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Research Article

Performance Evaluation of Joint Path and Spectrum Diversity Based Routing Protocol in Cognitive Radio Ad Hoc Networks under Critical Conditions

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Abstract: Cognitive Radio (CR) technology has been introduced to solve the problems of spectrum underutilization and spectrum scarcity caused by improper spectrum management policies. The main concept of Cognitive Radio Ad Hoc Network (CRAHN) is that, in a wireless ad hoc network, the unlicensed users (or Secondary Users (SUs)) are allowed to access the temporally unused licensed spectrum bands for data communications without harmful interference to the licensed users (or Primary Users (PUs)). In CRAHNs, the mobile SUs communicate with each other without the use of any centralized network infrastructure. Routing in CRAHNs is an important task and faces various challenges including PU interference, frequent network topology changes, energy constraint, volatile bandwidth and fragile connectivity. In this study, an attempt is made to evaluate the performance of the Dual Diversity Cognitive Ad-hoc Routing Protocol (D2CARP) in CRAHNs under critical conditions, i.e., high node mobility rate and number of PUs. The D2CARP protocol is a joint path and spectrum diversity based routing protocol for CRAHNs. The performance evaluation is conducted through simulation using NS-2 simulator. The performance metrics to be considered include average throughput, percentage of packet loss, average end-to-end delay and average jitter. The simulation results prove that the protocol performance is significantly affected in the networks with high number of PUs and mobility rate, leading to high path failure rate and severe service outages.

Keywords: Cognitive radio ad hoc network, critical condition, joint path and spectrum diversity, performance evaluation, primary user activity, routing protocol

INTRODUCTION

Due to huge advancement of wireless technologies and rapidly increasing demand of wireless services, the radio spectrum has become an expensive and scarce resource. Moreover, the static spectrum allocation policy which allows specific wireless services to access fixed spectrum bands for data transmission leads to the spectrum underutilization problem (McHenry, 2003). According to the Federal Communications Commission (FCC)'s report (FCC's Spectrum Policy Task Force, 2002), many statically allocated licensed spectrum bands are used sporadically and their average utilization varies from 15 to 80%. Consequently, as shown in Fig. 1, there are large parts of the licensed bands still available in different time and location (Akyildiz *et al*., 2006). In order to enhance the spectrum utilization and solve the spectrum shortage problem, Cognitive Radio (CR) technology (Akyildiz *et al*., 2006; Haykin, 2005; Mitola, 2009) has been proposed to enable the unlicensed users (or Secondary Users (SUs)) to exploit the underutilized licensed spectrum bands in intelligent and cautious manner without harmful interference to the licensed users (or Primary Users (PUs)). Cognitive

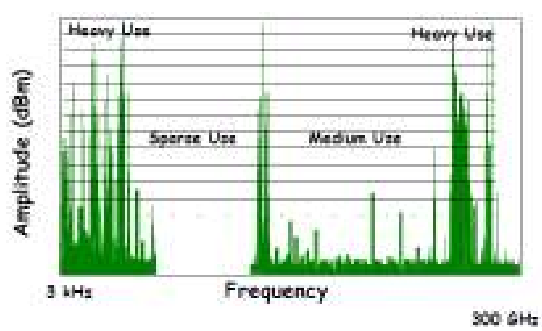

Fig. 1: Spectrum utilization (Akyildiz *et al*., 2006)

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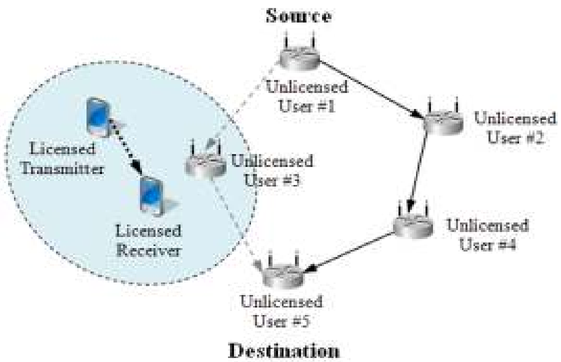

