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A COMPREHENSIVE STUDY OF ROUTING PROTOCOLS FOR COGNITIVE RADIO NETWORKS

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ABSTRACT

The rapid development of wireless communication technologies results in the problem of radio spectrum shortage. Additionally, the traditional fixed spectrum allocation scheme can lead to the significant spectrum underutilization. Cognitive radio (CR) is an emerging technology to solve those problems by enabling unlicensed users to opportunistically access the available licensed bands in an intelligent and cautious manner. In cognitive radio networks (CRNs), the data routing is one of the most important issues to be taken into account and requires more study. This paper surveys recent routing protocols for CRNs and introduces the classification of routing techniques as well as presenting significant challenges which need to be considered for routing design. The main purpose of this survey is to provide a comprehensive and critical study on the current routing schemes in order to expose new open issues as well as being utilized to either improve the existing routing techniques or to develop new routing solutions. The possible future research in routing for CRNs is also given.

Keywords: *Routing Protocols, Cognitive Radio Networks, Routing Challenges, Routing Categories*

1. INTRODUCTION

Due to the huge advancement of wireless technologies, the radio spectrum is one of the most heavily used and costly natural resources. However, the recent radio spectrum measurements [1] show that the fixed spectrum allocation policy is becoming unsuitable for current wireless system. Moreover, most of the spectrum bands (licensed bands) assigned for licensed users are under-utilized (many portions of the radio spectrum are not utilized for a significant period of time or in particular areas) while unlicensed spectrum bands used to operate by various well-known wireless technologies, such as Wi-Fi, cordless phones, Bluetooth, NFC (Near Field Communication), ZigBee and so on, are always crowded, as proved by Federal Communications Commission (FCC)'s experiment results [2].

Cognitive radio (CR) [3][4][5] is a key promising technology for future wireless communications and mobile computing proposed to solve the problems of spectrum scarcity and spectrum underutilization as well as address the increasing congestion in the unlicensed bands by enabling unlicensed users (also called CR users or secondary users: SUs) to opportunistically access the vacant portions of the spectrum bands, referred as Spectrum Opportunities (SOP) [6], which is always statistically underutilized by licensed users (also known as primary users: PUs) while ensuring that the interference to the licensed users is below an acceptable threshold level. In accordance with the network architecture, cognitive radio networks (CRNs) can be deployed as both an infrastructure network and an ad hoc network. The infrastructure-based CRN, as shown in Figure 1, has a central network entity (base station) to coordinate communication. For CR ad hoc network (CRAHN), a CR user can communicate with other CR users through ad hoc connection on both licensed and unlicensed spectrum bands without any infrastructure backbone (see Figure 1).

In fact, CRNs are an emerging research domain and there are many open issues that are remained to be solved. Most of the research on CRNs to date has focused on lower layer (PHY and MAC) issues [7][8][9][10], as a result, the study of CRNs routing

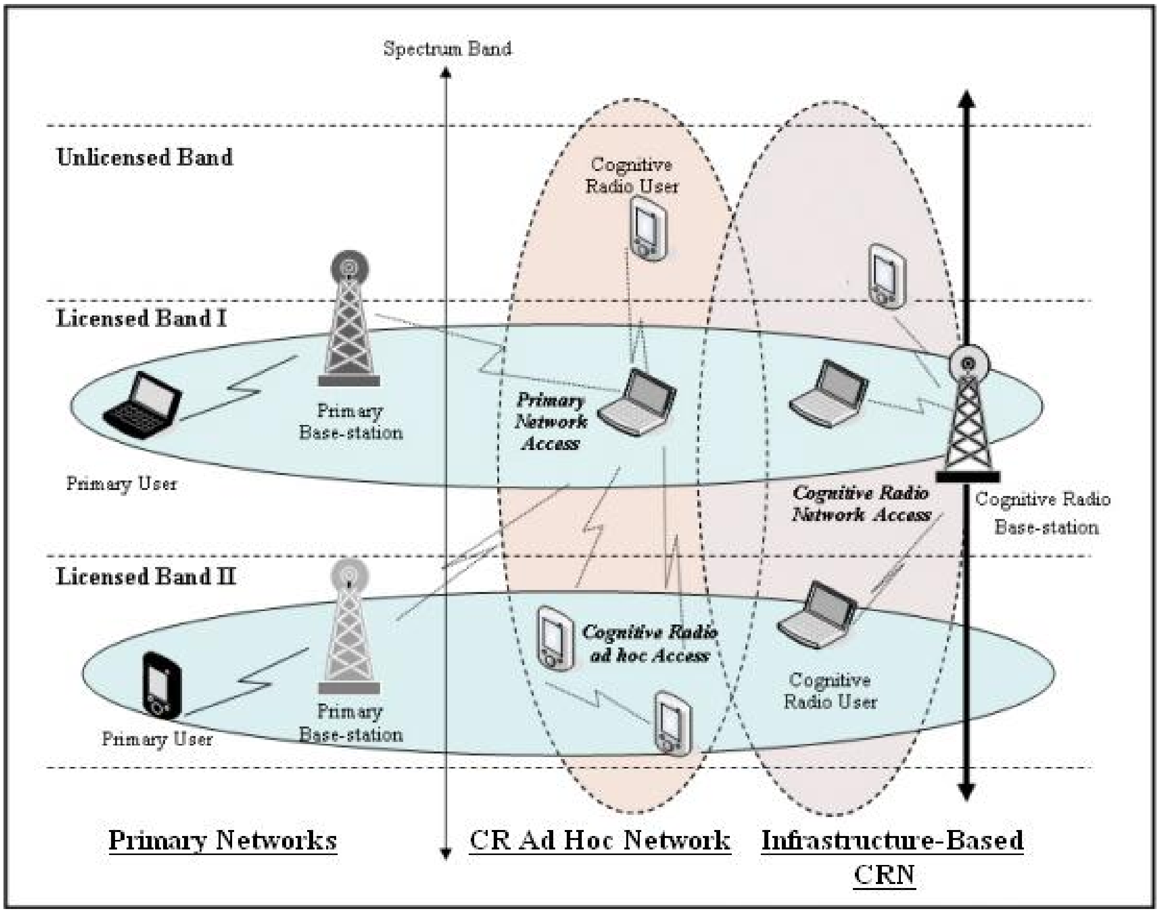


Figure 1. CRN Architecture

protocol (on network layer) has been largely unexplored.

