

## Priority Based Routing and Link Scheduling for Cognitive Radio Networks

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### Abstract

To address the challenges caused by the time-varying rate requirement for multimedia communication sessions, we propose a *Priority Based Routing and link Scheduling* (PBRs) scheme for multi-hop cognitive radio networks. The objective is to minimize disruption to communication sessions due to channel switching as well as to minimize network resource consumption for multimedia applications based on a prioritized routing and resource allocation scheme. PBRs includes a priority based optimization formulation and an efficient algorithm to solve the problem. The main idea is to allocate the available resource to different types of services with their Quality of Experience (QoE) expectation as well as maintain a priority service queue. Services with higher priority such video conference with cognitive radio expects a lower latency during the communication, whereas services with lower priority such as file transferring could tolerate more interruptions. Based on the different QoE requirements of services, PBRs will decide whether or not to change the routing and link scheduling. If a session has a higher priority than the others, PBRs will maintain its routes, channels, and links to the next timeslot as long as the total white space resource is enough to support all sessions. This eliminates unnecessary channel switching due to rescheduling. Simulation results demonstrate that PBRs effectively reduces channel switching and hence reduce disruption to communication sessions.

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**Keywords:** Cognitive Radio Network, resource allocation, QoE

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### 1. Introduction

The fast growth of wireless devices and services in past decades is exhausting the valuable spectrum resource. Traditional static spectrum allocation policy is not well prepared to face the ever-growing spectrum demands. Although the spectrum resource is in extremely shortage, a significant amount of spectrum is experiencing low utilization in rural areas and even crowded metropolitan areas. For example, even at downtown Washington, DC, only 38% of licensed spectrum is actively utilized [1]. To address the spectrum scarcity issue, IEEE proposed the 802.22 Wireless Regional Area Networks (WRAN) standard to provide an opportunity for unlicensed or *secondary users* (SU) to opportunistically access licensed DTV spectrum without degrading the licensed or *primary user* (PU) performance [2, 3]. Thanks to the advancement of radio technology, the recent emerged *cognitive radio* is frequency agile and

capable of detecting and switching to idle spectrum segments on a wide range for opportunistic access. The cognitive radio technology is one of the most promising technologies to address the spectrum shortage problem.

Like traditional wireless networks, the performance of cognitive radio networks (CRNs) is directly determined by the efficiency of multiple access among the cognitive radio nodes and the inter-node interference. Hence, there have been many studies on routing and link scheduling in wireless networks, to minimize traffic delay, total energy consumption, or maximize throughput while reducing or eliminating interference in multiple access. For example, the authors in [4] focused on maximizing throughput in routing and link scheduling for wireless mesh networks, and the work in [5] presented a non-linear optimization formulation for broadband wireless multi-hop networks to minimize total energy consumption. Authors in [6] proposed an

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approach to reduce the number of channel switching by monitoring the data rate change of each communication session and then decides whether or not to change the routing and link scheduling.

For opportunistic spectrum access, SUs must evacuate from a licensed channel when the associated PU becomes active again. There have been several studies to address the opportunistic spectrum access for routing and link scheduling in CRNs. In [7], the authors formed a near-optimal topology to enhance throughput for CRNs by using a layered graph algorithm to allocate channels and assign the interface among communication nodes. The work in [8] analyzed the total computation time and overhead for rebuilding routing tables in multi-hop CRN, when channels are experiencing significant rate variance. The authors in [9] studied an opportunistic routing protocol based on the node geographical locations and usage statistics to improve network performance. Moreover, in [10], the authors split each channel into small sub-channels and formulated the joint routing and link scheduling for multi-hop CRNs. The work in [11] proposed a joint link scheduling and routing scheme based on the long-term statistics to address the unpredictable spectrum supply in CRN.

In this paper, we study the impact of the priority of the traffic class on the routing and link scheduling problems. Some services such as voice, live conference or gaming are sensitive to the delay. Other services such as file transfer or video streaming may tolerate a higher delay as long as the throughput requirement is met. Hence, services can have different priorities based on their requirement on traffic delay. In CRNs, a PU may re-appear at any time, which causes the SUs on its channel to evacuate. Moreover, the SUs traffic load may change over the time, which may also force the SUs to switch to other channels or paths to accommodate the new traffic load. As the channel switching takes time, it may result in timeout of TCP connections. This can significantly degrade the performance of TCP, causing large delay to SU communication sessions.

In this paper, we propose a *Priority Based Routing and link Scheduling* (PBRS) scheme to reduce delay of high priority SU traffic, through reducing the number of channel switchings. PBRS includes an optimization model and an efficient algorithm to solve the routing and link scheduling problem, to reduce delay to high priority traffic classes. With PBRS, there are  $k$  priority classes. Each priority class has a weight  $\beta_k$ . In resource allocation and path computation, rescheduling links for a high priority communication session results in a higher cost in the optimization model. Therefore, PBRS aims to maintain the communication stability for higher priority services.