Fig. 2: Challenge on data routing in CRAHNs due to PU activity

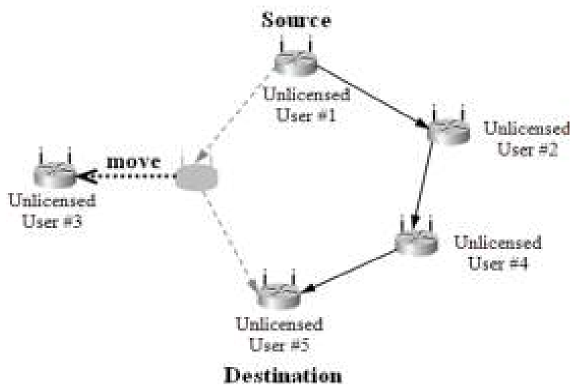

Fig. 3: Challenge on data routing in CRAHNs due to node mobility

Radio Ad Hoc Networks (CRAHNs) (Akyildiz *et al*., 2009) is an emerging class of mobile ad hoc networks which provides CR capability. In CRAHNs, SUs cooperate in a distributed fashion to build network connectivity and communication (without the use of any centralized network infrastructure). With the help of Software Defined Radios (SDRs) (Marinho and Monteiro, 2012), SUs can observe the current status of spectrum, make proper decisions and perform appropriate actions (such as changing the transmitter parameters or switching the transmission channel) according to the current environmental condition. In the networks, the available spectrum (or Spectrum Opportunity (SOP) (Akyildiz *et al*., 2008)) is divided into multiple channels. SUs can opportunistically access the vacant channels which are currently not occupied by PU. In case a SU detects a PU activity during data transmission, the SU must immediately vacate the currently used channel which overlaps with the PU's transmission frequency in order not to cause harmful interference to the PU transmissions (Fig. 2).

Most of research works for CRAHNs are carried on MAC (Medium Access Control) and physical layer which try to develop new efficient techniques on spectrum sensing, spectrum decision and spectrum sharing. However, issues on data routing which is an important and challenging task operating on network layer have been still largely unexplored and require more in-depth studies (Cesana *et al*., 2011; Sengupta and Subbalakshmi, 2013). Different from traditional wireless ad hoc networks where each node has a fixed frequency channel for communications, in CRAHNs, SUs at different locations may have different available channels. Furthermore, the channel availability of a SU may vary at different time and not be continuous depending on the behavior of PUs. With the nature of CRAHNs, SUs are free to move (Fig. 3), thus resulting in frequently network topology changes. These characteristics may produce a significant impact on communications and need to be seriously considered for the design of efficient routing protocol for such networks.

In this study, we evaluate the performance of a joint path and spectrum diversity based routing protocol for CRAHNs, called the dual Diversity Cognitive Ad-hoc Routing Protocol (D2CARP) (Rahman *et al*., 2012), under various critical conditions, i.e., high node mobility rate and high number of PUs. The performance evaluation is conducted through simulation using the NS-2 simulator (Issariyakul and Hossain, 2009). The simulation results generated by the NS-2 simulator are analyzed using the NS2 Visual Trace Analyzer (Rocha, 2012). The evaluation metrics include average throughput, percentage of packet loss, average end-to-end delay and average jitter. The simulation results show the impact of different node mobility rate and number of PUs on the network performance.

METHODOLOGY

Overview of dual diversity cognitive ad-hoc routing protocol: Rahman *et al*. (2012) has introduced a joint path and spectrum diversity technique in routing over CRAHNs, referred to as the dual Diversity Cognitive Ad-hoc Routing Protocol (D2CARP), with an aim to provide an effective solution to alleviate the performance degradation caused by PU activities which vary in location and frequency domain. The protocol is an extension of AODV protocol (Perkins *et al*., 2003) and shares some common features with the Cognitive Ad-hoc On-demand Distance Vector (CAODV) protocol (Cacciapuoti *et al*., 2010). Furthermore, the protocol is under the assumption that all SUs are equipped with multiple wireless interfaces. In presence of PU activity during data transmission which may cause path failure, the protocol enables the affected SUs to dynamically switch to different paths and channels to continue their communications without triggering a new route discovery process. Therefore, the performance degradation caused by the activity of PUs can be mitigated.