Applying CR technology in wireless network improve the system capability and spectrum utilization efficiency. Nevertheless, due to unique network characteristics, it comes out with several significant challenges which need to be considered for routing design as follows:

- **Network topology change:** The topological changes in CRNs occur primarily due to fluctuations of PU activity and node mobility. When PU activity is detected, the SU must immediately vacate the channel which overlaps the PU's transmission frequency in order not to cause a harmful interference to PUs. Therefore, the available channel set at each SU varies over time and location.

- **Different spectrum characteristics:** In a practical CRNs, spectrum channels at each SU may have different channel properties, such as bandwidth, delay, loss rate, propagation characteristic, etc., as well as being available for unequal period of time. As a result, different channels may support different transmission ranges.

- **Effect of spectrum handoff:** The end-to-end route in CRNs may be composed of multiple hops which use different channels for data transmission according to the spectrum availability. Large numbers of spectrum handoff (the process for a SU to change its frequency of operation) caused by multi-channels transmission or route recovery process may lead to the increased end-to-end delay and high energy consumption.

- **Interference impact:** According to the principle of the CRNs, preferable routes should be selected with the minimum interference to the PU networks and the interference effect must keep below the acceptable threshold level. Furthermore, the interference among links that use the same channel should be taken into account as well.

However, it is also difficult to determine the acceptable level of interference impact.

- **Route recovery mechanism:** For general wireless networks, link failures may result from node mobility, node fault or link degradation. However, route breakages in CRNs can be also caused by PU activity. Different causes of link failure may need different route recovery mechanism to deal with, i.e. finding another detour route by using same channel or changing the spectrum channel by using same route. Therefore, a SU must identify the correct cause of link failure and select the suitable route recovery algorithm.

- **Common control channel:** SUs usually coordinate with each other by utilizing a common medium for spectrum related information exchange, known as a common control channel (CCC). A CCC [11] in CRNs facilitates the neighbor discovery and helps in channel access negotiation as well as routing information updates. However, the additional control channel in each SU is likely to be harmful for energy-constrained CRNs due to extra overhead of CCC establishment. Moreover, a CCC is vulnerable to PU activity and may be occupied by PUs at any given time. In addition, since a CCC is used to facilitate cooperation among SUs and other network operations, so it may be exposed to the risks of security attacks.

- **Energy consumption:** In some CRNs, such as CR mobile ad hoc networks [12] or CR sensor networks [13], SUs generally are small in size, and have limitation on energy capacity. However, SUs must be capable of sensing the spectrum in a wide frequency band, so the efficient power control is required. Besides, the dynamic nature of channel availability in CRNs can cause energy consumption due to packet loss and retransmissions. Consequently, the network partitioning problem may occur easily due to the energy exhaustion of the relay nodes. In such networks, routing protocol with energy awareness is challenging and should be taken into account.

Incidentally, several routing protocols have been proposed for CRNs to deal with the inherent issues of these networks, which include opportunistically spectrum access, dynamic spectrum availability, interference protection towards PU activity, multi-channels transmission and high energy consumption. These routing protocols may be categorized as:

- **PU activity aware routing:** The protocol is designed with a purpose to establish a transmission path which avoids regions of PU activity. The reason behind the design is to make routes less vulnerable to the impact of PU activity during data transmission. When a PU region is encountered, the path will enter into a detour to avoid the PU region.

- **Location-based routing:** The protocol utilizes the location information of the nodes to transmit the routing messages to the desired regions that make most progress towards the destination rather than the entire network in order to reduce control overhead. To obtain the whole geographical topology of the network, each node will flood its location and ID to all nodes in the networks (after the end of this process, only a topology change will be announced). In addition, the position of each node can be also determined by using GPS (Global Positioning System).

- **Cluster-based routing:** The protocol divides the network nodes into a number of clusters. The clustering algorithms can be categorized into two categories, i.e. clusters with or without cluster head. For the former category, the cluster head is elected for each cluster to help in the data transmission management and to maintain cluster membership information. The main aim of cluster-based routing is to increase network scalability, optimize the bandwidth usage, and balance the distribution of resources.

- **Multipath routing:** The protocol allows the establishment of multiple alternative paths between source-destination pair in order to transmit multiple data streams simultaneously or be used for backup purpose. It is typically proposed to provide load balancing, increase the reliability of data transmission and maximize the utilization of network resources.

- **Reinforcement learning based routing:** The protocol applies a reinforcement learning [14] to form a route for data delivery. The reinforcement learning provides a framework of learning a control policy (a mapping of observations into actions) based on experiences and rewards. The goal of applying the reinforcement learning for data routing in CRNs is to effectively address the challenges of uncertainty on spectrum availability.

- **Mobility aware routing:** The protocol is designed with an aim to support the mobile CRNs in which the nodes (SUs or PUs) are movable, i.e. the nodes are free to move at any time, towards any direction and at any speed, resulting in frequent link breakages. To deal with these challenged networks, the protocol may establish the reliable path containing maximum number of less mobile nodes, or provide the efficient route recovery mechanism in order to recover the failed link caused by node mobility.

The rest of the paper is organized as follows. A comprehensive study of the state-of-the-art routing protocols for CRNs is presented in the section 2. Various routing techniques will be described as well as their performance will be analyzed and criticized. Finally, conclusion along with open issues is provided in section 3.

2. COMPREHENSIVE STUDY OF ROUTING PROTOCOLS FOR CRNS

2.1. Spectrum-Tree Based On-Demand Routing Protocol (STOD-RP)

Zhu et al. [15] proposed the Spectrum-Tree based On-Demand Routing Protocol (STOD-RP) to solve the problem of collaboration between spectrum decision and route selection by building a spectrum-tree in each spectrum band. Each spectrum-tree selects only one root node which stores the route information to other nodes in the spectrum-tree.

The STOD-RP is a hybrid routing protocol which combines tree-based proactive routing and on-demand route discovery that is an extension of the original AODV [16]. In route discovery process, the Spectrum Route REQuest (SRREQ) and Spectrum Route REPly (SRREP) are used to obtain routes for data transmission. Moreover, the protocol presents two types of routing in multi-hop CRNs: 1) Intra-Spectrum Routing which operates in a single spectrum-tree; and 2) Inter-Spectrum Routing which performs in multiple spectrum-trees. The new cognitive route metric was defined by considering QoS (Quality of Service) requirements and PU activity, which is based on the route stability and resource consumption.