The contributions of this paper can be summarized as follows: 1) develop an optimization model for

routing and link scheduling to avoid disruptions to higher priority communication sessions while reducing the network resource consumption, and 2) develop an efficient algorithm to solve the routing and link scheduling problem.

The remainder of the paper is organized as follows. Section 2 describes the system model. Section 3 presents the formulation of the routing and link scheduling problem. Section 4 describes the PBRS algorithm. Section 5 presents the performance evaluation and Section 6 concludes the paper.

## 2. System Model

A time-slotted system is assumed. For example, we can set one timeslot as the required maximum channel evacuation time for SUs when a PU becomes active on an idle licensed channel. The channel availability to an SU is at the unit of one timeslot.

We consider a multi-hop CRN with  $N$  cognitive radio nodes and  $M$  channels, and study the scheduling in a duration of total  $T$  timeslots. Let  $\mathcal{N}$ ,  $\mathcal{M}$ , and  $\mathcal{T}$  denote the set of nodes, channels, and timeslots, respectively. Among the cognitive radio nodes, there are a set of  $\mathcal{E}$  communication sessions. Let  $s(l)$  and  $d(l)$  denote the source and destination of session  $l \in \mathcal{E}$ . It typically has a variable data rate along the time. Let  $r^l(l)$  denote the data rate requirement of session  $l$  at timeslot  $t$ . The routing and link scheduling problem is how to route the communication sessions and assign channels and links to them, while eliminating the interference between simultaneous transmissions and maximizing network performance.

Recall that cognitive radio nodes are allowed to opportunistically access the licensed bands (channels) when the corresponding PUs are not active. Due to the geographical location diversity of cognitive radio nodes, the set of channels may vary from node to node. Let  $\mathcal{M}_i \subseteq \mathcal{M}$  represent the set of accessible channels at node  $i \in \mathcal{N}$ .

We assume all cognitive radio nodes have the same power spectral density  $\rho$  during the transmission. We adopt the following widely used model to describe the channel gain [10].

$$g_{ij} = \gamma \cdot d_{ij}^{-n}. \quad (1)$$

where  $n$  is the path loss factor,  $\gamma$  is a constant mainly related to antenna property and  $d_{ij}$  is the distance between nodes  $i$  and  $j$ . We define a successful data transmission between two nodes if and only if the received power spectral density at the receiver exceeds the threshold  $\bar{\rho}$ . On the other hand, if a receiver captures a signal from another ongoing transmission whose power spectral density exceeds the threshold  $\bar{\rho}$ , we assume this node is experiencing a non-negligible interference. Based on the threshold  $\bar{\rho}$ , the transmission

Table 1. Notations

Symbol	Definition
$\mathcal{M}$	The set of available channels for all SUs
$\mathcal{N}$	The set of SUs in the network
$\mathcal{T}$	The set of timeslots for scheduling
$\mathcal{M}_i$	The set of available channels for node $i \in \mathcal{N}$
$\mathcal{P}_k$	The set of session with $k$ th priority
$R_T$	Transmission range
$R_I$	Interference range
$\rho$	Transmission power spectral density from a transmitter
$\bar{\rho}$	The minimum power spectral density required for a receiver to decode a transmission
$\hat{\rho}$	The maximum power spectral density allowed for a receiver to neglect the interference from other transmissions
$c_{ij}^{m,t}$	The link capacity between node $i$ and node $j$ on channel $m$
$\tau_i^m$	A set of nodes in the transmission range of node $j$ on channel $m$
$\tau_i$	$= \cup_{m \in \mathcal{M}_i} \tau_i^m$
$\omega^{(m)}$	The bandwidth of channel $m \in \mathcal{M}$
$\mathcal{X}_j^m$	The set of nodes that can use channel $m$ and are within the interference range of node $j$
$\xi_{ij}^{m,t}$	Binary decision variable to indicate whether channel $m$ is occupied by link $(i, j)$ at timeslot $t$ or not
$f_{ij}^l(t)$	Data rate assigned for session $l$ on link $(i, j)$ at timeslot $t$
$\beta_k$	The weight of $k$ th priority class
$C_{ij}^{m,t}$	The cost of link between node $i$ and $j$ on channel $m$ at timeslot $t$

range for a node is computed as

$$R_T = (\rho/\bar{\rho})^{1/n},$$

which comes from  $(R_T)^{-n} \cdot \rho = \bar{\rho}$ . And similarly, based on the interference threshold  $\hat{\rho}$ , the interference range for a node is

$$R_I = (\rho/\hat{\rho})^{1/n}.$$

Since we should have  $\hat{\rho} < \bar{\rho}$ , so  $R_I > R_T$ .