In the route discovery process, in order to apply the spectrum diversity, a source node broadcasts a RREQ

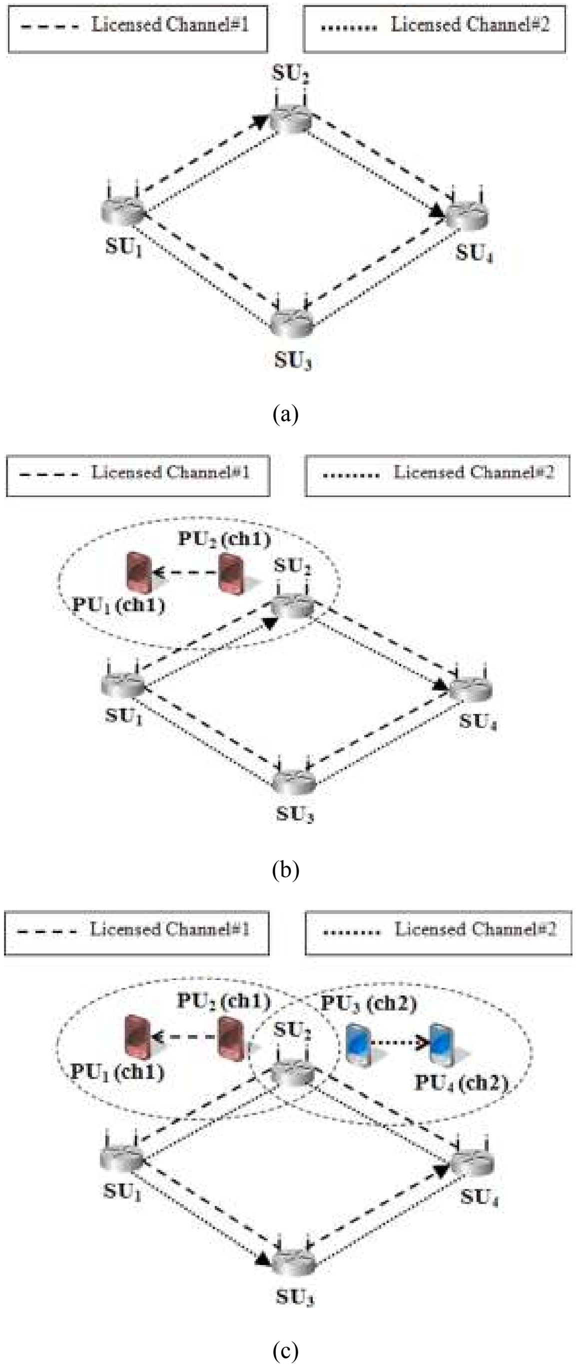

Fig. 4: Advantage of exploiting the joint path and spectrum diversity, (a) no PU activity is detected, (b) PU activity over channel 1 is detected, (c) PU activities over channel 1 and channel 2 are detected

packet to its neighbors through all available channels (i.e., not occupied by a PU). When the destination or an intermediate node that has a valid route to the destination receives the RREQ packet, a RREP packet is generated and broadcasted back to the source node via available channels which are not affected by a PU activity. Moreover, in order to exploit the path diversity, the source and destination node will not ignore an additional RREQ packet which is received from different First Hop Node (FHN) and Next Hop Node (NHN) as well as containing equal or lower hop-count value. At the end of route discovery process, multi-path and multi-channel routes are provided. The minimum hop-count is used as routing metric to select an optimal transmission path.

