Routing Protocols in CRAHNs: A Review

Anukiran Jain, S. Umang and M.N. Hoda

Abstract Cognitive radio, CR is a promising technology to authorize the competent usage of restricted natural resource radio frequency spectrum for the wireless devices. The technology authorizes the secondary (unlicensed) users, SU to exploit underutilized spectrum allocated to primary (licensed) user, and PU by renovating the traditional static spectrum access approach to dynamic spectrum access without creating any/allowable interference for PU. Design and implement routing protocol in Cognitive Radio Ad Hoc Networks, is an upcoming challenge. Such protocols require addressing the issues like environmental awareness to identify the licensed spectrum which is comparatively underutilized by PUs and can be use by SUs respecting the privilege of PUs usage and avoidance any interference to them. This paper presents the revised analytical model using domain object model of Dynamic Spectrum Management Functions (DSMF) that also represents the concept of cognitive routing in Cognitive Radio Ad Hoc Networks (CRAHNs). The presented analytical model facilitates to enhance the understanding of the concept of routing protocol in CRAHNs. The paper designates suggested routing protocols in recent years. Based on the literature survey, the paper also provides the research gap in the area of cognitive routing protocol in CRAHNs and ends with concluding remarks.

Keywords Primary users · Secondary users · CRAHNs · Cognitive radio · DSMF · Cognitive routing protocols

A. Jain (✉) · M.N. Hoda
BVICAM, New Delhi, India
e-mail: anukiranjain@gmail.com

M.N. Hoda
e-mail: mca@bvicam.ac.in

S. Umang
ITS, Ghaziabad, UP, India
e-mail: Singh.umang@rediffmail.com

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1 Introduction

Cognitive Radio Ad Hoc Networks (CRAHNs) is the network of cognitive radio(s) (the unlicensed radio devices comprise to cognitive technology) to utilize the spectrum allocated to licensed users in an opportunistic approach respecting the privileged policy for the action of licensed user within its allotted spectrum to maximize the spectrum utility in efficient manner [1, 2]. Routing in CRAHNs is similar to traditional Ad Hoc networks with additional complexities to address the issues like spectrum awareness, primary user activities awareness, route maintenance and lack of common control channel. These issues restrict the applicability of stable Ad Hoc networks routing protocols for CRAHNs. So there is a need to identify optimized cognitive routing protocol in terms of throughput end to end delay packet ratio. This paper helps to understand the routing protocol in CRAHNs through analytical model and review the various routing protocols in CRAHNs suggested by the researcher. Based on the literature survey, the paper also highlights the research gap with concluding remark. The paper is organized in five sections Sect. 1 provides the introduction; Sect. 2 introduces routing protocol in CRAHNS and discuss the analytical model for the same; Sect. 3 discusses the existing literature related to cognitive routing protocols; Sect. 4 discusses the research gap in the same domain, and Sect. 5 ends with the concluding remarks.

2 Routing Protocol in CRAHNs

Due to dynamic spectrum access, DSA, feature, CRAHNs need to face obscure topology and diverse QoS in comparison to Mobile Ad Hoc Networks which necessitate the proper routing protocol that also address the cognitive radios capabilities and reconfigure ability issues [1, 3, 4]. DSA exploits the spectrum utilization efficiently without interfering primary user activities. To realize the CRAHN, cognitive radio (CR) devices must have the capability to sense the white holes in licensed spectrum using spectrum sensing techniques that can result in multi-channel availability at a time for the secondary users. It makes the cognitive users to exploit the capability of spectrum decision to select the best available spectrum for the opportunistic use and vacant the spectrum or reconfigure the CR transmitter parameters (operating spectrum, modulation, transmission power, and communication technology) on detecting any primary user in the same spectrum to respect the PUs priority usage policy through spectrum sharing and spectrum mobility.