The protocol also provides an efficient and fast spectrum-adaptive route recovery method by applying the spectrum handoff and path rerouting methods for resuming data transmission in situation that the available spectrum band between two SUs is occupied by a PU or disappears due to SU mobility during data delivery.

As compared to the Cognitive Tree-Based Routing (CTBR) protocol [17], the simulation results proved that STOD-RP reduced the average end-to-end delay with the increased number of gateway nodes (the nodes which belong to multi spectrum-trees). It also decreased the control overhead when compared with the Multi-radio Multi-channel AODV (MM-AODV) protocol [18].

2.1.1. Critiques of STOD-RP

In CRNs, the condition of available spectrums varies over time and space. For the STOD-RP, the spectrum tree formation process is implemented only one time in each spectrum band to select a root node which may result in the non-updating root node that always has outdated spectrum information. Moreover, to obtain a route for data transmission between the source and the destination, the protocol runs tree-based proactive routing to find a root node and then triggers on-demand route discovery to search the destination, which may provide longer delay, high control overhead and more resource consumption, especially in the highly mobile CRNs that suffer a large number of route failures and re-routing. Furthermore, without utilizing a dedicated CCC for supporting the control signaling and spectrum related information exchange between SUs, the available spectrum channel used for ongoing transmission of data will be also used for the transmission of control messages which may decrease the end-to-end throughput and affect the data delivery.

2.2. Spectrum Aware Routing Protocol For Cognitive Ad-Hoc Networks (SEARCH)

Chowdhury and Felice [19] presented the SpEctrum Aware Routing protocol for Cognitive ad-Hoc networks (SEARCH) based on geographic routing (as similarly used in GPSR [20]) which jointly performed channel and path selection to elude areas of PU activity during path establishment. The SEARCH is an extension of the existing AODV [16] routing protocol. Each node in the network is equipped with a single tunable radio transceiver and has location awareness. The location information is exchanged among neighbors periodically by using beacon updates.

In the process of route formation, the source and intermediate node(s) transmit a route request (RREQ) packet to its neighbors within its focus region (see Figure 2) on each channel which is not interfered by PU activity until it reaches the destination by operating in two modes: 1) Greedy Forwarding Mode (for transmitting the RREQ along the greedy shortest path on each channel); and 2) PU Avoidance Mode (for avoiding a region of PU activity). Then, the destination combines all selected paths on the individual channels according to the joint channel-path optimization algorithm with an objective to minimize the hop-count, the end-to-end delay and channel switching. Afterwards, the route reply (RREP) packet is forwarded back to the source along the optimal path. The data transmission can start instantaneously after the source receives the RREP. After the stage of initial route establishment, the route enhancement stage will be activated to optimize the current path until no further improvement in term of end-to-end delay is found.

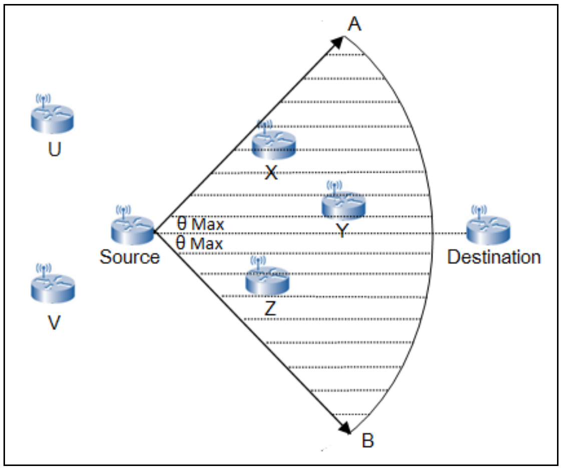


Figure 2. The Focus Region Of The Source Node

2.2.1. Critiques of SEARCH

The SEARCH protocol is based on location awareness, i.e. each node in the network can determine the location of other nodes, so that the RREQ message can be transmitted to only the neighboring nodes which are located in the focus region. To achieve this requirement, large numbers of control packets are produced and periodically exchanged within the network which may lead to network congestion and wasteful usage of network resource. Moreover, the route maintenance algorithm (in case of route breakage during data transmission) is not taken into account. Additionally, the shortest path approach may be inadequate to be used to select the optimum path for data delivery; other factors, e.g. route quality and interference impact, should be considered as well. Lastly, although the proposed protocol was designed to support mobile CR ad hoc networks, however, the effect of node mobility has not been evaluated.

2.3. Ant-Based Spectrum Aware Routing (ASAR)

In [21], the Ant-based Spectrum Aware Routing (ASAR) protocol, which is a biologically inspired routing solution (based on swarm intelligence) for CRNs, was introduced by Bowen Li et al. The ASAR protocol applied the ant colony algorithm [22] providing the features of adaptation and self-learning in order to solve the problem of dynamic spectrum availability on CRNs in distributed manner.

The routing table at each node is used to store the routing information including: 1) Local Heuristic Information which characterizes the common available channels with its neighbors; 2) Pheromone Concentration that indicates its preference to select a next hop for data forwarding; and 3) Statistical History Information which presents the statistical history of path quality. A path that is shorter and possesses more common available channels will be considered as a higher-quality path.

When a source node requires to find or maintain a path towards a destination node for data delivery, it generates an F-ant packet which will be broadcasted to all its neighbors if it lacks the routing information to the destination, or, otherwise, will be forwarded directly in a stochastic unicast manner towards the destination node through the dedicated CCC [26] according to the information in the routing table that is more relying on the local heuristic information. During the travel period, the F-ant records a spectrum-feasible path towards the destination. Once the F-ant arrives at the destination, a B-ant packet will be generated by the destination node and travel back along the reverse path towards the source node through the data channel by copying the F-ant's node address information. While travelling along the reverse path, the B-ant collects the local heuristic information of each node and updates the information in its routing table.

The data transmission process is triggered when the B-ant reaches the source node. The next hop selection for forwarding data is depending on the information in the routing table which is more relying on the pheromone concentration (i.e. more stability). In addition, the ASAR protocol also utilizes the reinforcement learning function in order to accelerate converging to the better path.

