Routing Layer Solution for Mitigating Frequent Channel Switching in Ad Hoc Cognitive Radio Networks

Gyanendra Prasad Joshi, Sung Won Kim, and Seung Yeob Nam, *Senior Member, IEEE*

***Abstract*—This letter analytically shows the requirements of cross-layer-based routing in ad hoc cognitive radio networks. This work estimates the number of channel switching in various scenarios and analyzes how non-cross-layer-based protocols suffer from delay. We suggest a route selection method to mitigate the frequent channel switching.**

***Index Terms*—Cognitive radio networks, routing protocols, cross-layer, channel switching delay.**

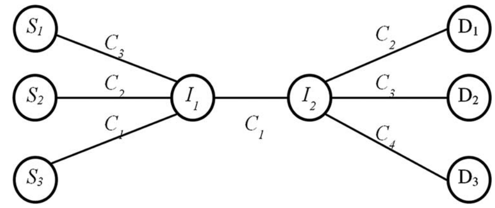

Fig. 1. A multiple hop and multiple channel CRN scenario.

I. Introduction

In cognitive radio network (CRN), nodes change route if primary user (PU) arrives on the channel. In fact, changing the channel according to the presence or absence of the PU is a medium access control (MAC) layer issue.

The spectrum availability for CRNs has a geospatial correlation and it is necessary for routing protocols to obtain the spectrum information from the MAC layer to calculate the route cost. To elaborate, the simplest scenario is described in Fig. 1.

Assume that S_1, S_2, and S_3 are three source nodes, I_1 and I_2 are two intermediate nodes, D_1, D_2, and D_3 are the destination nodes. $C_1 \sim C_4$ are the channels available to communicate, as shown in Fig. 1. Source and destination nodes select one idle common channel to communicate with the intermediate node from all available channels. Assume that intermediate nodes I_1 and I_2 have selected C_1 as a common channel. When I_1 receives a packet from node S_1 on channel C_3, it needs to tune its transceiver to channel C_1 to forward the packet to D_1. Again, I_1 needs to switch back to channel C_3 to receive another packet. This situation can be bad if the intermediate node needs to forward the packets for different destinations and delay may increase exponentially, leading to a channel bottleneck problem.

Switching a channel for each packet is more expensive in terms of the delay, particularly to the CR node, which has only one or two transceivers. If nodes select the same channel in every hop, the channel switching delay due to the frequent channel hopping can be mitigated. This is our motivation to propose the cross layer solution in this letter. Nodes can obtain the spectrum-related information from the MAC layer and include the spectrum availability-related parameter in the route cost so that nodes can select a route with the least number of channel switching. However, some existing protocols do not discriminate link failures due to spectrum mobility from node failure. Nodes simply reroute if there is a link failure [1].

Ding *et al.* [2] proposed a cross-layer routing and dynamic spectrum allocation (ROSA) that shares the resources such that the link capacity is maximized. This protocol assumes that the PU locations and PU activity are known in advance, which is against the basic principle of CRNs and not always possible.

Saifan *et al.* [3] proposed a cross-layer routing (CLRP) to calculate route cost considering that all channels are available for route setup with given probability. Unlike some existing protocols, each CR node senses channels and determines the probability of availability with 0 and 1. The other channels that are not sensed are considered as available with given probability.

The intrA-Route dIversity (ARI-AODV) [4] and self-adaptive routing (SAR) [5] protocols are cross layer-based routing schemes for the CRNs and based on AODV [6]. Among two approaches in [4], ARI-AODV is similar to intEr-Route dIversity cognitive AODV (ERI-AODV), where nodes use different channels for different routes, but each route is restricted to evolve through the same channel. ARI-AODV relaxes the constraint in ERI-AODV that the same channel must be available in the entire route. In ARI-AODV, intermediate SU sends the route a request (RREQ) in every idle channel. ARI-AODV generates a primary user route error (PU-RERR) packet, whenever a PU is detected on the channel. The PU-RERR is broadcasted to the neighbors through the same channel occupied by the PU. Also, sending RREQ in every idle channel is the waste of bandwidth resources.

