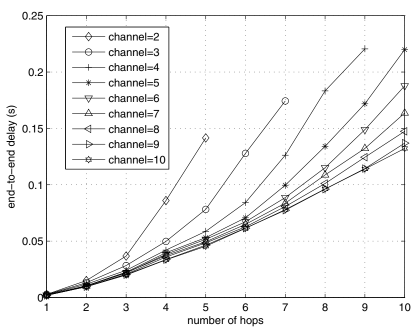

Fig. 11. End-to-end delay for channel selection based on minimal unavailability

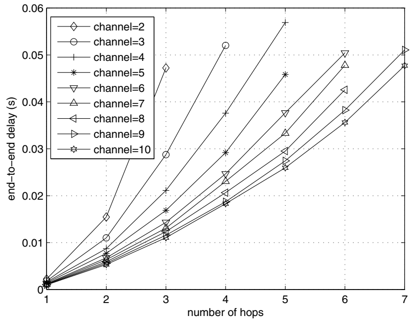

Fig. 12. End-to-end delay for channel selection based on minimal delay

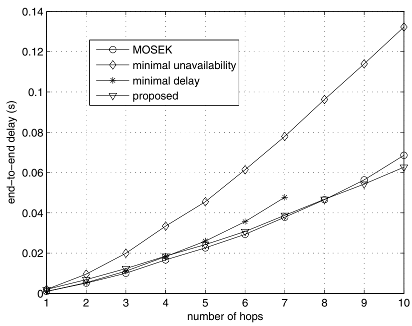

Fig. 13. End-to-end delay comparison for different channel selection schemes (when the number of available channel is 10)

5.2 End-to-End Delay

We show the performance in terms of average end-to-end delay in the following. For those cases of no valid solution by a certain scheme, their end-to-end delay are not taken into account the caculation of the average end-to-end delay. Thus, we introduce a solution rate threshold, above which the result is shown for every scheme. In Figure 9, 10, 11, 12, and 13, the solution rate threshold is set as 0.6.

As shown in Figure 9, 10, 11, and 12, the end-to-end delay increases with the number of hops increases. In the same case of number of hops, for more channels, the end-to-end delay decreases.

Figure 13 compares the end-to-end delay with different schemes in the case of 10 available channels for each link. The minimal unavailability scheme always achieves the highest delay since it doesn't consider delay while choosing channels for each link.

6 Conclusion

In this paper, we have investigated the joint channel selection and routing problem in cognitive radio mesh networks. We formulated this problem and transformed it to a variant of multiple-choice knapsack problem, then we proposed a heuristic method to solve this problem. Simulation results showed that our proposed heuristic method and MOSEK solution can achieve the closest in performance. It outperforms the minimal unavailability scheme and minimal delay scheme in terms of end-to-end delay and solution rate.

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