According to the Shannon-Hartley theory, if there is a channel  $m$  available for nodes  $i$  and  $j$ , the capacity of the link between nodes  $i$  and  $j$  is given as

$$c_{ij}^{m,t} = \omega^{(m)} \log_2 \left( 1 + \frac{g_{ij}\rho}{\eta} \right) \quad (2)$$

where  $\eta$  is the ambient Gaussian noise density,  $\omega^{(m)}$  is the bandwidth of unoccupied spectrum  $m$  and  $g_{ij}$  is the channel gain between nodes  $i$  and  $j$ .

### 3. Routing and Link Scheduling Formulation

We formulate the time-dependent routing and link scheduling problem as a nonlinear programming

problem. For easy reference, we first list major notations in Table 1. Next, we first present the formulation for link scheduling, then discuss session routing, and at last present the full formulation.

#### 3.1. Link Scheduling

In this subsection, we focus on the channel assignment and interference avoidance. The goal is to make sure that there is no node encountering interference during the transmission.

Given a channel  $m$  available for nodes  $i$  and  $j$  at timeslot  $t$ , then we denote

$$\xi_{ij}^{m,t} = \begin{cases} 1, & \text{If node } i \text{ transmits data to node } j \\ & \text{on channel } m \text{ at timeslot } t \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

$\xi_{ij}^{m,t}$  is a binary variable which indicates the link status.  $\xi_{ij}^{m,t} = 1$  means the channel  $m$  is occupied by nodes  $i$  and  $j$ .

We use  $\tau_i^m$  to denote the set of nodes that are located in the transmission range of node  $i$  and can also opportunistically access channel  $m$ , defined as follows.

$$\tau_i^m = \{j : d_{ij} < R_T, j \neq i, m \in \mathcal{M}_i\}. \quad (4)$$

Note that a transmitter cannot transmit to multiple nodes on the same channel at the same time. Thus we must have the following constraint.

$$\sum_{q \in \tau_i^m} \xi_{iq}^{m,t} \leq 1. \quad (5)$$

Moreover, to avoid self-interference, a receiver  $j$  cannot use the same channel for both transmission and reception, which means if  $\xi_{ij}^{m,t} = 1$  for any  $i$ , then for any  $q \in \tau_i^m$ , we have  $\xi_{jq}^{m,t} = 0$ . In other words, we have

$$\xi_{ij}^{m,t} + \sum_{q \in \tau_j^m} \xi_{jq}^{m,t} \leq 1. \quad (6)$$

That is, if a node  $i$  uses channel  $m$  to transmit to node  $j$  ( $\xi_{ij}^{m,t} = 1$ ), then node  $j$  is not able to use the same channel  $m$  for transmission ( $\sum_{q \in \tau_j^m} \xi_{jq}^{m,t} = 0$ ).

In addition to the above constraints to avoid self-interference at the same node, there are also constraints to avoid the inter-node interference, i.e., eliminating the interference between different nodes. Specifically, for a certain channel  $m$  at timeslot  $t$ , if node  $i$  uses the channel to transmit data to node  $j$ , then other nodes which may cause interference to node  $j$  should not use the channel. We denote  $P_j^m$  as the set of nodes that can

cause interference to node  $j$  on channel  $m$ , i.e.,

$$P_j^m = \{p : d_{pj} < R_I, p \neq j, \tau_p^m \neq \emptyset\}, \quad (7)$$

where  $\tau_p^m \neq \emptyset$  defined in (4) means that the interference node  $p$  may use channel  $m$  for a valid transmission to a node in  $\tau_p^m$ . Then we need to ensure

$$\xi_{ij}^{m,t} + \sum_{q \in \tau_p^m} \xi_{pq}^{m,t} \leq 1 \quad (p \in P_j^m, p \neq i). \quad (8)$$

In (8), if  $\xi_{ij}^{m,t} = 1$ , which means node  $i$  transmits data to node  $j$  on channel  $m$  at timeslot  $t$ , then any node  $p$  that may cause interference on node  $j$  should not transmit on channel  $m$  at this timeslot, i.e., we need to have  $\sum_{q \in \tau_p^m} \xi_{pq}^{m,t} = 0$ . On the other hand, if channel  $m$  is not occupied by node  $i$  and node  $j$  at timeslot  $t$  ( $\xi_{ij}^{m,t} = 0$ ), then there is only one node  $q \in \tau_p^m$  that can transmit on channel  $m$ , i.e.,  $\sum_{q \in \tau_p^m} \xi_{pq}^{m,t} \leq 1$ .

