Dynamic Path Switching Routing Protocol for Cognitive Radio Networks

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***Abstract*—The majority of this paper is to develop a reliable and high-performance routing protocol for cognitive radio networks (CRN). Due to the presence of the high-priority users (primary users) in the CRN, an existing routing path may easily become unavailable for any link on the path being occupied by primary users (PUs). The most intuitive way to avoid this problem is to select the path in which fewer PU activities are observed at the cost of performance sacrifice. This paper proposes a novel CRN routing protocol which aims to maintain the performance by utilizing the high-quality link as much as possible and to alleviate the route repair cost due to the occurrence of PUs. The experimental results show that in most situations, the proposed protocol outperforms other routing protocols including one traditional and two CR routing protocols in terms of packet round-trip delay, total system throughput and packet loss rate. The results also show that the proposed protocol is very resistant to the variation of PU activities.**

Keywords—cognitive radio; routing protocol; route repair cost

I. INTRODUCTION

With the explosive growth of mobile devices and mobile applications, the demands for increasing the usable spectrum become an eager craving from the public. The emerging of the CRN [1] and its commercial substance, the TV White Space (TVWS) system, can promptly ease the overcrowded utilizations in both the licensed and unlicensed spectrum nowadays, and also can efficaciously utilize the vacant or the under-utilization of the licensed spectrum, such as frequencies licensed for television broadcast or public service. This is done by allowing a CRN device to use a spectrum band licensed to a PU when it is temporarily unused.

Recently, due to the emergence of Smart City and Smart Grid, the coverage of CRN needs to be far enough to support such kinds of applications. This implies the CRN should be capable of multi-hop transmissions; in other words, the CRN should be carried out in the mesh network. This requirement stimulates the development of the CRN routing protocols. Several challenges on the CRN routing are pointed out in the holistic survey done by M. Youssef et al. [2]. First, the routing in CRN should be able to adapt to the dynamic changes of spectrum availability due to the stochastic occurrences of the PUs and secondary users (SUs). It also needs to deal with heterogeneity of resources (availability of different channels, allowable transmission power in each channel) in the same node, as well as the synchronization between nodes on different channels.

The routing protocols in CRN usually combine multiple metrics to determine the route for a transmission [3]–[9]. The commonly used metrics include delay, hop counts, power consumption, location, spectrum availability, and routing stability. Among these metrics, the routing stability is the most CRN-attributed metric since it is used to reflect the stability of a route based on PU activities. An unstable route will lead to frequently triggering route reestablishment event which consumes network resources and degrades the system performance. Therefore the strategy of the routing stability metric is simply to avoid choosing the route in which PU activities are often observed.

The STOD-RP [6] protocol uses a routing metric that combines route stability and end-to-end delay. For the stability part of the routing metric, the stability in terms of link's available time, denoted as T, is used as a denominator in the routing metric. Since T is defined as the time duration during which a spectrum band is available to the link which can be predicted from the statistical history of PU's activities, it can become infinity for a link having no PU activity at all. As a result, the cost of the link will become zero even if the link itself is very lossy. The work proposed by I. Filippini et al. [10] introduces the new cost that will be paid if a route needs to be changed. The link cost is defined as $(C_{Sw}+\alpha C_{Rep})$ / E[TTS], where C_{Sw} is the cost of switching from the current link to another links, C_{Rep} is the expected cost to repair the link in the future, and α allows gauging of different cost contributions. Since E[TTS], the average time the link remains stable, is used as a denominator in the metric too, this protocol also has the same problem of over-considering the PU activity as STOD-RP does.

In order to enhance the service quality experienced by the CRN user, a novel CRN routing protocol named 'Dynamic Path Switching (DPS)' is proposed. The proposed protocol aims to utilize the good-quality link as much as possible even if there is a lot of PU activities observed on the link. To alleviate the cost induced by the PU interruption, the DPS routing protocol switches aggressively among available paths. This strategy is motivated by the fact that the cost for the proactive path switching is always less than the cost for the passive path switching, where the path is forcedly switched due to the link unavailability.