Figure 4a to c depict the advantage of exploiting the joint path and spectrum diversity in the D2CARP protocol. As shown in Fig. 4a, after the route discovery process is successfully completed, SU_1 (source node) begins transmitting data packets along an optimal path with minimum hop count (i.e., $SU_1 \xrightarrow{ch1} SU_2 \xrightarrow{ch2} SU_4$) towards SU_4 (destination node). During data delivery, in case SU_2 is moved into the PU_1-PU_2 region and the PU activity on channel 1 is detected (Fig. 4b), it notifies its neighbors (i.e., SU_1 and SU_4) of the PU activity detection. Then, SU_1 immediately uses another available channel (i.e., channel 2) to transmit data packets without changing path direction. Consequently, the new transmission path is $SU_1 \xrightarrow{ch2} SU_2 \xrightarrow{ch2} SU_4$. Afterwards, if SU_2 detects another PU activity over channel 2 (Fig. 4c), it must instantaneously disable the channel 2 for data transmission and notify its neighbors of the PU activity detection. Subsequently, since SU_2 is unable to operate over both channel 1 and channel 2, SU_1 immediately switches to another available path (i.e., $SU_1 \xrightarrow{ch2} SU_3 \xrightarrow{ch1} SU_4$) for data delivery without triggering a new route discovery process.

Simulation configuration: The efficiency of the D2CARP protocol is evaluated through simulation using the NS-2 simulator (Issariyakul and Hossain, 2009) with an extension to support the CR environments. Table 1 summarizes the simulation parameters used for this study. A simulation area of 1000×1000 m^2 in which 100 movable SUs are located is specified. There are varying numbers of PUs randomly placed in the simulation area. The PU

Table 1: Simulation parameters

Parameter name	Value
Simulation area	1000×1000 m^2
Simulation time	400 sec
Number of SUs	100
Number of PUs	Varied
PU activity parameter (λ)	100
Number of channels	3
Traffic type	CBR
Data packet size	512 bytes
Data packet interval	Every 50 msec
MAC layer	IEEE 802.11
Transport layer	UDP
SU transmission range	150 m
PU transmission range	150 m
Radio propagation	Two-ray ground reflection
PU activity checking interval	Every 5 sec
Interface queue type	Drop tail/pri queue

activities are modeled according to the ON/OFF process (Chowdhuryand Felice, 2009) with exponential distribution with parameter λ of 100, referred to as PU activity parameter. The ON state denotes the period where the channel is occupied by a PU and the OFF state represents the period where the channel is available for SUs' communications. The transmission range of SUs and PUs is set to 150 m. The traffic load is modeled as CBR (Constant Bit Rate) data packets with size of 512 bytes at the packet interval of 50 ms over UDP (User Datagram Protocol) connections. The duration of simulation run is set to 400 sec. There are 3 non-overlapping channels (or SOPs) given for multi-channel data communications. The two-ray ground reflection model is specified as the radio propagation type and the IEEE 802.11 is used for MAC protocol.

PERFORMANCE METRICS

In this section, the performance metrics used for evaluation are explained in detail as follows.

Average throughput: The average throughput is defined as the ratio of the total amount of data successfully received by the destination to the time it takes from the data start time to the data stop time, which can be calculated by using the following formula:

$$\text{Avg. Throughput (B/s)} = \frac{\text{Total no. of (data) bytes received by Destination}}{T_{end} - T_{start}} \quad (1)$$

where,
T_{end} = The data stop time
T_{start} = The data start time

In case all data streams have the same scheduling priority, the data throughput may be too low if varying traffic loads from multiple users share the same communication link. A lot of packets may be dropped due to network congestion.

Percentage of packet loss: Packet loss occurs when one or more data packets travelling across a network fail to reach the destination. The percentage of packet loss can be calculated by using the following formula:

Percentage of Packet Loss = Percentage of total no. of data packets dropped during simulation period (2)

Packet loss can result from various factors such as channel congestion, link degradation, bit error, faulty networking hardware, etc. The receiving application may ask for the retransmission of data packets that have been dropped, possibly causing high packet delay.

Average end-to-end delay: The average end-to-end delay is defined as the average time taken by data packets to be delivered across a network from source to destination, which can be calculated by using the following formula:

$$\text{Avg. End-to-End Delay} = \frac{\sum_{i=1}^{n} D_i}{n} \quad (3)$$

where, the D_i is the end-to-end delay of data packet i received by the destination and n is the total number of data packets received by the destination.

In the congested network, it may take long time for a data packet to reach the destination because of long queuing or packet retransmission. Moreover, in order to avoid severe congestion, data packet may be transmitted towards the destination via indirect route, thus leading to large end-to-end delay.

