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Routing in Cognitive Radio Networks - A Survey

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ABSTRACT
Cognitive Radio Networks (CRNs) have been emerged as a revolutionary solution to migrate the spectrum scarcity problem in wireless networks. Due to increasing demand for additional spectrum resources, CRNs have been receiving significant research to solve issues related with spectrum underutilization. This technology brings efficient spectrum usage and effective interference avoidance, and also brings new challenges to routing in multi-hop Cognitive Radio Networks. In CRN, unlicensed users or secondary users are able to use underutilized licensed channels, but they have to leave the channel if any interference is caused to the primary or licensed users. So CR technology allows sharing of licensed spectrum band in opportunistic and non-interfering manner. Different routing protocols have been proposed recently based on different design goals under different assumptions.

Keywords-About five key words in alphabetical order, separated by comma

I. Introduction

The continuously growing number of wireless devices has resulted in growing congestion in crowded ISM bands. Current wireless networks are regulated by governmental agencies mainly according to the fixed spectrum assignment. Licenses are granted the rights for the use of various frequency bands on a long term basis over vast geographical areas. Due to the use of wireless technologies operating in unlicensed bands, especially in ISM band with the development of various applications in different fields (e.g., sensor networks, mesh networks, WLANs, personal area networks, body area networks etc.) causes the overcrowding in this band. On the other hand, the licensed band is used very uneven and depends on the specific wireless technologies, their market penetration, and the commercial success of the operators to which the frequencies have been assigned. According to studies sponsored by the Federal Communications Commission (FCC) of America, many allocated spectrum blocks are used only for a brief periods of time over a particular geographical area [10].The utilization of assigned spectrum varies from 15% to 85%. So to address this problem, cognitive radio (CR) is a promising technology to solve the spectrum scarcity problem [11].Cognitive radio technology offer the solution as a disruptive technology innovation that will enable the future wireless world .By efficiently utilizing the unused available spectrum, CR technology improves the spectrum efficiency.

To address this problem, the notion of Dynamic Spectrum Access (DSA) has been used. In DSA, the unlicensed users may use licensed spectrum bands opportunistically in a dynamic manner. In CRNs, SUs are allowed to opportunistically access any idle frequency that is originally allocated to the Primary (licensed) users (PUs) but currently not occupied. The spare frequency bands are called spectrum holes, which can be used by SUs under certain usage constraints of preventing interference to primary users(fig.1). There are several channels in every spectrum hole. Different from multi-channel multi-radio networks [5][6],cognitive radio networks operate over wide spectrum with unpredictable channel availability. They can tuned to any frequency to any frequency band in that range with limited delay[2][3].Cognitive radio transceivers have the capability of changing their transmitter parameters(operating spectrum, modulation, transmission power and communication technology) based on interactions with the surrounding spectral environment. A cognitive radio has no prior knowledge about the frequency channels to be used due to spectrum dynamics. They can sense and after sensing, channels that can be used for the communication are assigned through spectrum management without causing any interference or link quality degradation to primary users. The transmission of secondary users can be interrupted if the primary user interrupted on the burrowed channel. So cognitive nodes have to vacate channel and switch to other available channel. So routing in CRNs has to address many challenges such as availability of different channels and radios on the same node and synchronization between different nodes on same channel.

Recently various routing protocols have been proposed (e.g.,12,13,14,15,16,17,18,19,20,21,22,23, 24,25). Besides the main goal of protecting PU transmissions, each protocol is designed with different goals and based on different routing metric e.g. maximizing available bandwidth, minimizing end to end delay, minimizing interference, minimizing hop count, maximizing spectral opportunities etc. The performance of the protocol can be measured with respect to its specific design goal and by using different assumptions and scenarios. To improve the performance of routing in multi-hop CRN, a novel routing metric is essential to minimize the impact of spectrum takeover by PUs.