The rest of the paper is organized as follows. Section II describes the main functions as well as the key strategies of the DPS routing protocol. Section III demonstrates the performance of the DPS routing protocol by comparing it with other CRN and traditional routing protocols. Section IV concludes the paper.

II. Dynamic Path Switching Routing Protocol

There are three core strategies applied to the proposed DPS routing protocol; they are: 1) predict the stable time for the link and path; 2) utilize the good-quality link as much as possible; 3) aggressively switch among paths since the path switching cost is always smaller than the service suspension and route repair costs induced by the occurrence of PUs.

A. Predict the Stable Time for the Link and Path

To determine a suitable path between a source node and a destination node, it is required to know for each link when the PU will be active again based on the historic statistics of the PU. Each link is predicted separately for its own link stable time, and the predicted stable time reflects directly to the link metric. After a path is determined, the remaining stable time of the path will be the nearest time when any PU is predicted to be active among the links constituting the path. The prediction for the PU activity should be simple since a path consists of multiple links, and each prediction may reduce the impact of another prediction. In this sense, too complicated prediction is meaningless. This is further true when we consider the limited computing power in the router. Simple prediction lets the proposed DPS routing adaptable to all kinds of router and reduces the complexity significantly.

Exponential Distribution is used to model the inter-arrival time between two continuous occurrences of PU activities on a link, because the arrivals of PU activities are assumed to follow the Poisson distribution. Therefore, the next occurrence of the PU activity will be expected at t_{prev} + E[T_{exp}], where t_{prev} is the occurrence time of the previous PU activity, and E[T_{exp}] is the mean value of the historic inter-arrival times of the PU activity.

B. Utilize the Good-Quality Link

To avoid the service suspension and route repair cost due to the occurrence of PUs, some works (STOD-RP [6], the work proposed by I. Filippini et al. [10]) introduced the spectrum available time into the routing metrics. However, the PU influence may be over-considered since the stability parameter (spectrum available time) is used as a denominator in the metrics. As a result, a good link could never be picked, and the service performance may become poor in such a case. The strategy of the DPS routing is to utilize the good link as much as possible when determining the path. It is because if PU occurrence can be predicted precisely, one can optimize the performance by utilizing the good-quality link till the last minute and switching to anther link before any PU interruption.

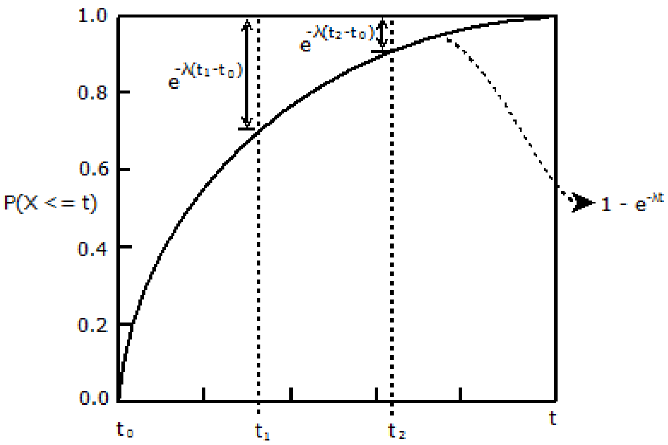

Fig. 1. The impact of time on the DPS routing metric.

To alleviate the impact of PUs on the routing metric and to utilize the good-quality link as much as possible, when constructing the metric, a sum operator is used in this paper (instead of a denominator operator) to connect the traditional metric and the stability metric. The inter-arrival times of PU occurrences are assumed to follow Exponential Distribution, and thereby the link cost between node *i* and *j* ($C_{i,j}$) is denoted as

$$C_{i,j} = C_{i,j}^T + \frac{C_{susp}}{e^{-\lambda(t_{curr}-t_{prev})}}, \quad (1)$$