2.3.1. Critiques of ASAR

Large numbers of ants packets (F-ants and B-ants) generated in ASAR protocol for establishing routes towards the destination is a severe drawback of this algorithm, which may lead to the huge energy consumption. Furthermore, each ant contains a list of all visited nodes' address which may result in the large-size overhead, especially in a huge CRN. Another weakness of the ASAR protocol is the long delay before the source-destination routes are created. In addition, the issue of node mobility is still not taken into account and the protocol also lacks the efficient route recovery algorithm in case the link failure occurs during the transmission of data, which may cause a large number of dropped packets and long network delay. Besides, to define the routing metric by considering only two criteria (spectrum opportunities and hop-count) may not be efficient enough, especially in a heterogeneous CRN where available channels have different characteristics. Other factors, such as link bandwidth, link delay, interference impact, etc., should be taken into account as well.

2.4. Reliable Link Routing (RLR)

Han and Huang [23] proposed Reliable Link Routing (RLR) protocol which combined proactive and reactive routing approach, called hybrid routing, as well as taking into account for spectrum mobility. The novel reliable link routing metric was presented by focusing on decreasing routing overhead and improving link reliability in multi-hop CRNs. Each SU in the network selects its reliable neighbors based on the link reliability for forwarding routing packets and data; one radio is used for data delivery and another (CCC) is dedicated for exchanging the control messages. The distributed approach is applied in this protocol where each SU independently detects the environment condition and gathers the information as well as making the routing decision based on local information and its own condition which can be obtained by exchanging routing packets with its neighbors or its observation. As a result of utilizing the distributed approach, SUs are able to be deployed easily in the network and control overhead is reduced efficiently by avoiding network-wide flooding.

For considering the link reliability, if a pair of nodes has more common available channels, the probability of successful data delivery to each other becomes higher. Moreover, a link between two SUs which is rarely used by PUs is considers as more robust link. In order to decrease some packet overhead, a SU will not monitor the condition of a spectrum channel that is only available to a single SU but unavailable to any of its neighboring nodes. The *link reliability*, r_{ij}, between adjacent secondary users SU_i and SU_j can be defined as follows:

$$r_{ij} = \alpha \cdot [1 - \prod_{l^n \in L_{ij}} (1 - p_n)] + \beta \cdot \frac{|L_j|}{|L|} \qquad (1)$$

where L is the available channel set , L_j is the available channel set at SU_j, and L_{ij} is the common available channel set between SU_i and SU_j. The p_n is probability that the PU does not occupy the channel n (l^n), $l^n \in L$. The α and β are coefficient ($\alpha, \beta \in [0,1]$ and $\alpha + \beta = 1$).

When a source node, without route information, desires to send data to a destination node, it initiates a route discovery process by flooding a RREQ packet and waiting for a RREP packet from the destination. Then a transmission path between them will be established; this process is known as a reactive routing scheme. The concept of Reliable Relays (RR) was introduced to avoid flooding of routing messages in the entire network. A set of RR for each node contain its one-hop neighboring nodes with the highest link reliability and the neighbors of those nodes which are able to cover a set of its two-hop neighboring nodes. Each SU only sends routing packets to nodes in its RR set to reduce control overhead in the network. The end-to-end path for data transmission is composed of the reliable link between RR nodes. In this protocol, the HELLO message, which is exchanged among nodes in the network through a CCC, is used to update the link status, detect neighboring nodes, and select the RR.

The protocol works as proactive routing scheme when the destination node is within two-hop range. The source node can start sending data immediately to the destination node because each SU already has the route information of one-hop and two-hop neighboring nodes. However, if the destination is beyond two-hop range, the protocol applies the reactive routing scheme as mentioned above.

2.4.1. Critiques of RLR

The advantage of the proactive routing scheme as applied in the protocol may be useless in a large CRN where the distance between the source and the destination is always more than two-hop range. Moreover, the protocol lacks the efficient route recovery mechanism to deal with route failures during data delivery. When the currently used transmission route is interrupted, the long service outage occurs until the source node is able to search for a new route by flooding a RREQ packet in the network and waiting for a RREP packet from the destination node. Consequently, the protocol may be unsuitable to be applied in a mobile CRNs where SUs are not stationary that can cause high rate of link breakage. Furthermore, the data path is selected based on link reliability only, which does not take into account for link quality, e.g. bandwidth, link delay, energy consumption, fairness, etc. As a result, the path may be inefficient, especially, in a heterogeneous CRN where spectrum channels at SUs have different bandwidths, propagation characteristics and are dynamically available.

2.5. Cognitive Ad-Hoc On-Demand Distance Vector (CAODV)

In [24], Cacciapuoti et al. introduced the Cognitive Ad-hoc On-demand Distance Vector (CAODV) protocol which is based on modification of existing AODV routing protocol [16]. The proposed protocol was designed in accordance with three principles: 1) avoiding areas of PUs' activity during the process of route establishment and packet discovery; 2) applying a joint path and channel selection to reduce the route cost; 3) providing multi-channel communication to improve the overall performances. The protocol was proposed to support a dynamic CRN with mobile SUs and stationary PUs. The SUs communicate with each other through the primary (licensed) spectrum bands without requiring the dedicated CCC [26]. During data transmission of SUs, if a PU activity is detected, the channel which overlaps the PU's transmission frequency, as well as the adjacent channels, cannot be used by the SUs that are located in the PU transmission range due to interference impacts.

For establishing a route for data delivery, a source node starts the route discovery process by broadcasting a RREQ packet within the network through each channel, which is not interfered to PU activity, and waiting for a reception of a RREP packet from a destination node or an intermediate node that has the valid route information to the destination.

Differently from AODV, a SU is able to store various paths with different available channels, which can be composed by different intermediate nodes. Moreover, in the process of route maintenance, the protocol applied two types of route error (RERR) packet: 1) RERR packet used to deal with changing of network topology; 2) PU-RERR packet used for handling the presence of PU activity. For data delivery process, each data forwarder selects the shortest path in its routing table for forwarding data towards the destination.