SAR protocol is an underlay approach that adjusts the transmission range of a SU whenever required and possible. This protocol assumes that all SUs are in the proximity of the minimum transmission range. When a PU is detected, it assumes route failure, attempts to calculate the distance between the PU and SU, and adapts the transmission range. However, adapting the transmission range is difficult in a heterogeneous network.

The aforementioned protocols do not include the channel selection parameters in routing. This letter analytically shows that, when the idle channels are sufficiently large and the network is small (i.e. packets need to travel only few hops), we can substantially reduce the number of channel switching by including channel selection parameters in routing.

Manuscript received April 3, 2015; accepted September 7, 2015. Date of publication September 14, 2015; date of current version November 9, 2015. This work was supported by the 2015 Yeungnam University Research Grant. The associate editor coordinating the review of this paper and approving it for publication was M. A. Imran. *(Corresponding author: Sung Won Kim.)*

The authors are with the Department of Information and Communication Engineering, Yeungnam University, Gyeongsan 38541, Korea (e-mail: joshi@ynu.ac.kr; swon@yu.ac.kr; synam@ynu.ac.kr).

Digital Object Identifier 10.1109/LCOMM.2015.2478781

This work proposes a smart-routing scheme to select a better route by selecting the same channels in the last hop. This mitigates frequent channel switching and decreases the MAC layer delay. This scheme differentiates a link failure due to spectrum mobility from a node failure. It switches channel only if the link failure happens due to spectrum mobility and avoids unnecessary rerouting.

II. Number of Channel Switching Estimation

This section validates one of the design parameters and explains the reason why the selection of a common channel in the last hop and the next hop is necessary.

We assume that the number of data channels for each link is constant and is denoted by n. Let h be the number of hops between the source and the destination (end-to-end hops). The aim is to calculate the average number of switching needed to transmit a packet from the source to the destination. Let S_s denote the random variable of the number of required switching in case of absence of PU, i.e. all channels are idle and the same channel is selected in each link. Then, the mean value is $E[S_s] = 0$. Let S_r denote the random variable of the number of required switching when the channels are selected randomly on each link. Then $E[S_r]$ can be calculated in the following manner:

$$E[S_r] = \sum_{i=2}^{h} 1 \cdot \Pr(\textit{switching on link } i) \tag{1}$$

$$= \sum_{i=2}^{h} 1 \cdot Pr(\textit{channel on link } i-1 \neq \textit{channel on link } i)$$

$$= \sum_{i=2}^{h} \left(1 - \frac{1}{n}\right) = (h-1)\left(1 - \frac{1}{n}\right) \tag{2}$$

Because channel switching is directly related to the delay, (2) shows that the random channel selection strategy is more expensive in terms of channel switching even in a very simple scenario.

Now, let us take another case, where we assume that m channels are occupied by the PUs among n channels. Let m_b^i denote the set of busy channels on the i-th link by the PUs. We consider the following probability p:

$$p = \Pr\left(c \in m_b^i \middle| c \in m_b^{i-1}\right), \tag{3}$$

where c represents a channel. If the sets of busy channels are the same between two adjacent links, then p becomes 1. If the set of busy channels is selected randomly on each link, then p becomes m/n. Thus, p reflects the correlation between busy channels on two adjacent links, and the range of p is confined to $[m/n, 1]$.

The channel on each link is selected so that the same channel can be used on as many hops as possible from the source node. Let X be the maximum number of hops that can go without switching.

Let us consider the range of X for the proposed scheme. If the number of hops between the source and the destination is h, then X has an upper bound of h. X has the minimum value when the number of overlapping idle channels between the adjacent links are the minimum. Thus the lower bound of X can be represented as

$$X \geq \left\lceil \frac{n}{m} \right\rceil - 1. \tag{4}$$

$\lceil y \rceil$ means the smallest number, which is greater than or equal to y. Therefore, $\lceil \frac{n}{m} \rceil - 1$ becomes a lower bound of X. Then, it is possible to show that

$$S_s' \leq \left\lceil \frac{h}{\lceil \frac{n}{m} \rceil - 1} \right\rceil - 1, \tag{5}$$

where S_s' means the number of channel switches required when the same channel is selected in each link.