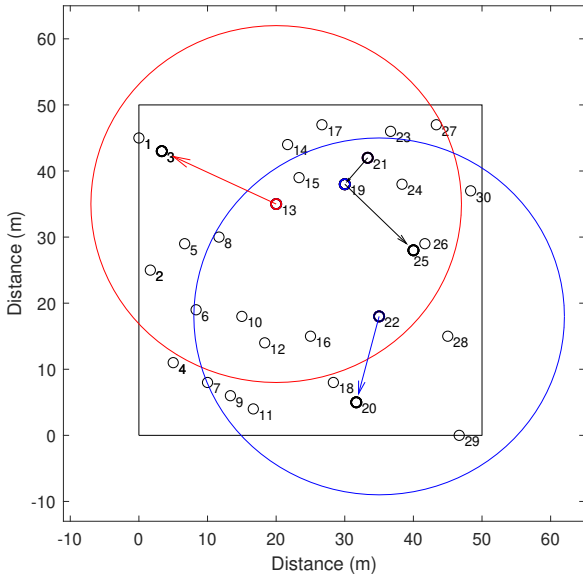


Figure 1. An illustration of node interference constraints

Next we use Figure 1 to illustrate (6)–(8). Two circles marked in red and blue in the figure represent the interference ranges ( $R_I$ ) of node 13 and 22, respectively. Suppose node 19 is a relay for nodes 21 to 25. Due to the constraint in (6),  $m$  and  $j$  cannot be the same channel. Furthermore, (8) means that any node that can cause interference to node 19 or 25 (i.e., node 13 or 22) cannot use the same set of channels ( $m, j$ ) for transmission. On the other hand, if node 19 is not using channel  $m$  to transmit to node 25, then node 13 may use this channel to transmit (to node 3), which is allowed by (8). Likewise, node 22 may also use this channel to transmit (to node 20).

We can combine constraints in (6) and (8) into a general constraint at the receiver side. We define

$$\mathcal{X}_j^m = \{p : d_{pj} < R_I, \tau_p^m \neq \emptyset\} \quad (9)$$

Then we can use the following constraint to include both (6) and (8).

$$\xi_{ij}^{m,t} + \sum_{q \in \tau_p^m} \xi_{pq}^{m,t} \leq 1 \quad (p \in \mathcal{X}_j^m, p \neq i) \quad (10)$$

### 3.2. Session Routing

Each communication session needs to be routed onto one or more paths between the source and the destination nodes. The session routing can be formulated as a multi-commodity flow problem. Let  $f_{ij}^t(l)$  denote the data rate of session  $l$  between two adjacent nodes  $i$  and  $j$  on the path of session  $l$  at timeslot  $t$ , where  $i \in \mathcal{N}$ ,  $j \in \cup_{m \in \mathcal{M}_i} \tau_i^m$ , and  $l \in \mathcal{L}$ . To streamline the notation, let  $\tau_i = \cup_{m \in \mathcal{M}_i} \tau_i^m$ . We classify the constraints in three scenarios. First, if node  $i$  is a source node of session  $l$ , i.e.,  $i = s(l)$ , then we have

$$\sum_{j \in \tau_i} f_{ij}^t(l) = r^t(l). \quad (11)$$

Second, if node  $i$  is an intermediate relay node for session  $l$ , i.e.,  $i \neq s(l)$  and  $i \neq d(l)$ , then we have

$$\sum_{j \in \tau_i, j \neq s(l)} f_{ij}^t(l) = \sum_{p \in \tau_i, i \neq d(l)} f_{pi}^t(l). \quad (12)$$

Third, if node  $i$  is the destination node of session  $l$ , i.e.,  $i = d(l)$ , then

$$\sum_{p \in \tau_i} f_{pi}^t(l) = r^t(l). \quad (13)$$

The total flow rates on each link should not exceed the link capacity, which is defined in (12). Taking the interference and channel availability into consideration, the link capacity  $c_{ij}^{m,t}$  in (2) should be rewritten into

$$c_{ij}^{m,t} = \omega^{(m)} \xi_{ij}^{m,t} \log_2 \left( 1 + \frac{g_{ij} \rho}{\eta} \right). \quad (14)$$

Thus, the flow rate on each link( $i, j$ ) should not exceed the link capacity. We can write this constraint as follows.

$$\begin{aligned} \sum_{l \in \mathcal{L}} f_{ij}^t(l) &\leq \sum_{m \in \mathcal{M}_i \cap \mathcal{M}_j} c_{ij}^{m,t} \\ &= \sum_{m \in \mathcal{M}_i \cap \mathcal{M}_j} \omega^{(m)} \log_2 \left( 1 + \frac{g_{ij} \rho}{\eta} \right) \xi_{ij}^{m,t} \end{aligned} \quad (15)$$