2.5.1. Critiques of CAODV

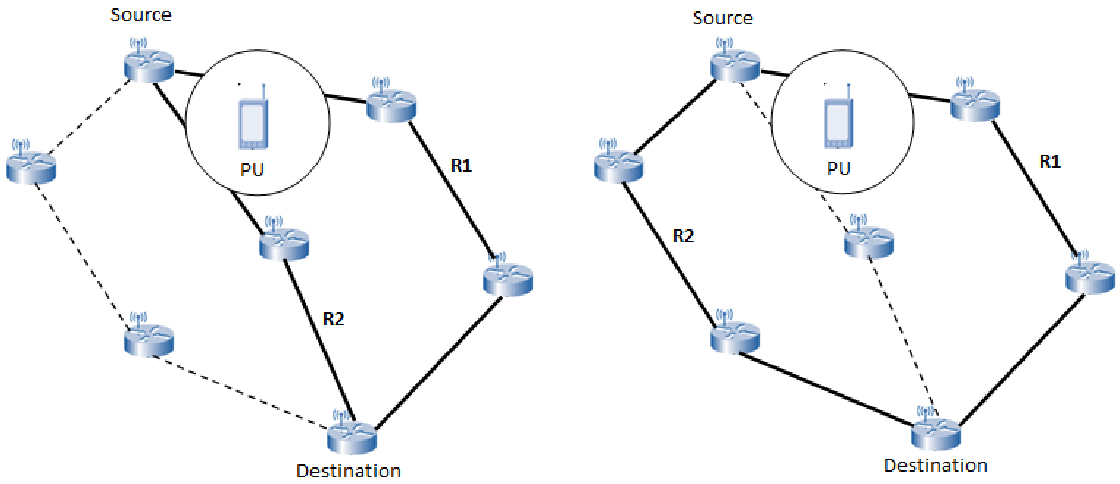
Applying the shortest path scheme for route selection may not provide optimal solutions in CRNs when both the spectrum channel characteristics and the interference impact are taken into account. Furthermore, in route discovery process, flooding the RREQ packet to whole network through all channels without any flooding control method can lead to produce a lot of control overhead and consume huge network resources. Additionally, using common licensed spectrum bands, without utilizing the dedicated CCC, for control message exchange between the SUs may affect the data transmission, interfere the PU activity and decrease the data throughput. Also, the CAODV protocol lacks the effective route recovery algorithm to cope with the route breakage during data transmission; therefore, the network may suffer long service disruption during re-assigning a new path.

2.6. Non-Close Multipath Routing (NCM)

Beltagy et al. [25] addressed the problem of multipath routing in CRNs caused by mobile PUs. The "*Route Closeness*" metric (a new routes selection metric for multipath routing) was proposed where transmission routes were selected based on non-closeness to each other. For the reason behind this routing design, if the distance between selected routes is far enough, an active mobile PU is unable to interrupt all the selected routes in the same time as shown in Figure 3(b). In case the currently used route is failed during data delivery caused by a PU's activity, another candidate route will be utilized instead; typically, the PU is not able to affect both selected routes concurrently. Figure 4 depicts the closeness of two routes which is the area of the hatched regions. The protocol is under the assumption that a PU located in the hatched areas is able to interrupt both routes concurrently (see Figure 4), but, for other location in the network, the PU may interrupt none or at most one of them.

The protocol was designed to suit with multi-hop CRNs with mobile PUs and stationary SUs. Each SU in the network knows all users' location information and the average transmission range of PUs. In addition, the dedicated CCC [26] was used by SUs for sensing spectrum information and reserving the channel before actual data transfer.

The routing protocol with *Route Closeness* metric is an extension of the existing Dynamic Source Routing (DSR) [27] protocol. A source node starts the route discovery process to search for a set of different routes to the destination. It is required to find a set of candidate routes in the network rather than one shortest path between the source and the destination as applied in DSR. Therefore,



(A) Close Routes (B) Non-Close Routes

Figure 3. Close And Non-Close Routes Selection

every duplicate RREQ packet cannot be discarded. For controlling a large number of flooding in the network and high resource consumption, a RREQ packet will be forwarded to all neighboring nodes which have an angle between –90° to 90° with the destination node. Furthermore, the number of times to forward the RREQ packets for each node is limited according to the number of hops from the node to the source. Also, a path which contains first-hop neighbors of a node more than one hop is prevented.

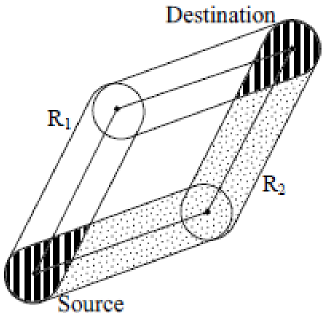


Figure 4. The Closeness Of Two Routes [25]

The data delivery process begins instantaneously, once the first candidate route is known by the source node; other candidate paths may be informed later. The data is transmitted over the selected routes in a round robin fashion [28]. The route failure can be caused by nodes' fault or PUs' activities. When a node detects a failed link, a RERR packet will be sent towards the source node to select a new path for data transmission.

The simulation results showed the effectiveness of *Route Closeness* metric on increasing the end-to-end throughput and reducing the number of routes discoveries up to 48% as compared to other route selection metrics, e.g. the zone-disjoint metric [29], node-disjoint metric [30], and shortest routes metric.

2.6.1. Critiques of NCM

Although the protocol provides more reliable data communication because of multipath routing scheme and awareness of PU activity, the network suffers from flooding of large numbers of routing packets which is subject to more consumption of network resources. Moreover, the protocol does not address the issue of spectrum diversity, which is a main characteristic of CRNs, for providing multi-radio or multi-channel communication and is also unable to be applied in the highly dynamic mobile CRN, i.e. mobile SUs. Finally, the protocol is under assumption that each SU knows the location of all users which may be feasible only in a specific CRN that all SUs are equipped with GPS device.

2.7. IP Spectrum Aware Geographic Routing (IPSAG)

In [31], Badoi et al. proposed the IP Spectrum Aware Geographic based Routing Protocol (IPSAG) for CRNs which applied the concept of the IP hop-by-hop, spectrum aware and geographic based routing algorithm. The IPSAG combines the packet signaling and data forwarding as similar to the IP routing that is applied in a wired network. In the IPSAG protocol, the data packet contains a header field with the information needed for the local decision to select the next hop for packet forwarding. The data packets will be transmitted through available channels that are not occupied by PUs using a hop-by-hop routing decision based on the information of node position, spectrum opportunity and channel quality over a neighborhood, which makes the IPSAG protocol quickly adaptable to the network topology change. The "*greedy forwarding*" approach is used for routing method; the current node will select the next hop that is its neighbor and closest to the destination node as well as fitting the QoS requirements. To obtain the global network topology, the flooding approach as used in OSPF [32] is utilized by applying a CCC for exchanging of the general signaling information (node locations, topology change report, etc.) among CR users.

The CRN in which the IPSAG is applied presents two way of routing (see Figure 5): 1) existing routing protocols used for nodes that operate in the pre-existing wireless systems (WiFi, WiBro, WiMAX, etc.); and 2) IPSAG based routing used for the CR users which operate outside the pre-existing wireless systems. However, a data packet that is forwarded into the pre-existing wireless systems will be routed according to their existing routing protocols based on the tunneling routing scheme.