where $C_{i,j}^T$ is the traditional link cost (e.g., link quality, packet loss, energy consumption) between node *i* and node *j*, C_{susp} is the service suspension cost if the link is occupied by the PU activity. C_{susp} is highly related to the delay requirement of the running service and therefore is suggested to be equal to $1/t_{delay}$, where t_{delay} is the end-to-end delay requirement (in seconds) of the most used service. The denominator $e^{-\lambda(t_{curr}-t_{prev})}$ comes from the CDF of Exponential Distribution, with the idea that the cost should increase with the time that the PU activity has not occurred since the last PU activity. λ denotes the rate of Exponential Distribution and t_{curr} denotes the current time. Considering the example illustrated in Fig. 1, the last PU activity is observed at time t_0, and there are two time instances t_1 and t_2. Given that $t_2 > t_1 > t_0$, the value of $e^{-\lambda(t_1-t_0)}$ will be larger than the value of $e^{-\lambda(t_2-t_0)}$, and therefore the cost calculated at t_1 will be smaller than the cost calculated at t_2. Moreover, if the PU activity is never observed on the link, the link cost is simply the tradition link cost.

$$C_{i,j} = C_{i,j}^T. \quad (2)$$

C. Aggressively Switch among Routes

Knowing that the cost for the proactive path switching is less than the cost for the passive path switching, the proposed protocol switches and reestablishes paths more aggressively than other routing protocols do. The proposed protocol aims to approach the ideal situation in which a good link is fully utilized till the last minute before the PU activity interrupts.

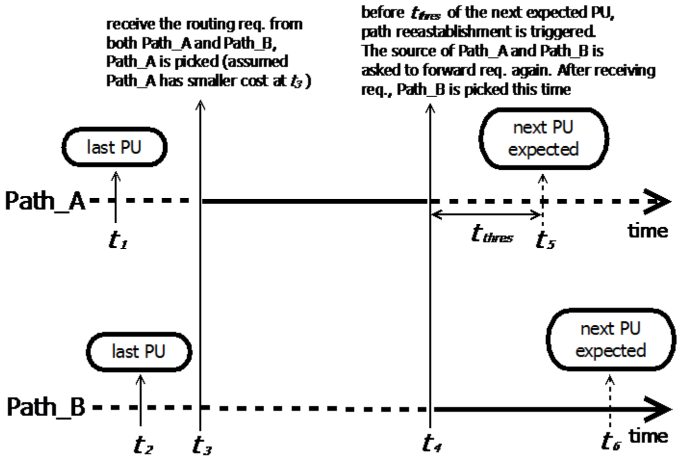

Fig. 2. Illustration of the aggressive path switching.

Considering the example illustrated in Fig. 2, even if Path_A was picked for a transmission at the beginning, DPS will still trigger a path reestablishment procedure at t_4, which is t_{thres} before the expected arrival of the next PU (t_5 in the example). The time duration between t_5 and t_1 is equal to the mean value of the Exponential variable determined by the previous PU activities on Path_A. When the reestablishment procedure is triggered, the source node will be asked to forward the routing request to the destination node again, and then the destination node will determine again which path is going to be picked based on the newly received routing requests. In the example, another path (Path_B) is picked instead of the original one, which will cause the path switching procedure.

III. Experimental Results

Several experiments are conducted to compare the performance of the DPS routing protocol (with the t_{thres} value equal to 5 seconds) with the performance of other routing protocols including two CR routing protocols and one traditional routing protocol. The traditional routing protocol used in the experiments is the high-profile AODV routing protocol which considers both the hop-count and link quality as its routing metrics. The link quality of a link is estimated by counting the number of lost packets on the link in a given time.

As to the first comparative CR routing protocol, it is built based on the STOD-PR [6] protocol, which uses the 'spectrum available time' as the denominator when calculating the link-cost. Therefore, it can be used to represent the typical type of stability routing protocol which considers the PU influence and the stability characteristic as the denominator in the link-level routing metric (e.g., the work proposed by I. Filippini et al. [10]). In the remaining of this section, the first comparative CR routing protocol is named as 'CR Stability Routing (strong ver.)' instead.

The second comparative CR routing protocol is constructed based on the Coolest-Path [11] protocol, with the 'Minimum Highest Spectrum Temperature Path' configuration applied to the protocol. Compared to the 'CR Stability Routing (strong ver.)' protocol, this type of CR routing gives a relative light weight to the PU influence when constructing the link-level routing metric. In the remaining of this section, this kind of CR routing protocol is named as 'CR Stability Routing (mild ver.)' instead.