In this paper, we conduct the extensive study of routing schema used in multi-hop CRNs. The contribution of the paper is divided as follows. Section II discuss the routing scheme and defines the different routing metrics. To better characterize the unique features of cognitive radio networks, we discuss different routing metrics used for designing the routing protocols, basically divided as node based, channel based and other metrics. Node based metrics include the metrics calculated including the node's features e.g. mobility, node energy etc. Channel based metrics include the metrics calculated as a result of channel characteristics like channel flow, link cost, throughput etc. Other metrics are end to end delay, probabilistic functions. Also it presents the routing procedures and protocols proposed which can find the optimal path efficiently employing the proposed routing metrics. Section III discusses the issues and designs related to route recovery and maintenance procedures. The purpose of this work is two-fold: first we aim at discussing the different routing metrics, clearly highlighting the design rationale. Section IV summarizes the different routing metrics used by different routing protocols. Different routing protocols proposed using these metrics are elaborated.

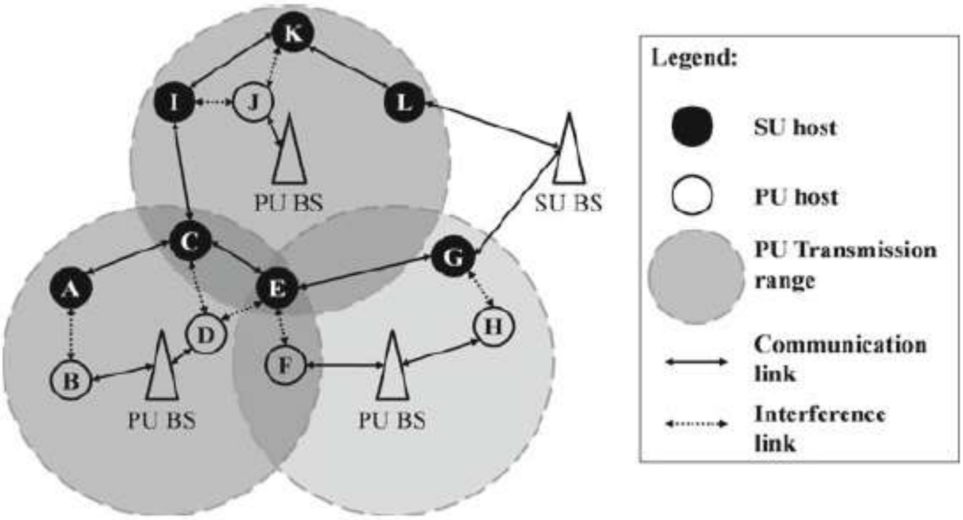

Figure 1: CRN scenario

II. Routing Schema in Cognitive radio Networks

Routing in CRNs is a joint decision of channel selection and next hop node decision. Many research work have been already made regarding the routing issues and protocols in CRNs [4][7] based on spectrum sensing, spectrum decision and spectrum sharing. This section discusses the various steps of routing performed in CRN. Fig. 2 shows the taxonomy of the schema. We broadly categorize the proposed routing procedures into three main classes depending on the steps performed namely metric computation and sensing, routing procedure and route recovery and maintenance. We assign each step as a label, for instance, the step metric computation and sensing is assigned a label 1.

2.1. Metric Computation and Sensing

Traditional routing metrics (designed for both wired and wireless environments) for link state or distance vector are not well suited to be applied to CRNs. The main reason is that there are frequent dynamic changes in the CRN that may trigger a large number of updates and lead to rapidly changing routing tables. One of the main tasks of the cognitive radio is to sense and determine whether a channel is available or not. Each node senses spectrum, divide the available band into channels, saves the list of available channels and then chooses the channel according to the priority depend upon the suitability according to the link metrics and The dynamic behavior of CRN inherits many characteristics of wireless mobile networks like: nodes mobility, nodes limited power and network life time along with some of the constraints like interference, signal fading, channel scarcity, conflict with licensed users. So a number of routing metrics are proposed in different routing protocols.

In the routing protocol STOP-RP [8], the author involves all parameters that must be taken care for cognitive environment. Route quality and spectrum availability must be reflected in metric used for multi-hop CRNs [8].

A good routing metric for CRNs has to assign different weights to different channel based on different factors and their probability that the transmission will be interrupted by any PU activity or SUs conflict. So it can estimate the future activity and hence efficient routes can be find by minimizing the interruption time and maintenance cost. Different routing metrics are categorized as in fig. 3.