Average jitter: Data packets from the source may reach the destination with different delays. The jitter is defined as a statistical variance of inter-arrival time of data packets. The formula for estimating jitter is as follows:

$$J(i) = J(i-1) + [(|D(i-1,i)| - J(i-1))/16] \quad (4)$$

where, $J(i)$ is the jitter after the destination receives an i-th data packet and $D(i\text{-}1, i)$ is the difference of relative transit times for the two data packets, which can be calculated as:

$$D(i-1, i) = (Ri - R_{(i-1)}) - (Si - S_{(i-1)}) = (Ri - Si) - (R_{(i-1)}) - S_{(i-1)}) \quad (5)$$

where,
S_i = The timestamp from the packet i
R_i = The time of arrival for packet i

Consequently, the average jitter can be computed as:

$$\text{Avg. Jitter} = \frac{\sum_{i=2}^{n} J(i)}{n-1} \quad (6)$$

where, n is total number of data packets received by the destination.

The jitter can result from network congestion, bottleneck access links, route changes, or timing drifts. High jitter can seriously affect the quality of real-time applications such as audio/video streaming, videoconference applications, VoIP, online gaming, etc.

SIMULATION RESULTS AND EVALUATION

In order to obtain the simulation results for performance analysis, the NS2 Visual Trace Analyzer (Rocha, 2012) is used to process the NS-2 simulation output trace files. The simulation results of average throughput, percentage of packet loss, average end-to-

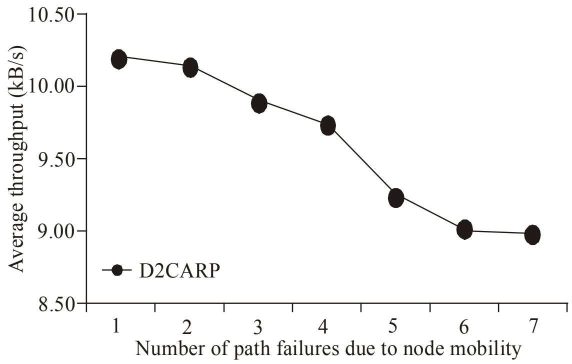

Fig. 5: Simulation results of average throughput against number of path failures due to node mobility

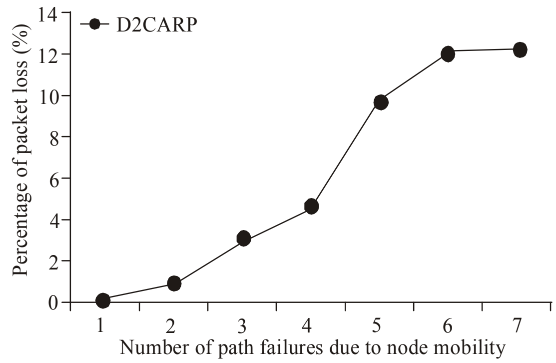

Fig. 7: Simulation results of percentage of packet loss against number of path failures due to node mobility