Now, we analyze a condition when the channel is randomly selected in each link, i.e. without considering the channel selected in the previous link.

For an arbitrary channel c, we can assume $\Pr(c \in m_b^1) = m/n$ for the first link without loss of generality. Let us consider the second link. If we define $q = \Pr(c \in m_b^2 | c \notin m_b^1)$, we can obtain

$$\Pr\left(c \in m_b^2\right) = \Pr\left(c \in m_b^2 \middle| c \in m_b^1\right) \Pr\left(c \in m_b^1\right) + \Pr\left(c \in m_b^2 \middle| c \notin m_b^1\right) \Pr\left(c \notin m_b^1\right) \tag{6}$$

$$= p \cdot \frac{m}{n} + q \cdot \left(1 - \frac{m}{n}\right), \tag{7}$$

where p is defined by (3).

We define a new random variable Y_i for the i-th channel (c_i) on the second link as

$$Y_i = \begin{cases} 1, & \textit{if } c_i \in m_b^2, \\ 0, & \textit{if } c_i \notin m_b^2. \end{cases} \tag{8}$$

Then, $\sum_{i=1}^{n} Y_i$ represents the number of channels in m_b^2, and we get $\sum_{i=1}^{n} Y_i = m$ from the m busy channel assumption. From (7), we can obtain that

$$m = E\left[\sum_{i=1}^{n} Y_i\right] = \sum_{i=1}^{n} E[Y_i] = \sum_{i=1}^{n} \Pr\left(c_i \in m_b^2\right) = n\left\{p\frac{m}{n} + q\left(1 - \frac{m}{n}\right)\right\} = pm + q(n-m). \tag{9}$$

Thus, q can be expressed in terms of p as

$$q = \frac{m}{n-m}(1-p). \tag{10}$$

Combining (7) and (10) yields $\Pr(c \in m_b^2) = m/n$. By similar reasoning, it is possible to derive the following relations by induction:

$$\Pr\left(c \in m_b^i\right) = \frac{m}{n}, \quad i \geq 2, \tag{11}$$

$$\Pr\left(c \in m_b^i \middle| c \notin m_b^{i-1}\right) = \frac{m}{n-m}(1-p), \quad i \geq 2. \tag{12}$$

Let $c_s^i \in m_b^i$ denote the channel selected by the secondary user pair on the i-th link. Since the secondary user cannot use the channels occupied by the PUs, $c_s^{i-1} \notin m_b^{i-1}$ and we have

$$\begin{aligned}\Pr(\textit{switching on link } i) &= \Pr\left(c_s^i \neq c_s^{i-1}\right)\\ &= \Pr\left(c_s^i \neq c_s^{i-1} \middle| c_s^{i-1} \in m_b^i\right)\Pr\left(c_s^{i-1} \in m_b^i\right)\\ &\quad + \Pr\left(c_s^i \neq c_s^{i-1} \middle| c_s^{i-1} \notin m_b^i\right)\Pr\left(c_s^{i-1} \notin m_b^i\right).\end{aligned} \tag{13}$$

If $c_s^{i-1} \in m_b^i$, then $c_s^i \neq c_s^{i-1}$ because $c_s^i \notin m_b^i$. Thus, we obtain

$$\Pr\left(c_s^i \neq c_s^{i-1} \middle| c_s^{i-1} \in m_b^i\right) = 1. \tag{14}$$

Let us consider the case where the channel is selected randomly among the non-occupied channels by the secondary user. Then we obtain

$$\Pr\left(c_s^i \neq c_s^{i-1} \middle| c_s^{i-1} \notin m_b^i\right) = 1 - \frac{1}{n-m}. \tag{15}$$