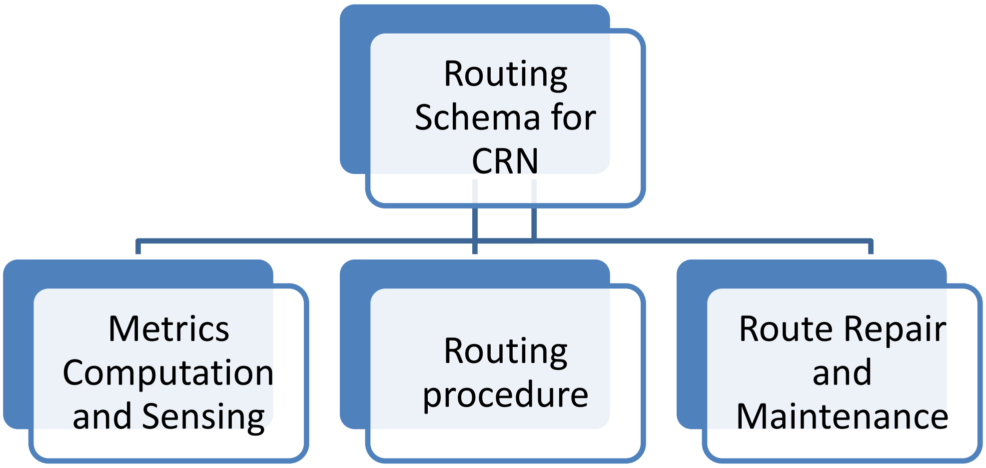

Figure 2: Routing Scheme for CRN

Metric Definition: A routing metric is a function that assigns a weight (or cost) to any given path [31]. Optimal path between source and destination in a connected network can be finding by considering these metrics.

Metric: The routing metrics for cognitive radio networks can be classified into three categories: a) *Channel based b) node based c) other metrics*

2.1.1 Routing metrics for CRN

In this section, we present an overview of the different routing metrics that are faced by CRNs and targets the creation of routes for multi-hop CRNs. Figure 3 summarizes the different routing metrics.

2.1.1.1. Channel Based

This section presents three types of Channel based metrics:

1. Channel Stability

In CRN, channel stability or link stability is the probability that the link will not experience any breakdown due to variation of channel and nodes could communicate with each other. It describes the function of the route maintenance cost. The paper [39] proposes a metric that combines link stability with the switching delays. The paper [40] introduces a CR metric describing the route stability. In [43], the author proposes a CR metric based on path stability and availability over time. The STOP-RD protocol uses a routing metric that combines route stability and end to end delay. It uses a metric for stability in terms of link's available time. As in [59], the author explained that how the spectrum dynamicity affects the channel availability. If they have very low dynamicity, it remains usable to SUs for many hours to days. Moreover in the coolest path protocol [9], total path cost is calculated which include the maximum stability cost over the Path links or a mixed cost between the maximum and