Analytical model [5] using domain object model can be used to enhance the understanding of Dynamic Spectrum Management Functions, DSMF, which includes cognitive capabilities and cognitive reconfigurability. Figure 1 represents the enhanced analytical model suggested in domain object model of CRAHNs functions [5], using domain object model to signify the involvement of DMSF

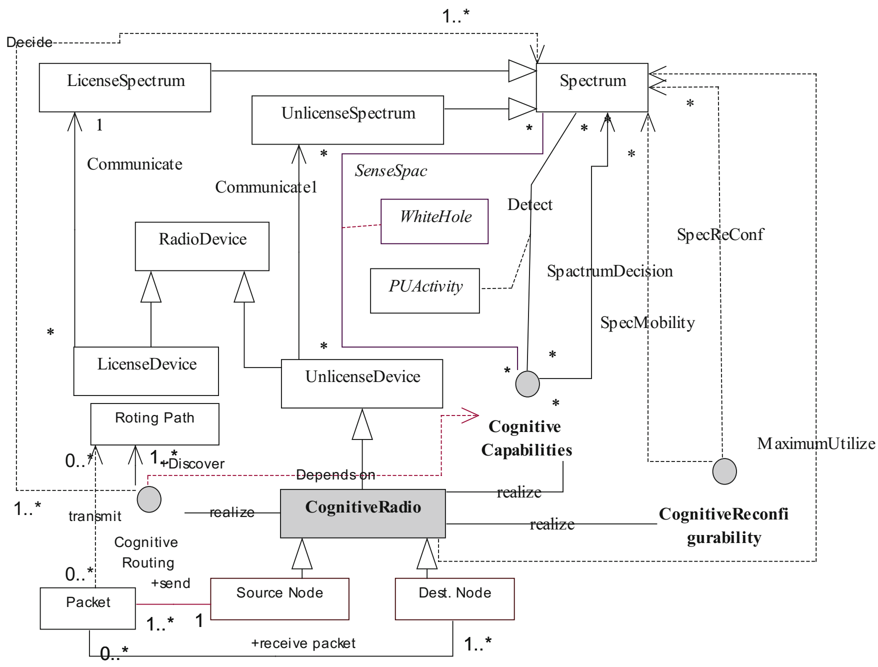

Fig. 1 Domain object model for cognitive routing in CRAHNs

to entail the appropriate routing protocols for CRAHNs. The model represents that each cognitive radio needs to implement the cognitive routing protocol which must be efficient to decide the finest available spectrum and transmit the data packets efficiently using its cognitive capabilities and reconfigurability for the competent usage of limited natural resource, i.e., spectrum. The model demonstrates the domain objects like spectrum which can be specialized as license spectrum and unlicensed spectrum; radio device which is specialized as license device or unlicense device; unlicense devise can be further specialized as cognitive radio which implements the cognitive capabilites and cognitive reconfigurability interface at the same time cognitive radio need to implement cognitive routing to maximize the spectrum usage and efficient data transmission.

3 Literature Survey

Cognitive routing protocols are required to deal with the changing spectrum of opportunities for cognitive radio(s); PUs privileged access for the licensed spectrum and no interference constraint by CR to any licensed PUs; for its action in its respective spectrum. Literature suggested several schemes to categorize the cognitive routing protocol based on full spectrum knowledge and local spectrum knowledge [1, 6–8]. Cognitive routing protocols (more than twenty) discussed in paper are generally based on local spectrum knowledge.

AODV—Ad Hoc *On-Demand Distance Vector Routing* suggested in 2003 [9] is a novel routing protocol for Ad Hoc network in which routes are attain as per the requirement suitable for dynamic self-starting networks. AODV is a novel protocol as the basis for cognitive routing in Ad Hoc network.

SORP—Spectrum Aware Routing Protocol and *DORP; Joint On-demand Routing and Spectrum Assignment* suggested in 2007 [1, 3, 6, 7, 10, 11] are AODV-based routing protocol(s) consider cumulative switching and backoff delay suitable for delay sensitive application. Both protocol(s) provide the solution for whole path selection but does not emphasize on neighborhood discovery and avoid spectrum dynamics. *STOD-RP—Spectrum tree-based on-demand routing protocol* suggested in 2008 [1, 6, 7, 12] provides end to end linking using tree-based proactive routing. Suggested protocol provides spectrum decision along with route selection. The protocol comprises the features of statistical PUs' activities and considers CR users' QoS as route metric and introduces spectrum adaptive route discovery method. Metric used in this protocol includes channel overhead, protocol overhead, packet size, link rate, packet error rate band availability, and spectrum band switches.

Local Coordination-Based Routing and Spectrum Assignment suggested in 2008 [1, 7, 8, 13]. Protocol is suggested to achieve efficient routing for whole path selection and spectrum assignment in multi-hop CRNs with minimal end to end delay. Protocol describes two sections: joint on-demand routing algorithm with spectrum selection and local coordination scheme for load balancing among multiple frequency band at intersecting relay node.