Since $\Pr(c_s^{i-1} \in m_b^{i-1}) = 0$ and $\Pr(c_s^{i-1} \notin m_b^{i-1}) = 1$, we have

$$\begin{aligned}&\Pr\left(c_s^{i-1} \in m_b^i\right)\\ &= \Pr\left(c_s^{i-1} \in m_b^i \middle| c_s^{i-1} \in m_b^{i-1}\right)\Pr\left(c_s^{i-1} \in m_b^{i-1}\right)\\ &\quad + \Pr\left(c_s^{i-1} \in m_b^i \middle| c_s^{i-1} \notin m_b^{i-1}\right)\Pr\left(c_s^{i-1} \notin m_b^{i-1}\right)\end{aligned} \tag{16}$$

$$\begin{aligned}&= \Pr\left(c_s^{i-1} \in m_b^i \middle| c_s^{i-1} \notin m_b^{i-1}\right)\\ &= \frac{m}{n-m}(1-p)\end{aligned} \tag{17}$$

where the last equality is valid by (12).

Combining (13)–(15), and (17) yields

$$\Pr(\textit{switching on link } i) = 1 - \frac{1}{n-m} + \frac{m}{(n-m)^2}(1-p). \tag{18}$$

If $p = 1$, then $\Pr(\textit{switching on link } i) = 1 - 1/(n-m)$. If $p = m/n$, $\Pr(\textit{switching on link } i) = 1 - 1/n$. Thus, when $m/n \leq p \leq 1$, the range of $\Pr(\textit{switching on link } i)$ can be summarized as

$$1 - \frac{1}{n-m} \leq \Pr(\textit{switching on link } i) \leq 1 - \frac{1}{n}.$$

We can also obtain

$$\begin{aligned}E\left[S_r'\right] &= \sum_{i=2}^{h} 1 \cdot \Pr(\textit{switching on link } i)\\ &= \sum_{i=2}^{h} 1 - \frac{1}{n-m} + \frac{m}{(n-m)^2}(1-p)\end{aligned} \tag{19}$$

where S_r' means the number of channel switches required when the channels are selected randomly on each link.

When the channels for the PUs are selected completely randomly independent of the selection in the adjacent channels, p becomes m/n. When $p = m/n$, (19) is identical to (2). The reason is that if m busy channels are selected randomly on each link and one channel for a new connection is selected randomly from the remaining $n - m$ channels, then the situation is the same as the case where one channel is selected randomly without any pre-occupied channel. This is valid because of the randomization of m busy channels.

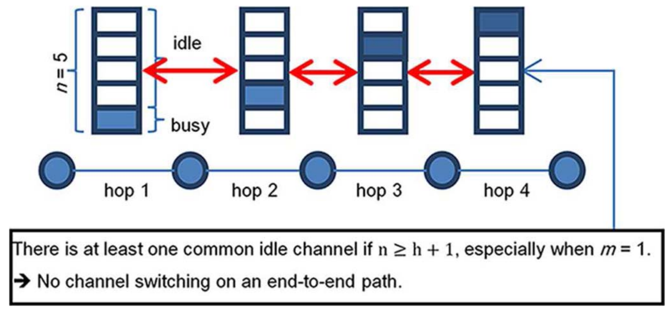

Fig. 2. Illustration of the condition that guarantees no switching on an end-to-end path under the proposed channel selection scheme.

Let us compare (5) and (19) for large n and small m, particularly when $m = 1$. If an algorithm that can select a channel in such a smart way that every node on the route selects the same channel whenever possible (i.e. *smart-selection*) can be used, then the expected number of switching on a given path is obtained from (5) as

$$E\left[S_s'\right] \leq \left\lceil \frac{h}{n-1} \right\rceil - 1. \tag{20}$$

From (19) with $m = 1$,

$$\begin{aligned}E\left[S_r'\right] &= (h-1)\left(1 - \frac{1}{n-1} + \frac{1}{(n-1)^2}(1-p)\right)\\ &\geq (h-1)\left(1 - \frac{1}{n-1}\right) \approx h-1\end{aligned} \tag{21}$$

Therefore, $E[S_s']$ can be much smaller than $E[S_r']$ in this case. (21) means that when the channels are selected randomly, switching is likely to occur on every link as the number of channels (n) becomes large. (20) is a special case of (5), obtained especially for $m = 1$. An interesting result can be obtained when $m = 1$. If $n = h + 1$,

$$E\left[S_s'\right] \leq \left\lceil \frac{h}{(h+1)-1} \right\rceil - 1 = 0 \tag{22}$$

That is $E[S_s'] = 0$, when $n = h + 1$. This means that if the number of channels (n) is sufficiently large compared to the number of hops (h) and $m = 1$, then the number of switching in the proposed scheme can be reduced to *zero*. Fig. 2 illustrates this case, particularly when $h = 4$.