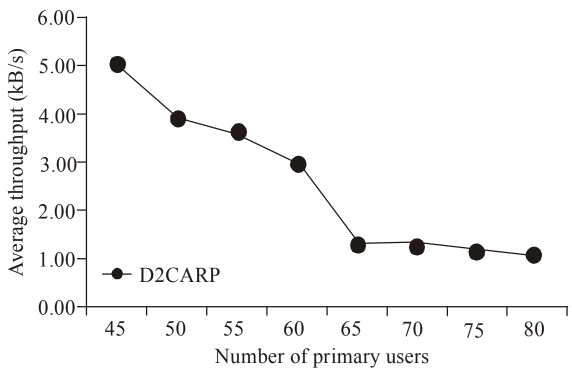

Fig. 6: Simulation results of average throughput against number of PUs

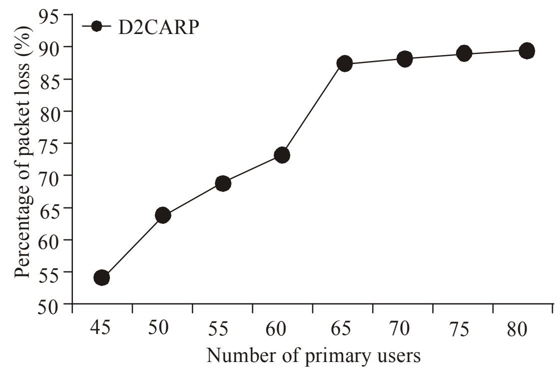

Fig. 8: Simulation results of percentage of packet loss against number of PUs

end delay and average jitter are shown in the form of line graphs. In this study, we evaluate the impact of increasing node mobility rate and number of PUs in CRAHNs. To accurately assess the impact of node mobility rate, the protocol performance is evaluated against varying number of path failures caused by node mobility. By increasing the node mobility rate in the networks, the occurrence of failure on transmission path is higher.

In Fig. 5 and 6, we analyze the effect of increasing number of path failures due to node mobility and increasing number of PUs on the average throughput, respectively. We observe that the protocol performance in terms of average throughput is significantly affected by increasing mobility rate and number of PUs. The results decrease dramatically in the networks with higher mobility rate and number of PUs. As expected, the protocol lacks the efficient route recovery mechanism to cope with a path failure caused by node mobility. When a transmission path is broken due to node movement, a lot of data packets are dropped in the network until a new path is found by triggering a route discovery process. With higher number of path breakages, percentage of packet loss increases rapidly as shown in Fig. 7. From the graph, it is observed that about 12.2% of data packets are dropped in the network with 7 path failures. Furthermore, although the D2CARP protocol applies a joint path and spectrum diversity approach to alleviate the impact of PU activity, a large number of data packets are lost in the networks with high number of PUs. In Fig. 8, it is shown that about 93.6% of data packets are dropped in the network where 85 PUs are deployed. In such network, the Spectrum channels (or SOPs) are rarely available for SUs to transmit data packets because they are always occupied by PUs. Also, a large number of PUs can cause a huge number of path failures.

Figure 9 and 10 illustrate the impact of increasing number of path failures due to node mobility and increasing number of PUs on average end-to-end delay, respectively. From Fig. 9, even though, in the scenarios with 2 and 4 path failures, average end-to-end delay slightly decreases when the number of path failures due to node mobility increases. This is because, after the previous path has been broken, the network may discover the new shorter transmission path. However, we can see that there is a tendency for average end-to-end delay to rise when the number of path breakages due to node movement increases. As expected, during data delivery, when the transmission path breaks because of node mobility, data packets will be buffered in a queue until a new path is discovered, thus

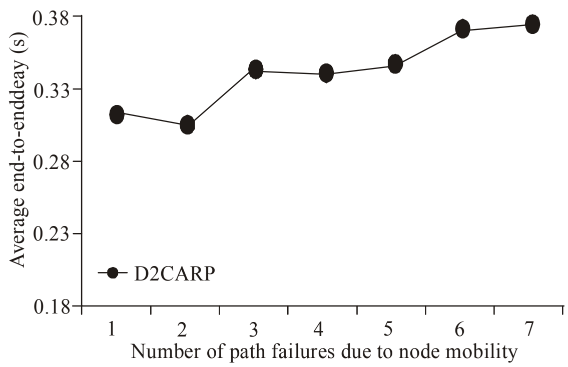

Fig. 9: Simulation results of average end-to-end delay against number of path failures due to node mobility