SAMER—Spectrum Aware Mesh Routing suggested in 2008 [1, 6, 14]. Suggested protocol provides whole path selection process considering spectrum awareness dynamics based on long-term and short-term spectrum availability. It considers the hop count and spectrum availability to balance the long-term optimality and short-term opportunistic gain. Protocol used Path Spectrum Availability (PSA) metric based on local spectrum availability and spectrum block quality (bandwidth/loss rate). Protocol provides rank to the alternative path based on activities of PU and SU as well. SAMER avoids congested and occupied links.

SPEAR—A multi-hop distributed channel assignment and routing algorithm suggested in 2008 [1, 6–8, 15] to support high-throughput packet transmission. The protocol takes the flexibility of link-based approach for the end to end optimization of flow-based approach. Protocol consider three subsections: (i) integration of spectrum discovery with route discovery (ii) minimization of inter-flow interference through coordination of channel assignments per flow basis (iii) minimization of intra-flow interference through exploitation of local spectrum heterogeneity and assigning different channels to link. Suggested protocol selects the best path by allowing multi-path propagation toward destination by embedding channel assignment in RREP. The protocol provides channel reservation, and simulation result indicates significant improvement in throughput. Protocol uses traditional routing metric with manual parameter setting.

MSCRP—multi-hop single transceiver cognitive radio network routing protocol suggested in 2008 [7, 16] is based on AODV contribute to improve network throughput. Suggested protocol supports CR transceiver to function on one channel at a particular time. MSCRP is based on the approach of joint selection of the spectrum with the choice of neighborhood node. Protocol solves the deafness problem that constraints if two consecutive nodes are serving same flow; they must not be switching nodes. Protocol supports the local coordination to focus on load balancing. MSCRP applies three states to the node single channel state, switching state, and non-free state.

Improved Ant Routing Algorithm suggested in 2009 [6, 17]. Suggested approach is based on the principle of swarn intelligence which is inspired from the communal behavior of social insects. The protocol is based on on-demand routing protocol without CCC to crack large-scale optimization problem in a distributed way. Protocol also instigates the route repair procedure in case existing route get disable.

SARP—Spectrum Aware routing protocol for cognitive Ad Hoc network proposed in 2009 [3, 18] discusses about two functions of SARP intelligent multi-interface selection function (MISF) and intelligent multi-path selection function (MPSF). SARP assigns the interface to a route through MISF by using the delay of the RREQ packet as a metric. The suggested protocol selects a path to route packet through MPSF by using the throughput increment as metric. Protocol results in high throughput, low delay, and overhead.

Spectrum Aware Highly Reliable Routing in CRN suggested in 2009 [6, 19] exploits concept of multi-path routing. Metric used in this protocol includes channel stability time (CST), link stability time (LST) PU on/off period, switching time, and path effective time (PET). It also provides path maintenance mechanism.

RACON suggested in 2009 [20] designs data transportation in CRN using link modeling to maximize data delivery rate, minimize latency, and minimize aggregate system resource consumed in all. In this protocol, link cost metric of a node is computed dynamically based on history of spectrum usage instead of current state. The link cost increases if node is disconnected for long period or having history of frequently disconnected-to-connected transitions. Suggested protocol always route the data packet closer to the destination by supporting limited packet buffering for short period even when the destination is not physically connected to the source or its current network partition.

GYMKHANA Protocol introduced in 2010 [6–8, 21] is capable to discover most stable routes. It is described in three classes: (a) to collect key parameters support distributed AODV style protocol (b) the basis of mathematical structure is represented through a graph associated to a given path (c) the second smallest eigenvalue of the Laplacian associated to the graph is evaluated to compute closed formula. Mathematical model for Gymkhana is very complex.

SEARCH suggested in 2009 [6–8, 22] is a geographic forwarding-based Spectrum Aware Routing protocol for CRAHNs that jointly undertake path and channel selection to avoid the PU activities during route formation, during route operations can be adapted to the newly discovered and lost SOP, and to consider distributed environment with node mobility in various cases. SEARCH protocol avoids the PU active region while routing. Author suggested that SEARCH can be extended to consider PU type with duty cycle and times of operation. More quality attributes may be added for next hop selection.