III. Evaluation

From the analysis, it is clear that channel switching can be mitigated by selecting the same channel in each link. To evaluate the analysis, the well-known dynamic source routing protocol for multi-hop wireless ad hoc networks [7] is extended, and a cross-layer protocol that obtains the spectrum-related parameter from the MAC layer and selects the next hop is proposed. The predictive MAC (PMAC) protocol [8] is used to receive the channel information. PMAC calculates the cost of the route considering: *(i)* the number of available common

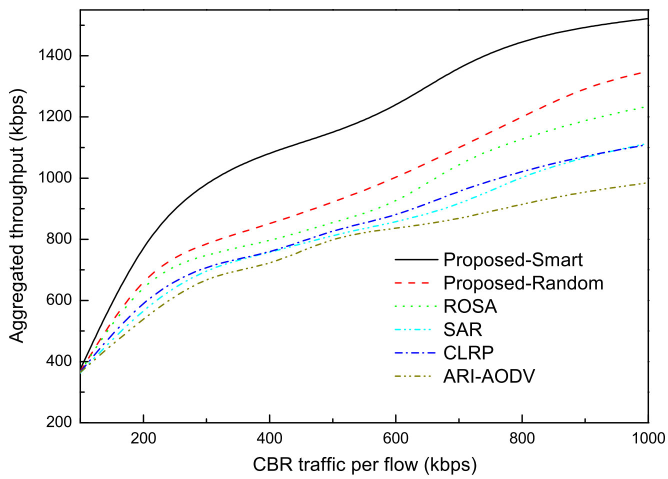

Fig. 3. Network throughput in various traffic rates, $n = 10$ and $m = 1$.

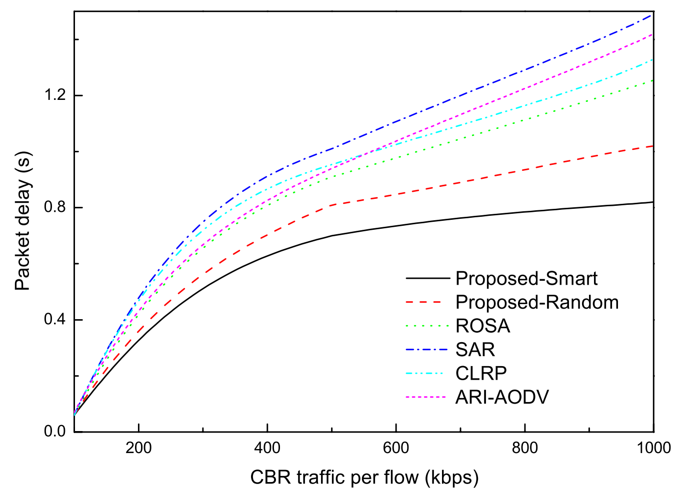

Fig. 4. Average end-to-end delay in various traffic flows, $n = 10$ and $m = 1$.

channels, *(ii)* the residual battery of the SU, and *(iii)* the number of hops. Network layer receives list of available idle channels, the channel selected in the previous link from MAC layer, and residual energy metric from the physical layer. Each SU calculates its own node cost as the ratio of full battery capacity of the node and its residual battery capacity. Route discovery and maintenance process is similar to [4].

Simulation is performed in the following scenario. The network consists of 80 SUs and 20 PUs confined in 1000×1000 m^2 area. Six flows of CBR traffic are generated over the UDP at various data transmission rates from 100 kbps to 1 Mbps. The packet size is 512 bytes. MAC layer parameters are taken from PMAC [8]. Each node has two transceivers, one transceiver is dedicated to the common control channel and the other transceiver (called data transceiver) is only used for data transfer.