2.7.1. Critiques of IPSAG

Typically, the IPSAG protocol is suitable for small CRNs where the global geographical topology of the network (node's ID and its location) can be obtained in real-time by each node. However, it may degrade the system performance in a large CRN. Moreover, a lot of control messages, which are generated and exchanged among CR users in order to provide the global and local information required for route selection, may increase network congestion and resource consumption. Additionally, the IP hop-by-hop routing approach, which does not separate the signaling phase and data transmission phase, may provide high average end-to-end delay because every node with a data packet must spend time for a route decision process to select a desired next hop for data forwarding. Furthermore, since an efficient route recovery mechanism is not presented in the IPSAG protocol, a large number of dropped packets may occur in case of route breakage. Lastly, the routing metric should take more consideration on the inference to PU activity in order to reduce the impact on PU network.

2.8. UNITED Node (UNITED)

The distributed and efficient cluster-based routing protocol, called the united node (UNITED), for mobile CR ad hoc networks was proposed by Talay and Altilar [33] with an aim to increase the data throughput and reduce the latency. A set of SUs operate in a distributed manner and are grouped autonomously into a number of clusters, with one individual cluster head (CH), depending on their location, transmission power, spectrum availability and network connectivity. Each SU is permitted to join only one cluster and a cluster's members can be changed dynamically according to the PU activity and node mobility.

In addition, the data routing is functioned, after the establishment of those clusters, by taking into account for both the interference and spectrum availability cost for selecting better routes. The interference metric is defined by considering the impacts of differences in link loss ratio, link transmission rate, as well as intra-system and inter-system interferences in order to avoid congested region and loss links. As for the spectrum availability cost, it is computed based on spectrum usage history. When a source node needs to create a path to transmit data towards a destination node, the source broadcasts a RREQ packet and eventually receives a RREP packet including the spectrum and route information from the destination node in return. For data forwarding strategy, the source node can transmit data packets directly to the destination node which is located in the same cluster by utilizing its routing table for intra-cluster routing. In case the destination node is placed in another cluster, the source node firstly forwards the data to its cluster head through the default route. Then, the data packet will be transferred to the cluster head of the destined cluster and finally the packet is transmitted to the destination node.

The route maintenance scheme is operated in situation that a node on transmission path finds a failure on the next hop during data delivery. The node may skip the failed node and continuously forward the data to the next hop of the failed node, if it is reachable, or, otherwise, select another reachable node(s) which is reachable by the previous node and the failed node's next hop as well as being out of the region of PU activity for data forwarding.

2.8.1. Critiques of UNITED

In case that the source and the destination node are located near to each other but in different cluster, the protocol may provide non-optimal or

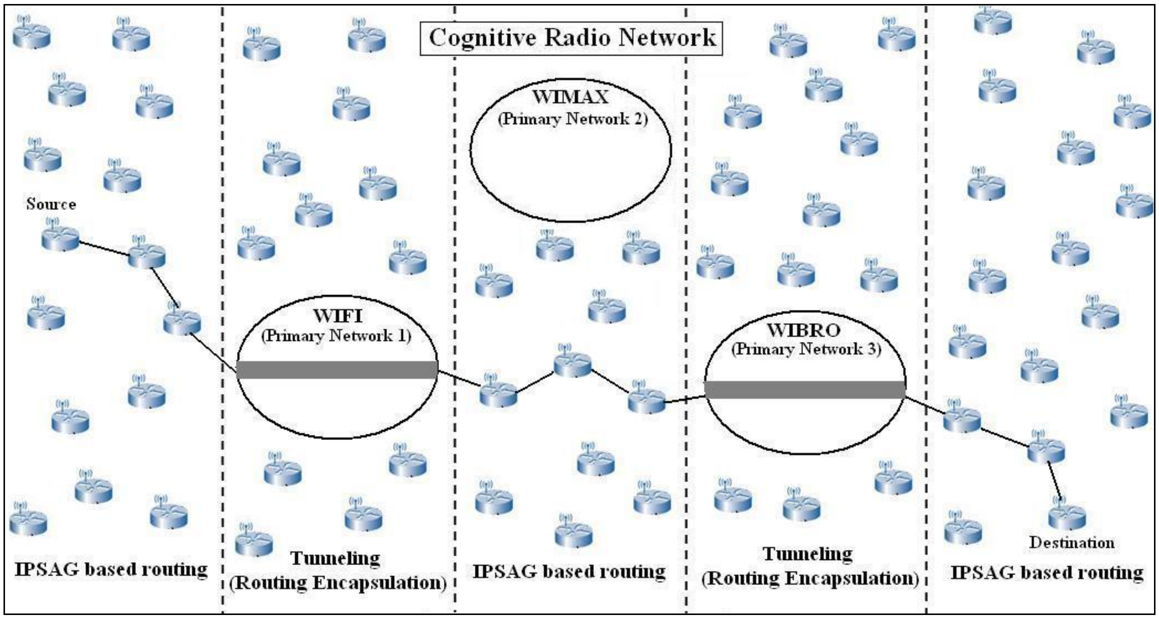


Figure 5. CR Routing Network Model

longer path because the data will be forwarded to the cluster head of both clusters before reaching the destination node. Furthermore, both global and local synchronization must be required for inter-cluster communication which leads to high routing complexity. Moreover, for the construction and maintenance of a cluster structure, numerous overhead of cluster formation and update may be generated throughout the network. As the network topology changes quickly in a dynamically mobile CRN, the number of control packet exchange may grow to reach a critical point which consumes a lot of network energy and bandwidths. For the cluster-based routing protocol, some SUs, especially cluster heads, may consume more power when compared to ordinary nodes since they are responsible to manage and forward packets for intra- and inter-cluster communication. As a result, it may cause the untimely shutdown to those nodes.

2.9. Spectrum And Energy Aware Routing (SER)

Kamruzzaman et al. [34] presented the on-demand Spectrum and Energy aware Routing (SER) protocol to support the energy-constraint multi-hop CR ad hoc networks, where each SU has limited energy supply, with an objective to give high throughput and robust routing as well as prolong the network lifetime.

The protocol provides the channel access scheduling in order to eliminate the contention of packet transmission between users. Moreover, by improving the network throughput, the protocol balances the network load by dividing the data traffic over different channels and timeslots according to the channel-timeslot assignment, i.e. channels and timeslots are assigned for a connection request during the route discovery process.