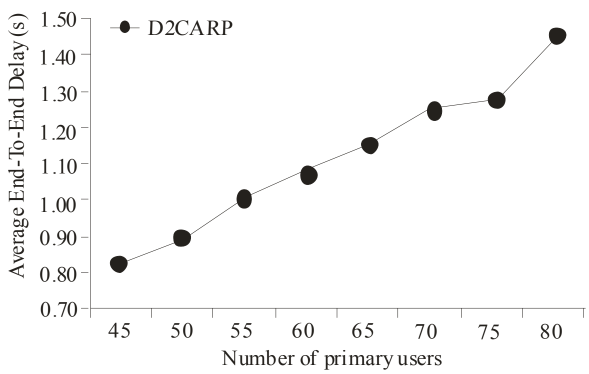

Fig. 10: Simulation results of average end-to-end delay against number of PUs

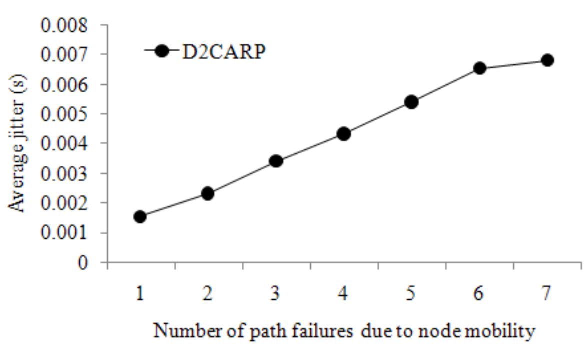

Fig. 11: Simulation results of average jitter against number of path failures due to node mobility

producing long delay. Consequently, the network with a large number of path failures generates high average end-to-end delay results. In Fig. 10, it is clear that, as the number of PUs increases, the results of average end-to-end delay rapidly rise. Therefore, large numbers of PUs significantly affect the network performance in terms of average end-to-end delay. In such network, available Spectrum channels (or SOPs) are frequently occupied by PUs. During data transmission, if all available channels are used by PUs, data packets will be buffered in a queue until the channel is vacated by a

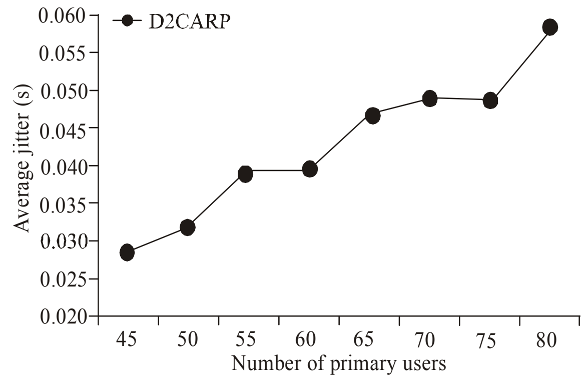

Fig. 12: Simulation results of average jitter against number of PUs

PU, thus leading high packet delay. As a result, the network with a large number of PUs also produces high average end-to-end delay result.

Figure 11 and 12 show the average jitter results against increasing number of path failures due to node mobility and increasing number of Pus, respectively. From both graphs, it is obvious that high node mobility rate (which results in huge numbers of path breakages) and large numbers of PUs in the network noticeably affect the network performance in terms of average jitter. When the number of path failures due to node mobility and number of PUs increase, the average jitter dramatically rises. As expected, a path breakage can be simply caused by node mobility. Consequently, the network with high node mobility rate can lead to large numbers of path failures. Additionally, during data transmission in CRAHNs, a SU must immediately vacate the currently-used transmission channel once the channel is requested by a PU activity, thus leading to a path breakage. As a result, high number of PUs in the network can cause huge numbers of path failures as well. When a transmission path breaks during data transmission due to either node mobility or PU activity, data packets may be buffered in a queue or dropped until a new transmission path is found, thus resulting in service outage. Therefore, the network with a huge number of path failures generates high average jitter result.

CONCLUSION

Cognitive Radio (CR) technology has been proposed as an effective solution for efficient utilization of radio spectrum. Operating in Cognitive Radio Ad Hoc Networks (CRAHNs) is fundamentally different from conventional wireless ad hoc networks. Consequently, a routing protocol for CRAHNs must satisfy the requirements of both CR networks and ad hoc networks. However, routing in CRAHNs is very challenging due to node mobility, dynamic spectrum availability, energy constraint, no centralized network infrastructure support, etc. In this study, we have briefly reviewed the dual Diversity Cognitive Ad-hoc Routing Protocol (D2CARP) which is a joint path and spectrum diversity based routing protocol for CRAHNs. Moreover, we have evaluated the performance of the D2CARP protocol in CRAHNs under critical conditions, i.e., high node mobility rate and number of PUs. The effects of increasing node mobility rate and number of PUs on network performance for the D2CARP protocol in CRAHNs have been investigated. The performance evaluation has been conducted through simulation using NS-2 simulator. The performance metrics used for evaluation include average throughput, percentage of packet loss, average end-to-end delay and average jitter. The simulation results obviously prove that large numbers of path failures due to node mobility and huge numbers of PUs noticeably affect the network performance. The D2CARP protocol lacks the efficient route recovery mechanism which can quickly and effectively cope with large numbers of path breakages leading to severe service interruptions in CRAHNs. As a result, in the networks with high node mobility rate and number of PUs, the results of percentage of packet loss, average end-to-end delay and average jitter are extremely high. On the other hand, the average throughput results are very low.