### 3.3. PBRS Formulation

We consider a CRN with a set of communication sessions. The data rate of each session is time-varying. Our objective is to minimize network resource consumption while reducing delay of higher priority traffic classes through reducing channel switching. We measure the network resource consumption as the total bandwidth on all links to support all sessions, which is also called space-bandwidth product in [12]. At the first timeslot, the cost of all links is the same. Then we assign the available channels and relay nodes to the communication sessions to achieve the lowest network resource consumption. After the best routing path is determined, we update the cost of the set of links associated with different priority sessions. The time-dependent link scheduling and routing problem is formulated as follows. The constraints discussed earlier are also listed here for completeness.

$$\min \sum_{i \in \mathcal{N}} \sum_{m \in \mathcal{M}_i} \sum_{j \in \tau_i^m} \omega^{(m)} C_{ij}^{m,t} (t = 1, 2, \dots, T) \quad (16)$$

**Subject to:**

$$\sum_{q \in \tau_i^m} \xi_{iq}^{m,t} \leq 1 \quad (i \in \mathcal{N}, t \in \mathcal{T}, m \in \mathcal{M}_i) \quad (17)$$

$$\forall i \in \mathcal{N}, t \in \mathcal{T}, m \in \mathcal{M}_i, j \in \tau_i^m, p \in \mathcal{X}_j^m, p \neq i$$

$$\xi_{ij}^{m,t} + \sum_{q \in \tau_p^m} \xi_{pq}^{m,t} \leq 1 \quad (18)$$

$$\sum_{j \in \tau_i} f_{ij}^t(l) = r^t(l) \quad (\forall l \in \mathcal{L}, t \in \mathcal{T}, i = s(l)) \quad (19)$$

$$\sum_{j \in \tau_i} f_{ji}^t(l) = r^t(l) \quad (\forall l \in \mathcal{L}, t \in \mathcal{T}, i = d(l)) \quad (20)$$

$$\forall l \in \mathcal{L}, t \in \mathcal{T}, i \in \mathcal{N}, j \neq s(l), j \neq d(l)$$

$$\sum_{j \in \tau_i, j \neq s(l)} f_{ij}^t(l) = \sum_{p \in \tau_i, i \neq d(l)} f_{pi}^t(l) \quad (21)$$

$$\forall l \in \mathcal{L}, t \geq 2, (i, j, m) \in \{(q, p, g) | f_{q,p}^{t-1}(l) \geq 0, \xi_{qp}^{g,t-1} = 1, p \in \mathcal{N}, q \in \mathcal{N}, g \in \mathcal{M}_k, l \in \mathcal{P}_k\}$$

$$C_{ij}^{m,t} = \xi_{ij}^{m,t-1} (1/\beta_k) \quad (22)$$

$$\forall i \in \mathcal{N}, j \in \mathcal{N}, m \in \mathcal{M}_i$$

$$C_{ij}^{m,1} = \xi_{ij}^{m,1} \quad (23)$$

$$\forall i \in \mathcal{N}, j \in \mathcal{N}, i \neq j$$

$$\sum_{l \in \mathcal{L}} f_{ij}^t(l) \leq \sum_{m \in \mathcal{M}_i \cap \mathcal{M}_j} \omega^{(m)} \log_2 \left( 1 + \frac{g_{ij} \rho}{\eta} \right) \xi_{ij}^{m,t} \quad (24)$$

The variable  $\xi_{ij}^{m,t}$  ( $i \in \mathcal{N}, t \in \mathcal{T}, m \in \mathcal{M}_i, j \in \tau_i^m$ ) takes binary values (0 or 1) and  $f_{ij}^t(l)$  ( $l \in \mathcal{L}, t \in \mathcal{T}, i \in \mathcal{N}, i \neq d(l), j \in \tau_i, j \neq s(l)$ ) takes non-negative real values. The  $\omega^{(m)}, g_{ij}, \rho, \eta,$  and  $r^t(l)$  are all constants to the formulation.

Constraints (22) and (23) ensure that the cost of all links will be updated after each timeslot. If the weight  $\beta_i$  of a communication session is large, the cost of the links associated with this session intends to be small, i.e., the number of channel switching is small. On the other hand, the links with a lower cost will be more likely to be reused by the same session. Therefore, the route, link, channel of a high priority session usually do not change. That is, there is no disruption to the ongoing communication of a high priority session. On the other hand, the sessions with a lower priority are re-scheduled in order to minimize resource consumption.