BCCCS—The Backup Channel and Cooperative Channel Switching Routing Algorithm suggested in 2010 [7, 8, 23] provides the concept of backup channel to focus on the route maintenance issue of CRAHNs. Each node periodically updates list of available channels with their priorities. Consider control packet channel request (CREQ), channel reply (CREP), and channel information (CINFO) required to maintain additional list and tables.

OSAB—Opportunistic Spectrum Access with Backup suggested in 2010 [24] discusses the CRAHNs challenge related to spectrum handoff that occurs when a channel occupied by SU and PU appears in the same channel. In this situation, SU needs to vacate the channel to respect the PU privileged usage of channel and results in degradation of performance of SU in terms of delay and link maintenance. OSAB offers the feature of reducing the number of spectrum handoffs. To evaluate the link maintenance probability and expected number of handoffs, a mathematical model is discussed by author. Results presented by author are positive for OSAB approach. Validation needs to be done through simulation for OSAB concept.

TACR—Traffic Aware Routing Protocol suggested in 2010 [6–8, 25] provides the combination of traffic aware routing and Q-learning algorithm based on on-demand routing protocol. It implements the cognitive packet to provide the current traffic information. Spectrum decision is based on the input parameters for traffic prediction and traffic perception. Q-learning technique helps to maintain route. The protocol results in reduced end to end delay, better throughput, and less packet loss in case of high traffic arrival rate.

WHAT based on weighted hop, spectrum awareness, and stability routing metric introduced in 2010 [8, 26] is able to capture overall quality of a path to have multiple consideration of metric calculation and enhance the network throughput. WHAT requires tuning of parameters to determine the metric value and path selection that can reduce the cognitive learning capabilities.

OSDRP—Opportunistic Service Differentiation Routing Protocol suggested in 2011 [27] addresses the cognitive routing issue where the average available communication time is shorter than the required communication time by cognitive radio(s). Author suggested a cross-layer cognitive routing protocol, for the dynamic CRNs. OSDRP emphasizes on minimum delay-maximum stable path for CRNs. OSDRP is a multi-metric routing that consider the availability of SOP with switching delay and queuing delay. Author identifies the possibility to explore implementation of geographical routing techniques to further reduce the overhead of proposed scheme.

CRP—A routing protocol for CRAHNs suggested in 2011 [6, 28]. CRP maximizes the bandwidth availability and provides explicit protection to PU receivers by considering the metrics for spectrum sensing, spectrum propagation characteristics, PU receiver protection, probability of bandwidth availability, and variance in the number of bits sent over the link. Suggested protocol works in two stages spectrum selection stage and next hop selection stage. CRP also considered route maintenance by utilizing proactive and reactive components. CRP works on the assumption that PU transmitter with known location is stationary in nature with maximum coverage range.

SER—Spectrum and Energy Aware routing protocol for Cognitive Radio networks proposed in 2011 [3, 29] which includes the basic operations like route discovery, data transmission, and route maintenance that combine the spectrum and route discovery results in less delay in end to end linking, high throughput, and less overhead.

Routing Protocol with Route Closeness Metric suggested in 2011 [6, 30] exploits multi-path routing to attain reliability and throughput. This protocol introduced a routing metric route closeness. It represents a variation of the DSR protocol for the route discovery phase.

CAODV—Cognitive Ad Hoc On-demand Distance Vector Protocol presented in 2012 [8, 31] based on graph theory and mathematical analysis. CAODV proposed with two versions; one exploits inter-route spectrum diversity and another exploits intra-route spectrum diversity. CAODV is reactive routing protocol with three objectives: (i) interference avoidance to primary users during both route formation and data forwarding; (ii) perform a joint path and channel selection at each forwarder; (iii) take advantage of the availability of multiple channels to improve the overall performance. Introduce additional control packet PU-RERR. The protocol results in high resource consumption due to the feature of discovery of multi-path or multi-channel routes and additional control packet. This protocol can be extended by using more effective route metrics.

Cooperative routing protocol in multi-hop CRAHNs proposed in 2012 [32]. This on-demand routing protocol helps to get minimum cost path between source and destination pair having maximum throughput and minimum delay with control message in comparison to previous work. Suggested protocol used the cooperative communication (CC) technique to resist fading effect and improved channel capacity. Author implemented the cooperative routing protocol in ns-2 2.31 with cognitive radio cognitive network Simulator [33].