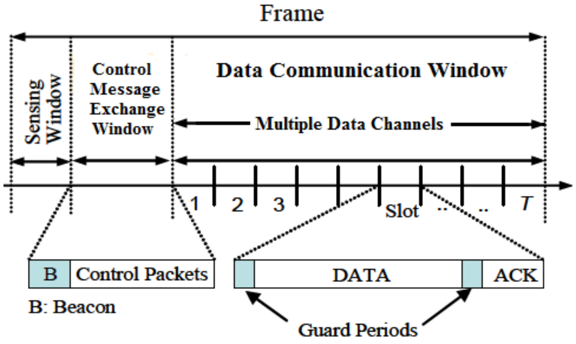


Figure 6. Frame Structure

The system time is decomposed into a number of fixed-length frames. Each frame is composed of a sensing, control message exchange, and data communication window as depicted in Figure 6. The channel sensing is performed in the beginning of each frame (sensing window) to find available spectrum channels that are not occupied by PU. A CCC is utilized during the period of control message exchange window. The data communication window is divided into timeslots, each of which includes the time required for a single data packet transmission, channel switching, and acknowledgement (ACK). The SUs, which are synchronized by periodic beaconing, will send or receive a data packet in a specific timeslot on a specific vacant channel or, otherwise, switch to the sleep mode for power saving.

In the process of route discovery, when a source node requires a route to send data packets to a destination node, a RREQ packet is flooded in the network, as based on DSR protocol [27], over the CCC. Once an intermediate node receives a RREQ, the channel-timeslot assignment process is triggered in order to find out good feasible channel-timeslot pair for the link on which the RREQ is received. After the first RREQ arrives at the destination node, before replying with a RREP packet to the source node through the CCC, the destination node sets up a timer to collect multiple RREQs for route selection process. The route utility is calculated using equation (2) and the selected route is defined using equation (3).

$$U_k = \frac{mE_{res,\,k}}{HC_k}, \qquad \forall k; \tag{2}$$

$$P = \max\{U_k\}, \qquad \forall k; \tag{3}$$

where U_k is the route utility of path k ($k = 1, 2, \ldots, K$). The $mE_{res,k}$ is minimum residual nodal energy of a path k. The HC_k is hop-count of a path k. A path with the maximum value of P which has maximal nodal residual energy and lower hop-count is selected for data transmission. While the RREP is forwarded back towards the source node, the communication segment (channel-timeslot pair) selected for each link along the reverse path is reserved for data delivery. Finally, the source node starts transmitting the data after receiving the RREP.

2.9.1. Critiques of SER

The channel-timeslot assignment used in the SER protocol may provide the underutilization of spectrum resources, when a SU transmits a lot of data packets during assigned timeslots through the same channel. As a result, the large period of time allocated for channel switching in the timeslots will not be utilized. Furthermore, with the lack of control on the number of channel switching over the link, the protocol may assign a different channel to each different timeslot for data transmission which produces high channel switching cost, i.e. large energy consumption and delay. Moreover, without consideration of the PU region avoidance during path establishment process, the protocol may create a transmission path across the region of PU activity which leads to frequent route breakage causing large numbers of dropped packets. In addition, by the absence of efficient route recovery mechanism and mobility support algorithm, the protocol may be not suitable for highly mobile CRNs that provide high link failure rate due to node mobility. Finally, further performance evaluation is still required due to the lack of comparing the results with that of other routing protocols.

2.10. Multi-Objective Reinforcement Learning Based Routing (MORL)

In [35], Zheng et al. proposed the Multi-Objective Reinforcement Learning based routing (MORL) protocol for CRNs. The reinforcement learning [14], which is learning what to do (how to map states to actions), is applied in the protocol to address the issue of uncertainty on spectrum availability in dynamic CRNs. As compared with walking in a random maze in which the walls appear and disappear randomly, the way of walking out of the random maze is similar to the routing in dynamic CRNs where the spectrum occupancy varies over time and space. In addition, the principle of multi-objective learning [36] is also utilized to address the challenge of multiple performance metrics. The network performance was evaluated using two performance metrics, i.e. transmission delay and packet loss rate.

The MORL protocol was designed with an aim to minimize the transmission delay under the desired constraint of packet loss rate. In MORL, the Q-learning [37] is applied to find a route with minimized transmission delay. Two Q-tables, which store the accumulated reward related to the state and the corresponding action, are utilized in the protocol. The first and second Q-table uses the one-hop transmission delay and the accumulated packet loss rate, respectively, as the intermediate reward.

For the procedure of MORL-based routing, a next hop will be selected by considering the information in the local Q-table. A route which has minimum value of the Q-table for transmission delay while maintains the corresponding value of Q-table for packet loss rate under the desired constraint will be established for data forwarding. In case that the currently used spectrum channel is occupied by PU, another channel will be randomly selected instead. The information in the Q-table will be updated after receiving ACK packet from the next hop.

2.10.1. Critiques of MORL

Since the information of destination location is not considered in the next hop selection process, the protocol may build a very long transmission path or, in the worst case, create a routing loop problem i.e. the data packets continue to be routed within the network in an endless circle (not reaching the destination), resulting a large network latency. Moreover, the efficient route recovery mechanism is not proposed in the protocol design which may lead to a large number of dropped packets in case of route breakage during data delivery, especially in a highly mobile CRNs in which the probability of route failures is high. Besides, in situation when the PUs are quite inactive (the PU activity has nearly insignificant effect on the data transmission), the protocol may produce a larger transmission delay as compared to that of the shortest path routing approach caused by the learning process which usually takes tens of trials before the optimal route is found. Lastly, in order to minimize the impact from the PU activity, the protocol usually forms a path with more hop-counts which may increase the packet loss rate.