### 4. PBRS Algorithm

Because of the binary variables  $\xi_{ij}^{m,t}$ , the formulation in Section 3.3 is a *mixed integer non-linear programming* (MINLP) problem and is an NP-hard problem. To reduce the complexity, we relax the formulation into a *linear programming* (LP) problem, by allowing variables  $\xi_{ij}^{m,t}$  to take values between 0 and 1, i.e.,  $0 < \xi_{ij}^{m,t} < 1$  for  $i \in \mathcal{N}, t \in \mathcal{T}, m \in \mathcal{M}_i, j \in \tau_i^m$ . We write the relaxed problem as follows.

$$\min \sum_{i \in \mathcal{N}} \sum_{m \in \mathcal{M}_i} \sum_{j \in \tau_i^m} \omega^{(m)} C_{ij}^{m,t} (t = 1, 2, \dots, T) \quad (25)$$

**Subject to** (17)–(21), with  $0 < \xi_{ij}^{m,t} < 1$  for all  $i, j, m, t$ , and  $f_{ij}^t(l) \geq 0$  for all  $i, j, l$ , and  $t$ .

This relaxed problem can be solved in polynomial time as it is a linear programming problem. Furthermore, instead of solving the entire problem for one time, we develop an algorithm as illustrated in Algorithm 1 to sequentially fix variables  $\xi_{ij}^{m,t}$  and  $f_{ij}^t(l)$  and iteratively solve the problem, to obtain better performance. Specifically, in the first iteration at the first timeslot, we solve the initial linear programming problem and get a solution set which contains the solutions of variable  $\xi_{ij}^{m,t}$ . Then we fix the variable  $\xi_{ij}^{m,t}$  that has the largest value among all  $\xi_{ij}^{m,t}$  to be 1. Next, considering the interference constraints in (17) and (18), we need to set  $\xi_{iq}^{m,t}$  to 0 for  $q \in \tau_i^m$  and  $q \neq j$ , and set  $\xi_{pq}^{m,t} = 0$  for  $p \in \mathcal{X}_i^m$  and  $q \in \tau_p^m$  as well. With these fixed variables

**Algorithm 1:** PBRs Algorithm

```

1 Input: nbSlot (number of timeslots ), nbSession
   (number of sessions);
2 for t = 1 to nbSlot do
3    $\xi' = \emptyset$ ;
4   while not all  $\xi_{ij}^{m,t}$  variables are fixed do
5     Solve the problem in (16) with the  $\xi_{ij}^{m,t}$ 
     variables in  $\xi'$  fixed;
6     Search for  $\xi_{ij}^{m,t}$  with the largest value that
     is not fixed yet ;
7     fix( $\xi_{ij}^{m,t}$ ) //see note at the end;
8   end
9   Solve problem (16) with all fixed  $\xi_{ij}^{m,t}$ 
   variables;
10  if t ≥ 2 then
11    Update cost matrix C;
12  end
13 end
Note:fix( $\xi_{ij}^{m,t}$ ) is a function with the following
steps:
a) set  $\xi_{ij}^{m,t} = 1$  and add it to  $\xi'$  ;
b) set  $\xi_{iq}^{m,t} = 0$  for ( $q \in \tau_i^m, q \neq j$ ) and add them to
 $\xi'$ ;
c) set  $\xi_{pq}^{m,t} = 0$  for ( $p \in \tau_i^m, q \in \tau_i^m$ ) and add them
to  $\xi'$ ;

```

in the first iteration, we then formulate a new linear programming problem at the beginning of the second iteration, and so on until all  $\xi_{ij}^{m,t}$  variables are fixed to 0 or 1. Moreover, we update the cost matrix  $C$  after obtaining the optimization result at the end of each slot.

Next, we give an example for the routing and link scheduling performed by PBRs. Figure 2 describes the change of the routing path and link scheduling between two adjacent timeslots. The sample network has 30 nodes randomly distributed in 50m by 50m area. There are 4 active sessions and 3 priorities. The source/destination pairs ( $s/d$ ) are marked with red / blue circles. The assigned channel and data rate of each session are represented in a tuple  $(m, r)$ . A timeslot is the minimum time interval to reschedule the network. Table 2 indicates the source and destination pair of each session and the rate changes at two adjacent timeslots.

Comparing Figure 2a and Figure 2b, because the data rate requested by session III increases from 67Mpbs to 83Mpbs, channel 6 cannot accommodate the increased traffic load. Therefore, channel 3, which has a larger capacity to accommodate the increased traffic load, is allocated to session III in the next timeslot. Furthermore, because of the interference introduced by node 13, any node within the interference