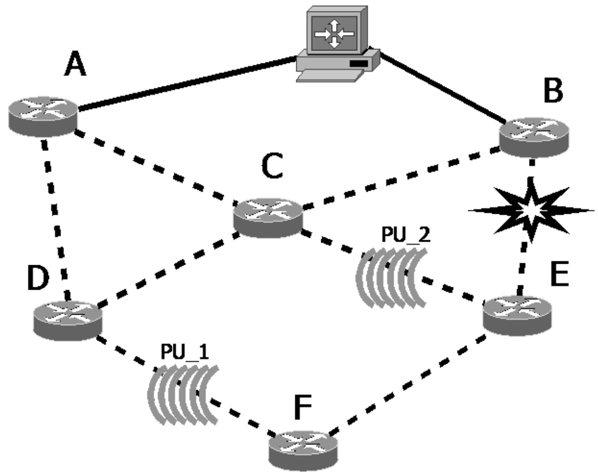

Fig. 3. The environment setup for a series of experiments.

As shown in Fig. 3, a real WiFi network is constructed for a series of experiments that will be described later. In the network, six WiFi routers are deployed with the ad-hoc mode configuration. Two of the routers (A and B) are wired-connected to the centre aggregator PC while the others are connected to each other with wireless connections. All routers are configured to operate in the IEEE 802.11g mode, with the operating frequency equal to 2.427 GHz (channel 4), operating bandwidths equal to 20 MHz, and with no RTS/CTS exchange. For the simplicity of experiments, the whole network is constructed as a single channel network. This means when a PU activity is presented in a certain link, that link will become unavailable until the PU becomes inactive again.

To simulate PU activities, two jamming sources are applied to the link between the router D and F, and to the link between the router C and E. The PU activity simulated between D and F is denoted as PU_1, and the PU activity simulated between E and F is denoted as PU_2. The activity density of PU_1 is always twice the density of PU_2, and each PU activity lasts constantly 25 seconds in all experiments. Moreover, the link between B and E is configured as an error-prone link by introducing a noisy source which keeps the packet drop rate on the link equal to 0.5.

To observe the throughput results, a big file is uploading from the FTP client located at the router F to the FTP server located at the centre aggregator PC. A PING testing is also conducted on the router F and the centre aggregator PC to obtain the results of the packet loss rate and averaged packet round-trip delay. By adjusting the PU activity density of PU_1 and PU_2 accordingly, the results of accumulated throughput, packet lose rate, and averaged round-trip delay within the duration of 15 minutes are observed as follows.

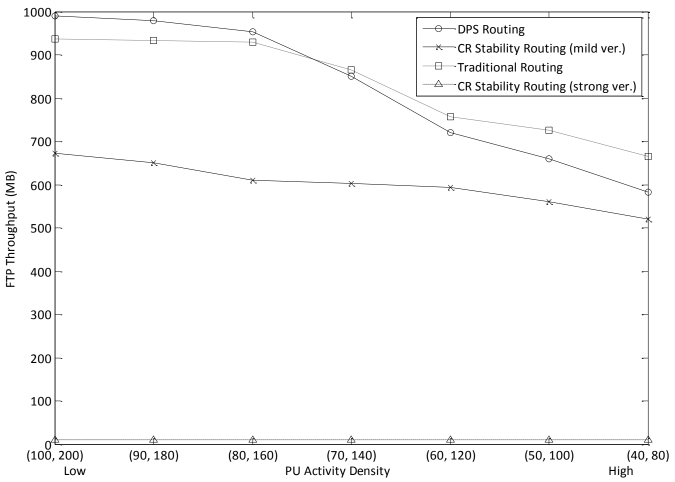

Fig. 4. The FTP throughput results observed on different protocols.