D^2CARP—Dual Diversity Cognitive Ad Hoc *Routing Protocol* suggested in 2012 [8, 34] is a variation of AODV. Protocol combines path and spectrum diversity. Route discovery process of the protocol offers multi-path and multi-channel routes. Suggested protocol offers improvement over CAODV in terms of packet delivery ratio, overhead, delay, and hop count. In D^2CARP protocol, RREP needs to be broadcast back to the source and need large routing table and more resource consumption.

RPCRAN—A Routing Protocol for Cognitive Radio Ad Hoc *Networks* suggested in 2013 [35] is sensitive to primary user activities and utilizes multiple channels to enhance performance. This protocol suggested the incorporation of channel selection mechanism in the routing layer instead of MAC layer. Simulation results are compared with AODV results.

LAUNCH—Location-based Cognitive Routing Protocol suggested in 2013 [6, 36] considers stochastic activities of PUs to select most stable route. The selection of next hop is based on greedy decision which satisfies the condition that the next hop must be closer to the destination and result in minimum expected delay. LAUNCH studies the impact of changing SUs density, number of PUs, heterogeneity in PUs, mobility of SUs, data rate, and number of channels.

TIGHT—A geographic routing protocol suggested in 2014 [37] put forward three modes of routing to exploit spectrum opportunity by SU over the dedicated spectrum to PU without imposing interference on them. The *greedy mode* routes around the PU region using shortest trajectory circumventing method, without knowledge of primary user location. Greedy mode works best if the PU known to be rarely active [38]. The *optimal mode* works when the primary user location is known. In this mode, SU needs to compute the optimal trajectory to the destination SU [39]. The suboptimal mode further reduces the computational complexity of optimal mode at the cost of driving suboptimal trajectory from source SU to destination SU. The protocol is relatively less sensitive to node mobility and comparatively bear low overhead due to routing dependability based on location instead of next hop and doesn't favor route discovery and route maintenance.

4 Research Gap

Nowadays researchers are working extensively on the challenges related to opportunistic spectrum access and spectrum utilization. The networking concern needs to be addressed in Cognitive Radio Ad Hoc Networks (CRAHNs) [1, 4]. The methods for flexible spectrum use, distributes networks that wisely cooperate, low power, scalable implementation of cognitive radios are open challenges among researcher. Choosing the suitable path and choosing the suitable band at each path are the two major routing problems in CRAHNs [2]. There are many challenges that require attention of researchers related to cognitive routing in Ad Hoc networks includes: spectrum awareness, primary user activities, quality routes, and spectrum maintenance. Traditional routing protocols need to address the challenges of CRAHNs to provide the efficient cognitive routing protocol which can consider the spectrum decision with path selection based on spectrum awareness to provide the end to end communication. The cognitive routing protocols need to support routing with spectrum decision considering PUs' activities and sustain through reconfigurability to avoid unnecessary spectrum handoff. Instead of several suggested cognitive routing protocols by the researcher, it is strongly believed that research in this field needs major contribution [1, 6–8]. Minimizing the frequent change in CRN topology due to PUs' activities is an open research challenge in CRAHNs. Need to identify the techniques to predict PUs' activities in a spectrum so that the influence of these activities must be minimized on CRN topology. Researchers are working toward the direction to minimize the rerouting requirements for cognitive routing in case any PU unexpectedly appear in a give location that can result in degradation of network performance or unpredictable route failure. Coupling of quality metrics of end to end routes (nominal bandwidth, throughput, delay, energy efficiency, and fairness) with metrics on path stability, spectrum availability/PU presence is an open research challenge. Effective signaling procedures are required to restore "broken" paths with minimal effect on the perceived quality. The neighbor discovery is an open issue of cognitive routing in Ad Hoc Networks, due to lack of CCC broadcasting.

5 Conclusion

The paper demonstrates cognitive routing in CRAHNs through domain object model and the importance of entire DSMF in cognitive routing. Through the discussed literature, it is known that the routing protocols suggested in recent years consider almost static CRNs with stable communication channel where the channel is available for longer time than required. PU activity can force the SU to vacant the available channel to maintain the precedence of PU for channel utilization. Cognitive routing algorithm need to be aware of spectrum availability, during CR in operation also, which is based on surrounding special environment. Researchers need to address the ways to couple routing algorithm with the entirely cognitive cycle of spectrum management. Dynamic self-organized, a well-known novel traditional Ad Hoc routing protocol, AODV, Ad Hoc on-Demand Distance Vector Routing protocol can be modified to propose a stable cognitive routing protocol in Ad Hoc networks.