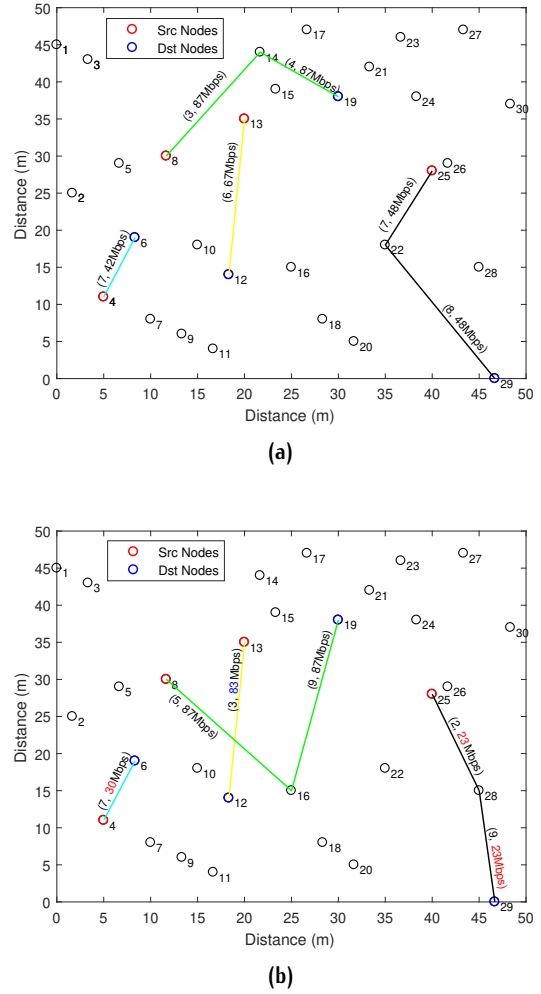


Figure 2. The routing path and link scheduling in two adjacent timeslots: a) timeslot 1, b) timeslot 2.

Table 2. Detailed session information in Figure 2.

Sess #	Src/Dst	Priority	Rate(Mbps)	
			T1	T2
I	(4/6)	HIGH	42	30
II	(8/19)	LOW	87	87
III	(13/12)	HIGH	67	83
IV	(25/29)	MEDIUM	48	23

range ( $R_I$ ) cannot use channel 3 simultaneously. Hence session II, due to its low priority, has to switch to other links and channels even though its data rate remains the same. The data rate of sessions I and IV decreases in the second timeslot. Session IV uses a new path in the second timeslot to reduce the network resource consumption. However, the link assignment of session I does not change, as it could not find a link re-assignment to reduce the network resource consumption.

## 5. Performance Evaluation

We evaluate the performance of the PBRS algorithm in a sample network with a  $50 \times 50 \text{ m}^2$  area. There are 10 random active cognitive radio communication sessions with  $k = 3$  traffic priorities, which are referred to as "High", "Medium" and "Low" in the ensuing discussions. In each run of simulation, the algorithm needs to compute the routing path for the upcoming 10 timeslots. The traffic rate is randomly generated between 30 and 100 Mb/s. The duration of each session follows the Poisson distribution with a mean of 7 timeslots. There are total  $M = 20$  licensed channels shared by all SUs for opportunistic access. The licensed channel occupation information is obtained through a database or spectrum sensing. We assume the transmission range of each node is  $20 \text{ m}$ , and the interference range is  $30 \text{ m}$ . The path loss index  $n$  is 4 and the power spectral density threshold for interference  $\bar{\rho}$  is equal to the Gaussian noise density, which is  $\eta$ . According to the analysis in Section 2,  $R_T = (\rho/\bar{\rho})^{1/n}$  and  $R_I = (\rho/\bar{\rho})^{1/n}$ . The power threshold for receiving is  $\hat{\rho} = \left(\frac{30}{20}\right)^n \bar{\rho}$  and the transmission power spectral density  $\rho = (R_T)^n \bar{\rho} = 20^n \bar{\rho} = 1.6 \cdot 10^5 \eta$ . The weights  $\beta_1, \beta_2, \beta_3$  for the "Low", "Medium", and "High" priority traffic classes are set as 1, 2, and 10, respectively.

In simulations, all experiments follow the same network topology, spectrum availability, and have the same number of node pairs, but with varying sources, destinations, and priorities. The simulation result is the average value of 100 experiments with a feasible solution.

In this paper, we use the total number of channel switching for each traffic priority as well as the total network resource consumption as the performance metrics. We compare the proposed PBRS algorithm

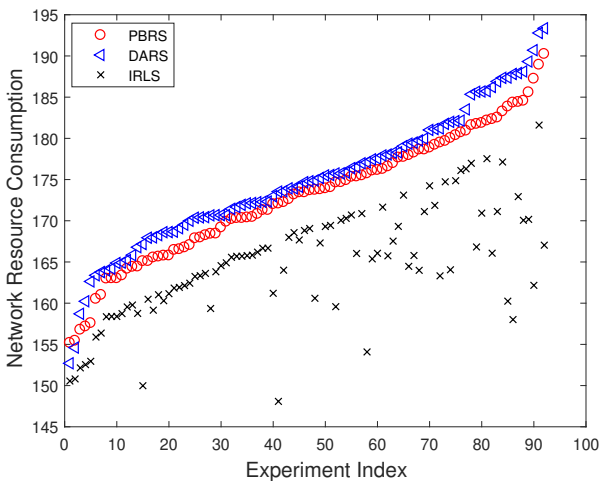


Figure 3. Network resource consumption.