We compare the proposed protocol with the abovementioned ROSA, CLRP, ARI-AODV, and SAR. Because there is no detail of MAC protocol, it is modified to make them compatible with each other. Therefore, the result may be different from the original paper.

Fig. 3 shows the aggregated throughput of the proposed protocol with smart-selection (*proposed-smart* in the legends), proposed protocol with random channel selection (*proposed-random* in the legends), ROSA, CLRP, ARI-AODV, and SAR. Aggregated throughput is the average rate of successful packet delivery over six communication flows. Because of the reduced number of rerouting, network partitioning, and channel switching, proposed protocols achieve higher throughput than ROSA, CLRP, ARI-AODV, and SAR even when it selects channel randomly. Because the size of outgoing packet queue is fixed in the simulation, SUs cannot deliver all the packets generated with higher traffic flow. Therefore, the protocols with higher network partitioning and frequent channel switching achieve lower aggregated throughput.

Fig. 4 compares the average end-to-end delay which is the average time between the transmission of data packets at the source SU and the successful reception of the packet at the destination SU. The higher CBR traffic rate generates more interference and the end-to-end delay increases. CLRP, ARI-AODV, and SAR have higher average end-to-end delay because they invalidate the route and reroute frequently.

IV. Conclusion and Future Works

We suggest a cross-layer-based routing layer solution that mitigates frequent channel switching. Because rerouting is expensive in terms of energy, delay, and throughput, it is better to select a route in such a way that requires less channel switching. CR node must discriminate a link failure due to spectrum mobility from a node failure for better performance.

We estimate channel switching with and without smart-selection and show that the channel switching can be reduced substantially, if we include channel selection parameters in routing. This work customizes well known DSR protocol and implements a smart-routing scheme to select a better route by selecting the same channels in the last hop. Simulation results show that the proposed cross-layer-based smart-selection performs better than random-selection and other existing protocols in the literature.

We will analyze the channel access delay and introduce intelligent channel selection method in future works.

References

[1] S. M. Kamruzzaman and D. G. Jeong, "Routing protocols for cognitive radio networks: A survey," *J. Inf. Ind. Eng.*, vol. 16, pp. 153–169, Aug. 2010.

[2] L. Ding, T. Melodia, S. Batalama, J. Matyjas, and M. Medley, "Cross-layer routing and dynamic spectrum allocation in cognitive radio ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 59, no. 4, pp. 1969–1979, May 2010.

[3] R. Saifan, A. Kamal, and Y. Guan, "A cross-layer routing protocol (CLRP) for cognitive radio network," in *Proc. IEEE GLOBECOM*, Dec. 2013, pp. 896–901.

[4] A. S. Cacciapuoti, M. Caleffi, and L. Paura, "Reactive routing for mobile cognitive radio ad hoc networks," *Ad Hoc Netw.*, vol. 10, no. 5, pp. 803–815, Jul. 2012.

[5] A. C. Talay and D. T. Altilar, "Self adaptive routing for dynamic spectrum access in cognitive radio networks," *J. Netw. Comput. Appl.*, vol. 36, no. 4, pp. 1140–1151, Jul. 2013.

[6] C. Perkins and E. Royer, "Ad-hoc on-demand distance vector routing," in *Proc. IEEE 2nd WMCSA*, Feb. 1999, pp. 90–100.

[7] D. B. Johnson, D. A. Maltz, and Y.-C. Hu, "DSR: The dynamic source routing protocol for multihop wireless ad hoc networks," Internet Eng. Task Force (IETF), Fremont, CA, USA, Manet Working Group (Draft 10), 2001. [Online] Available: https://tools.ietf.org/html/draft-ietf-manet-dsr-10

[8] G. Joshi, S. Nam, and S. Kim, "Decentralized predictive mac protocol for ad hoc cognitive radio networks," *Wireless Pers. Commun.*, vol. 74, no. 2, pp. 803–821, Jan. 2014.