References

1. Cesana, M., Cuomo, F., Ekici, E.: Routing in cognitive radio networks: challenges and solutions. Ad Hoc Netw. **9**, 228–248 (2011)
2. Bandyopadhyay, P.: Routing in cognitive radio ad-hoc networks. Cognitive networking and cross-layer interaction. University of Helsinki, Department of Computer Science, 15.01.2013–23.04.2013, pp. 134–138. www.hiit.fi/u/bayhan/uh/StudentReports/Payel_Bandyopadhyay_RA_finalreort.pdf
3. Walde, N., Barve, S.: A study: on routing schemes in cognitive radio network. Int. J. Adv. Res. Comput. Commun. Eng. **2**(8), 3262–3265 (2013)
4. Yu, F.R. (ed.): Cognitive Radio Mobile Ad Hoc Networks. Springer, New York, pp. 145–148
5. Jain, A., Umang, S., Hoda, M.N.: Conceptual understanding of cognitive radio adhoc networks. In: 2nd International Conference on Computing for Sustainable Global Development (INDIACom), pp. 2194–2198 (2015)
6. Abdelaziza, S., ElNainay, M.: Survey of routing protocols in cognitive radio networks. In: Preprint submitted to Elsevier, pp. 1–20 (2012)
7. Jain, S., Dhawan, A., Jha, C.K.: A survey: on routing protocols in cognitive radio ad hoc networks. Int. J. Comput. Sci. Inf. Technol. **5**(2), 2204–2206 (2014). ISSN: 0975-9646
8. Salim, S., Moh, S.: On-demand routing protocols for cognitive radio ad hoc networks. EURASIP, J. Wireless Commun. Netw. 24–29 (2013)
9. Perkins, C.E., Royer, E.M.: Ad hoc on-demand distance vector (Aodv) routing. Internet Engineering Task Force IETF, pp. 1–29, July 2003