with the *Disruption Aware Routing and link Scheduling* (DARS) algorithm [6] and the *Independent Routing and Link Scheduling* (IRLS) algorithm. DARS aims to reduce the disruption of the network path by monitoring the data rate change of each communication session and then decide whether or not to change the routing and link scheduling. If the data rate change of a session is larger than a predefined threshold  $\alpha$ , a new routing path should be explored. Likewise, if the data rate change is not significant (less than  $\alpha$ ), the current routing path will be maintained. IRLS solves the mixed integer non-linear optimization problem presented in 16-24 independently in each timeslot, i.e., without considering the disruption to communication sessions. Hence it minimizes the network resource consumption, but may result in more channel switchings than the other two algorithms. Note that both DARS and IRLS do not consider the priority class of the traffic.

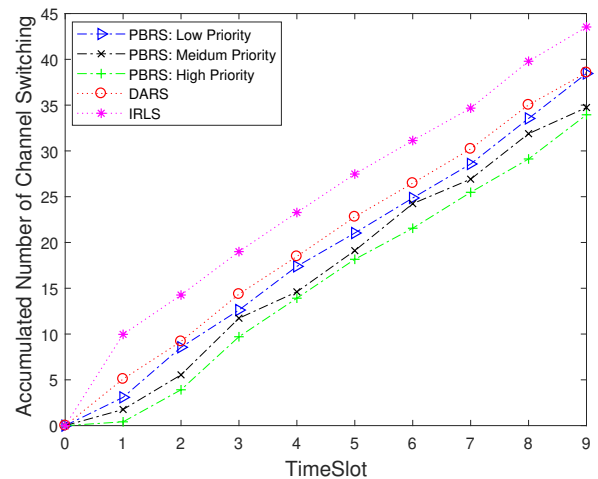


Figure 4. Accumulated average number of channel switching in 10 timeslots .

Figure 3 presents the network resource consumption in 10 timeslots obtained by the three algorithms for 100 experiments with different seeds. The results are sorted with regard to the network resource consumption of DARS. DARS uses a threshold  $\alpha=0.2$ . It is obvious that IRLS can reach a relatively lower network resource consumption without considering the disruption to the communication sessions. The network resource consumption of PBRS and DARS is slightly higher than IRLS; but both algorithms can reduce the number of channel switching to be discussed next.

Figure 4 plots the average accumulated number of channel switching among 100 experiments. Apparently, the IRLS algorithm has the highest number of channel switching among the three algorithms. Compared with IRLS, DARS can reduce the number of channel switching in each timeslot but still has more channel

switching than the PBRS algorithm. For PBRS, it is clear that the "High" priority traffic class has the smallest number of channel switching, while the "Low" priority traffic class has more channel switching than the "Medium" and "High" priority traffic classes. In other words, the traffic disruption to the "High" priority communication sessions is the least, while the traffic disruption to the "Low" priority traffic is the highest.

Table 3 presents the mean number of channel switching and its standard deviation in 10 timeslots with PBRS. The mean number of channel switching for the "Low", "Medium", and "High" priority traffic class is 22, 20, and 17, respectively. The "Low" priority traffic class needs about 8 more channel switching than the "High" priority traffic class. This observation holds even with 500 simulation experiments. The average number of channel switching implies the level of disruption for traffic communications. In other words, we can conclude that the higher the traffic priority, the fewer the number of channel switching is, i.e., having less communication disruption. Note that the number of channel switching for the same traffic class changes slightly when the number of experiments is different. This is because the source and destination pairs are randomly generated. Hence some variations on the number of channel switching are expected.

**Table 3.** Mean and std. of the number of channel switching with different priorities in 10 timeslots.

# of Simulation	Priority		
	Low	Medium	High
100	25/4.9	21/4.45	17/4.12
200	26/4.5	20/4.32	18/4.01
500	24/4.7	22/4.21	16/4.20

## 6. Conclusion

In this paper, we have proposed a priority based routing and link scheduling scheme for cognitive radio networks to address the different requirement of communication sessions on traffic delay. The proposed scheme is able to minimize the disruption to higher priority communication sessions, while the resource consumption is also reduced. Simulation results demonstrate that the proposed scheme effectively reduces channel switching and hence reduces disruption to high priority communication sessions.

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