We strongly believe that this study can inspire further study on CRAHN routing, especially on developing new routing metric or algorithm to rapidly and efficiently cope with large numbers of path failures in CRAHNs.

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REFERENCES

Akyildiz, I.F., W.Y. Lee, M.C. Vuran and S. Mohanty, 2006. Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey. Comput. Netw., 50(13): 2127-2159.

Akyildiz, I.F., W.Y. Lee and K.R. Chowdhury, 2009. CRAHNs: Cognitive radio ad hoc networks. Ad Hoc Netw., 7(5): 810-836.

Akyildiz, I.F., W.Y. Lee, M.C. Vuran and S. Mohanty, 2008. A survey on spectrum management in cognitive radio networks. IEEE Commun. Mag., 46(4): 40-48.

Cacciapuoti, A.S., C. Calcagno, M. Caleffi and L. Paura, 2010. CAODV: Routing in mobile ad-hoc cognitive radio networks. Proceeding of the 3rd IEEE/IFIP Wireless Days Conference (WD). Venice, Italy, pp: 1-5.

Cesana, M., F. Cuomo and E. Ekici, 2011. Routing in cognitive radio networks: Challenges and solutions. Ad Hoc Netw., 9(3): 228-248.

Chowdhury, K.R. and M.D. Felice, 2009. SEARCH: A routing protocol for mobile cognitive radio ad-hoc networks. Comput. Commun., 32(18): 1983-1997.

FCC's Spectrum Policy Task Force, 2002. Report of the spectrum efficiency working group. Technical Report, Federal Communications Commission (FCC). Retrieved from: http://transition.fcc.gov/sptf/files/SEWGFinalReport_1.pdf.

Haykin, S., 2005. Cognitive radio: Brain-empowered wireless communications. IEEE J. Sel. Area Comm., 23(2): 201-220.

Issariyakul, T. and E. Hossain, 2009. Introduction to Network Simulator 2 (NS2). Chapter 2, In: Issariyakul, T. and E. Hossain (Eds.), Introduction to Network Simulator NS2. Springer-Verlag, USA, pp: 1-18.

Marinho, J. and E. Monteiro, 2012. Cognitive radio: Survey on communication protocols, spectrum decision issues and future research directions. Wirel. Netw., 18(2): 147-164.

McHenry, M., 2003. Spectrum White Space Measurements. Presentation to New America Foundation's Broadband Forum. June 20, pp: 1-13. Retrieved from: http://www.newamerica.net/files/nafmigration/archive/Doc_File_185_1.pdf.

Mitola, J., 2009. Cognitive radio architecture evolution. P. IEEE, 97(4): 626-641.

Perkins, C.E., E.M. Belding-Royer and S.R. Das, 2003. Ad Hoc On-demand Distance Vector (AODV) Routing. RFC 3561, Internet Engineering Task Force (IETF). Retrieved from: http://www.ietf.org/rfc/rfc3561.txt.

Rahman, M.A., M. Caleffi and L. Paura, 2012. Joint Path and Spectrum Diversity in Cognitive Radio Ad-Hoc Networks. EURASIP J. Wirel. Comm., 2012(1): 1-9.

Rocha, F., 2012. NS2 Visual Trace Analyzer. Retrieved from: http://nsvisualtraceanalyzer.wordpress.com/.

Sengupta, S. and K.P. Subbalakshmi, 2013. Open research issues in multi-hop cognitive radio networks. IEEE Commun. Mag., 51(4): 168-176.