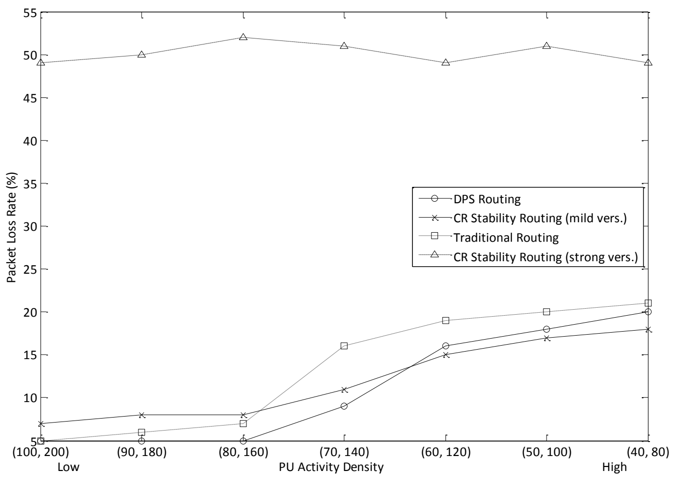

Fig. 5. The packet loss rate results observed on different protocols.

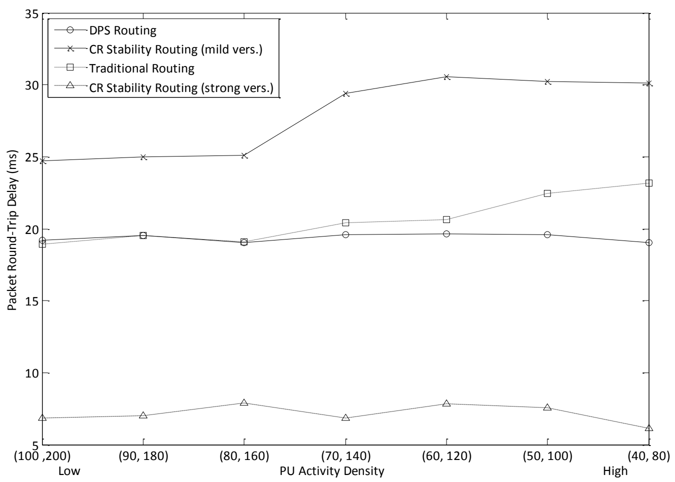

Fig. 6. The packet round-trip delay results observed on different protocols.

The FTP throughput results for different routing protocols are shown in Fig. 4. In the figure, the notation (x_1, y_1) in the x-axis denotes that the arrivals of PU_1 follow the Poisson process with the rate equal to $1/x_1$ per second, and the arrivals of PU_2 follow the Poisson process with the rate equal to $1/y_1$ per second. This means the left-hand side on the x-axis represents a lower PU activity density, and the right-hand side represents a higher PU activity density. The results in Fig. 4 show that the DPS routing protocol and the traditional routing protocol have similar throughput performance and they outperform other CR stability routing protocols. The DPS protocol performs a little better in low PU activity density situations while the traditional protocol performs a little better in high PU activity density situations. This is because when PU activity density becomes high, the DPS will aggressively switch from the optimized path to other sub-optimized paths, which lowers the utilization rate of the optimized path more than the traditional routing protocol does. The CR Stability Routing (strong ver.) obtains very poor results because the transmission always picks the path which contains the error-prone link (the link between B and E). The error-prone link causes a huge number of lost packets and retransmissions that will in turn degrade significantly the FTP performance.

The packet loss rate (of PING) results are illustrated in Fig. 5. We can see that in either low or medium PU activity density conditions, the DPS routing protocol has the smallest packet loss rate among all routing protocols. However, in high PU activity density conditions, the CR Stability Routing (mild vers.) protocol has the smallest loss rate which is slightly better than that in the DPS routing protocol. It is because in such conditions, the DPS protocol will have a higher chance to pick the error-prone link to construct the path (when it predicts the occurrence of PU_1 and PU_2 will overlap), while the CR Stability Routing (mild vers.) protocol will pick the error-prone link only when both PU_1 and PU_2 actually occur at the same time. The CR Stability Routing (strong ver.) protocol again has the worst packet loss rate since it always picks the path containing the error-prone link.