2.11. Bio-Inspired Stable Routing (BioStaR)

Hoque and Hong [38] introduced a routing technique for CRNs derived from biological systems named the Bio-inspired Stable Routing (BioStaR) protocol which was motivated by the adaptive “*Attractor Selection*” model [39] originated from E. coli bacteria with an objective to minimize the channel switching delay and control overhead as well as increase the route stability by maximizing the spectrum opportunity (SOP). In the network, each node is equipped with GPS (Global Positioning System) device to obtain the geographical location information of other nodes. The *routing metric*, ρ, was defined using equation (4), by considering four criteria: 1) channel switching; 2) hop-count; 3) SOP; and 4) destination location (D), to select the best attractor (next hop) from all the neighboring nodes for data forwarding.

$$\rho = \max_{0 \le i \le n} f\left(Channel\ Switching,\ SOP,\ Hop,\ D\right)$$

$$\rho = \max_{0 \le i \le n} \left(\frac{1}{2^x}\right)^{\alpha} \times \left(\frac{c_i}{c_{\max}}\right)^{\alpha} \times \left(\frac{h}{l_i}\right)^{\beta} \times \left(\frac{d}{d_i}\right) \quad (4)$$

where c_i is the number of common channels with neighbor i and c_{max} is the maximum number of available channels. h is the current hop-count and l_i is the shortest path length from neighbor i. The d is geographical distance from current node to the destination and d_i is the geographical distance from neighbor i to the destination. n is the total number of neighbors for the current node. If the channel switching is required, the value of x is equal to 1; otherwise, it is equal to 0. The α and β are weight factors. The BioStaR protocol prefers to choose a longer sub-optimal path which provides high spectrum opportunity and less vulnerability to the interference impact of PUs rather than a short term more vulnerable optimized path. Moreover, it attempts to avoid paths with frequent channel switching as well as always selecting the attractors that are closer to the destination node for the next hop.

The BioStaR protocol is based on a reactive routing approach which operates in a distributed manner. In the route establishment process, a source node only sends a RREQ packet to an attractor (one of its neighboring nodes), calculated by the routing metric, instead of broadcasting it to all neighbors. Then, the RREQ is forwarded to the next attractor until it reaches the destination. Afterwards, a RREP packet generated by the destination node is sent back to the source node in return. In case that the RREQ cannot reach the attractor or the path along the attractors does not lead to the destination, the RREQ will be forwarded to a randomly selected neighbor instead. For the route recovery mechanism, in case the transmission path is interrupted by PU activity, the effected intermediate nodes may switch its currently used spectrum channel to a non-interfering channel for keeping seamless communication without making a detour path.

2.11.1. Critiques of BioStaR

The BioStaR protocol may be suitable for only a specific CRN where all nodes are GPS enabled. Moreover, in the network where PU activity is rarely active, the transmission route established by the protocol may be inefficient since the longer (sub-optimal) path is always provided, which leads to large network latency. Furthermore, the issue of node mobility is still not taken into account in the protocol design. Therefore, the protocol may give low network performance in a highly dynamic mobile CRN. In addition, the routing metric should also consider more factors including the link quality, such as link bandwidth, link loss ratio, etc., to provide more routing efficiency for real CRNs that express the heterogeneous channel properties.

Table 1. Comparative summary of the surveyed routing protocols for CRNs

Routing Protocols	Re/Pro-active Routing	PU Activity Aware	Multi-Channel Routing	Multipath	Reinforcement Learning Based	Location Based	Cluster Based	SUs Mobility Support	PUs Mobility Support	Dedicated CCC	Routing Metric	Route Recovery Method
STOD-RP [15]	Hybrid	-	✓	-	-	-	✓	✓	-	-	Resource Usage and Route Stability	Spectrum Handoff
SEARCH [19]	Re-active	✓	✓	-	-	✓	-	✓	-	-	Shortest Path	Find New Route
ASAR [21]	Re-active	-	✓	-	✓	-	-	-	-	✓	SOP and Hop-count	Find New Route
RLR [23]	Hybrid	-	✓	-	-	-	-	-	-	✓	Reliable Link	Find New Route
CAODV [24]	Re-active	✓	✓	-	-	-	-	✓	-	-	Shortest Path	Find New Route
NCM [25]	Re-active	✓	-	✓	-	✓	-	-	✓	✓	Non-Close Route	Select Another Non-Close Route
IPSAG [31]	Re-active	-	✓	-	-	✓	-	✓	-	✓	Spectrum Availability, Channel Quality and Destination Location	Find New Route
UNITED [33]	Hybrid	-	✓	-	-	-	✓	✓	-	-	Interference and Spectrum Availability	Use Local Detour Route
SER [34]	Re-active	-	✓	-	-	-	-	-	-	✓	Residual Nodal Energy and Hop-count	Find New Route
MORL [35]	Re-active	-	✓	-	✓	-	-	-	-	-	Average Delay and Packet Loss Rate	Find New Route
BioStaR [38]	Re-active	-	✓	-	-	✓	-	-	-	-	Channel Switching, SOP, Hop Count and Destination Location	Spectrum Handoff

3. CONCLUSION AND OPEN ISSUES

Routing in CRNs has attracted a lot of attention in the recent years and introduced unique challenges compared to traditional data routing in wireless networks. In this paper, we have presented the routing design challenges and introduced the categories of routing protocols for CRNs. Moreover, we have analyzed and summarized the recent routing techniques for CRNs as well as providing their performance critiques. Table 1 gives a comparative summary of the surveyed routing schemes.

It is a well-known fact that CRNs suffer from various issues including dynamic spectrum availability, different spectrum characteristics, interference impact, high failure rate and more energy consumption. Therefore there is absolutely need of a routing protocol that is able to not only offer a better route selection but also address the routing related problems on CRNs.

The interesting open issue for routing protocols is the consideration of network security because the intrinsic nature of CRNs makes the security vulnerability. The available spectrum channels may be jammed and overused by a malicious attacker. Moreover, the spectrum sensing result may be modified spitefully by an adversary. These will obviously interrupt the data transmission and affect the quality of service.

Other interesting future research for routing protocols in CRNs includes cross-layer routing design. By improving the efficiency of routing scheme, the cross-layer design may be required by utilizing the collaboration between routing and spectrum management in order to efficiently adapt to changes in radio interference, link quality, node density or network topology.

In addition, due to the unique characteristics of CRNs including the dynamically topology changing and spectrum availability varying networks, the designs of efficient route recovery mechanism and routing metric still require more study. The routing protocol may apply the efficient local repair or backup route approach to reduce a number of dropped packets during path failure. Besides, many factors such as probability of route failure, signal strength, interference from other sources, signal fading, etc. can be taken into account for the design of optimal route selection.

We strongly believe that analyzing and criticizing the current routing techniques and their performance can expose new open issues and also be used to either enhance the existing routing schemes or to develop new routing solutions. However, some of the surveyed routing techniques lack with practical implementation. Therefore, their further performance evaluation on the practical experiment is greatly required as well.

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