10. Cheng, G., Liu, W., Li, Y., Cheng, W.: Spectrum aware on-demand routing in cognitive radio networks. In: Proceedings of 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, pp. 571–574 (2007)
11. Cheng, G., Liu, W., Li, Y.: Joint on-demand routing and spectrum assignment in cognitive radio networks. In: IEEE International Conference on Communications, pp. 6499–6503 (2007)
12. Zhu, G., Akyildiz, I., Kuo, G.: Stod-Rp: a spectrum-tree based on demand routing protocol for multi-hop cognitive radio networks. In: IEEE Global Telecommunications Conference, GLOBECOM, pp. 1–5 (2008)
13. Yang, Z., Cheng, G., Liu, W., Yuan, W., Cheng, W.: Local coordination based routing and spectrum assignment in multi-hop cognitive radio networks. Mobile Netw. Appl. 67–81 (2008)
14. Pefkianakis, I., Wong, S.H,Y., Lu, S.: Samer: spectrum aware mesh routing in cognitive radio net-works. In: 3rd IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN, pp. 1–5 (2008)
15. Sampath, A., Yang, L., Cao, L., Zheng, H., Zhao, B: High throughput spectrum-aware routing for cognitive radio based ad hoc networks. In: Proceedings of the International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), pp. 113–117 (2008)
16. Ma, H., Zheng, L., Ma, X., Luo, Y.: Spectrum aware routing for multi-hop cognitive radio networks with a single transceiver. In: Proceednigs of 3rd International Conference on Cognitive Radio Oriented Wireless Networks and Communications, pp. 1–6 (2008)
17. Song, Z., Shen, B., Zhou, Z., Kwak, K.S.: Improved ant routing algorithm in cognitive radio networks. In: ISCIT 9th International Symposium Communications and Information Technology, pp. 110–114 (2009)
18. Ju, S., Evans, J.B.: Spectrum-aware routing protocol for cognitive ad-hoc networks. In: Proceedings of the IEEE Globecom, pp. 1–6, November 2009
19. Song, H., Lin, X.: Spectrum aware highly reliable routing in multihop cognitive radio networks. In: IEEE Wireless Communications and Signal Processing, pp. 1–5 (2009)
20. Talay, A.C., Altilar, D.T.: RACON: a routing protocol for mobile cognitive radio networks. In: CoRoNet '09 Proceedings of the 2009 ACM workshop on Cognitive radio networks, pp. 73–78 (2009)
21. Abbagnale, A., Cuomo, F.: Gymkhana: a connectivity-based routing scheme for cognitive radio ad hoc networks. In: IEEE Conference on Computer Communications, INFOCOM, pp. 1–5 (2010)
22. Chowdhary, K.R., Felice, M.D.: Search: a routing protocol for mobile cognitive radio ad-hoc networks. Comput. Commun. **32**, 1–6 (2009)
23. Zeeshan, M., Manzoor, M.F., Qadir, J.: Backup channel and cooperative channel switching on-demand routing protocol for multi-hop cognitive radio ad hoc networks (BCCCS). In: Proceedings of 6th International Conference on Emerging Technologies, pp. 394–399 (2010)
24. Kalil, M.A., Al-Mahdi, H., Mitschele-Thiel, A.: Spectrum handoff reduction for cognitive radio ad hoc networks. In: 7th International Symposium on Wireless Communication Systems Wireless Communication Systems (ISWCS), pp. 1036–1040 (2010)
25. Xu, Y., Sheng, M., Zhang, Y.: Traffic-aware routing protocol for cognitive network. In: Proceedings of IEEE 72nd Vehicular Technology Conference, pp. 1–5 (2010)
26. Chen, J., Li, H., Wu, J.: WHAT: a novel routing metric for multi-hop cognitive wireless networks. In: Proceedings of the 19th Annual Wireless and Optical Communications Conference Shanghai, pp. 1–6, 14–15 May 2010
27. How, K.C., Ma, M., Qin, Y.: Routing and QoS provisioning in cognitive radio networks. Comput. Netw. **55**, 330–342 (2011)
28. Chowdhury, K., Akyildiz, I.: CRP: a routing protocol for cognitive radio ad hoc networks. IEEE J. Sel. Areas Commun. 794–804 (2011)
29. Kamruzzarman, S.M., Kim, E., Jeong, D.G.: Spectrum and energy aware routing protocol for cognitive radio ad hoc networks. In: IEEE ICC proceeding, pp. 1–5 (2011)

30. Beltagy, I., Youssef, M., El-Derini, M.: A new routing metric and protocol for multipath routing in cognitive networks. In: IEEE Wireless Communication and Networking Conference (WCNC), pp. 974–979 (2011)
31. Cacciapuoti, A.S., Caleffi, M., Paura, L.: Reactive routing for mobile cognitive radio ad hoc networks. Ad Hoc Netw. 803–815 (2010)
32. Sheu, J.P., Lao, I.L.: Cooperative routing protocol in cognitive radio ad-hoc networks. In: IEEE Wireless Communications and Networking Conference: Mobile and Wireless Networks, pp. 2916–2921 (2012)
33. Cognitive Radio Cognitive Network Simulator. http://stuweb.ee.mtu.edu/~ljialian
34. Rahman, M.A., Caleffi, M., Paura, L.: Joint path and spectrum diversity in cognitive radio ad-hoc networks. EURASIP J. Wireless Commun. Netw. 1–9 (2012)
35. Sieaj, M., Alshebeili, S.: RPCRAN: a routing protocol for cognitive radio ad hoc networks. Int. J. Innov. Comput. Info. Control Vol. **9**(11), 4583–4594 (2013)
36. Habak, K., Abdelatif, M., Hagrass, H., Rizc, K., Youssef, M.: A location-aided routing protocol for cognitive radio networks. ICNC, pp. 729–733 (2013)
37. Jin, X., Zhang, R., Zhang, Y.: TIGHT: a geographic routing protocol for cognitive radio mobile ad hoc networks. IEEE Trans. Wireless Commun. **13**(8), 4670–4681 (2014)
38. Walde, Nilima, Barve, Sunita: A study: on routing schemes in cognitive radio network. Int. J. Adv. Res. Comput. Commun. Eng. **2**(8), 3262–3265 (2013)
39. Jain, A., Umang, S., Hoda, M.N.: Exigency of cognitive radio network. IJCSI Mauritius IJCSI **12**(1) (2015)