The last results shown in Fig. 6 are the packet round-trip delay (of PING) comparisons. We can see that the DPS protocol is very resistant to the PU activity change since it almost maintains the same averaged delay around 19 milliseconds. The CR Stability Routing (mild ver.) protocol has the largest averaged delay because it often picks the path containing the link between the router C and E, and this path obviously requires more transmission hops than other paths do. Although the averaged delay seems to be excellent in the CR Stability Routing (strong ver.) protocol, about 50% of the packets are lost and not counted into the delay; therefore it is not meaningful to interpret the results in that way.

To link these observed performance metrics with the QoS satisfaction of real traffic, a web browsing service and a conversational voice service (their QoS requirements are listed in TABLE I) are evaluated by applying each routing protocol to them. The results of running the web browsing service on each of the routing protocols are shown in TABLE II. We can

TABLE I. THE QOS REQUIREMENTS OF THE WEB BROWSING AND CONVERSATIONAL VOICE SERVICES

Traffic class	**QoS Metrics**		
	End-to-End Delay	**Data Rate**	**Error Rate**
Web browsing [12]	< 400 ms	4 – 25 Kbps	Zero
Conversational voice [13]	< 150 ms	30.5 Kbps	< 3%

TABLE II. THE COMPARISON AMONG DIFFERENT ROUTING PROTOCOLS ON SATISFYING THE WEB BROWSING SERVICE

Web Browsing Service				
	DPS	CR (mild)	Traditional	CR (strong)
PU activity density	**% of packets which meet the delay requirement**			
(100, 200)	**95**	93	95	51
(90, 180)	**95**	92	94	50
(80, 160)	**95**	92	93	48
(70, 140)	**91**	89	84	49
PU activity density	**Number of concurrent users/services allowed**			
(100, 200)	**36.06557**	24.5173	34.13479	0.364299
(90, 180)	**35.62842**	23.67942	33.98907	0.364299
(80, 160)	**34.7541**	22.22222	33.84335	0.364299
(70, 140)	30.96539	21.93078	**31.51184**	0.364299

TABLE III. THE COMPARISON AMONG DIFFERENT ROUTING PROTOCOLS ON SATISFYING THE CONVERSATIONAL VOICE SERVICE

Conversational Voice Service				
	DPS	CR (mild)	Traditional	CR (strong)
PU activity density	**Exceed the required error rate by how many percentages**			
(100, 200)	**2% above**	4% above	2% above	46% above
(90, 180)	**2% above**	5% above	3% above	47% above
(80, 160)	**2% above**	5% above	4% above	49% above
(70, 140)	**4% above**	8% above	13% above	48% above
PU activity density	**Number of concurrent users/services allowed**			
(100, 200)	**44**	29.91111	41.64444	0.444444
(90, 180)	**43.46667**	28.88889	41.46667	0.444444
(80, 160)	**42.4**	27.11111	41.28889	0.444444
(70, 140)	37.77778	26.75556	**38.44444**	0.444444

see that the DPS routing protocol can meet the delay requirement of the web browsing service in the highest degree (around 95%), although 100% is impossible due to the PU activity. Also, it can be observed that the DPS routing protocol can accommodate the largest number of concurrent web browsing users. Similarly in TABLE III, we can see that although none of the protocols can meet the packet loss requirement of the conversational voice service, the DPS routing protocol exceeds the required packet loss rate in the smallest degree, and can accommodate the largest number of concurrent users.

It should be noted that while evaluating the QoS of both the web browsing and conversational voice service, only the low and medium PU activity density are considered. It is because under the high PU activity density, the evaluated service will degrade too much. In such cases, comparing the QoS satisfaction is meaningless.

IV. CONCLUSIONS

In this paper a novel CRN routing protocol name DPS routing is proposed. According to the observations from a series of experiments, it can be seen that the DPS routing protocol has better performance than other CRN stability routing protocols do in most situations in terms of throughput, packet loss rate, and packet round-trip delay. Therefore, the strategies of reducing the impact of PU activities on the routing metric, and switching among the paths more aggressively, are in the right direction. To enhance the usability of the proposed protocol, more works need to be done in the future. Such works include how to determine the best configurations of the DPS routing protocol for different PU activity densities, and how to optimize the proposed metric based on different PU prediction models.

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