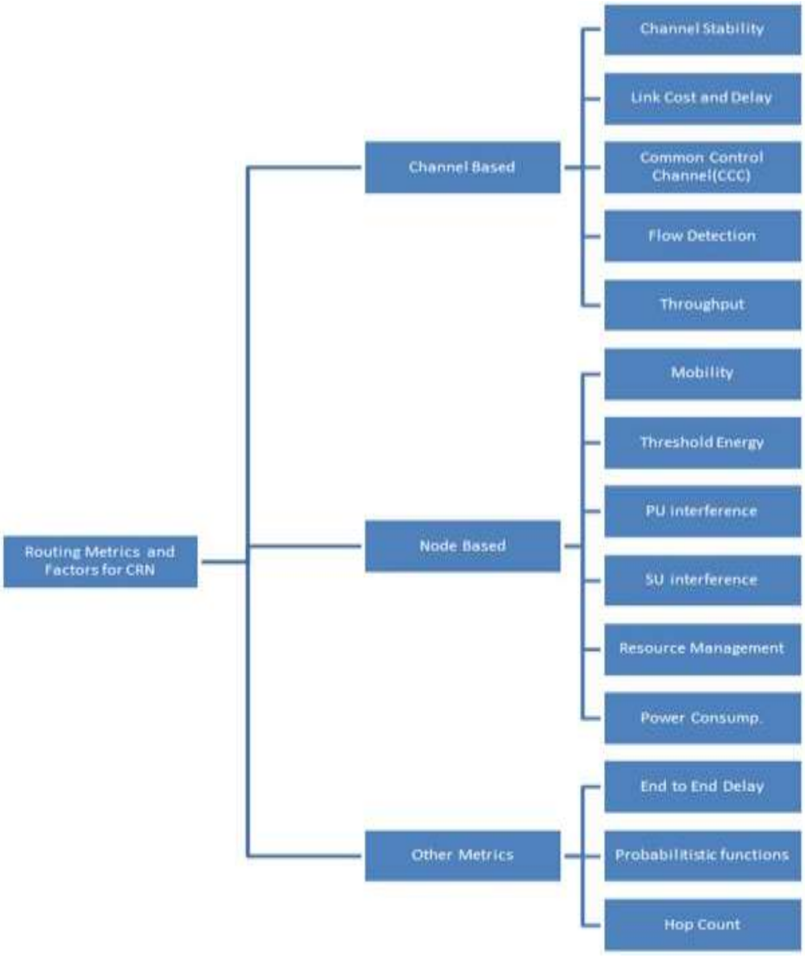

Figure 3:Routing metrics for CRN

accumulated cost along the path. Also it shows that the accumulated cost achieves better performance in terms of path switching ration and path longevity in case of frequent PU activities. The work of [26] defines thelink cost metric as a function of both the link holding time and communication capacity and reflects the usage pattern of primary user. The work in [27] defines a new route stability metric that reflects the cost that will be paid if the route needs to be changed. In [64], link cost is calculated based on route stability based metric. Also link cost is calculated first and then get the cumulative routing cost [8] as (1):

$$C_i = \left[O_{ca} + O_p + \frac{P_{kt}}{r_i}\right]\frac{1}{1-e_{pti}} \cdot \frac{1}{T_{li}} \quad (1)$$

Where T_{li} is the time duration during which a spectrum band is available to the link $l_{i.}$

Cost of an end to end route can be calculated as (2):

$$C = \sum_{i=1}^{k} C_i + M.D_{switc\,h}(2)$$

Where k is the link number, M is the number of spectrum band switches along the route and D_{switch} is the switch delay caused by a CR user switches between two different bands.

2. Link Cost and Delay

Mainly a SU node incurs two types of delays namely, a switch delay when it chooses to switch the channel and back off delay when it waits for the PU to release the channel if it chooses to remain in the same channel. The paper[32] describes the routing metric in which the author perform the asymptotic analysis of the delay for CRNs by taking into account the shortest path routing along with multipath routing and network coding techniques. On the other hand, sometimes channel switches along with load balancing may help to minimize the channel contention among SUs and hence lead to switch delays minimization [14, 33].

In [42],the Opportunistic Link Transmission (OLT) metric is proposed which captures three types of delay as OLT = $d_{tx} + d_q + d_{access}$ where d_{tx} is link transmission delay, d_q is packet queuing delay at a particular node and d_{access} is link access delay. Delayis used to select the main route, which is the main route whose RREQ packet arrives first in [45,46,47]

3. Common Control channel

In CRNs, there are mainly two types of channels: common control channel (CCC) and data channel.

The SUs exchange control information like packets such as, Route Request (RREQ) and Route Reply (RREP) through CCC and send data through data channels. As CRN works in the dynamic environment, the availability of a static CCC is not possible as SU have to vacate the channel once PU appears. The papers [34,35,36,37]have adopted the assumption of the availability of the static CCC, which is not practical. Also actual route characteristics are not defined by the use of CCC [22].So as a result, it is necessary to design routing schemes and protocols without depending on the CCC for feasibility of the implementation. To solve the deafness problem, the solution is to use a common control channel (CCC) shared between all nodes[48,49,50,51] for route initialization and maintenance data.

4. Flow Detection

As explained in [20] there are mainly two types of flow interferences along a route namely *intra-flow* and *inter-flow* interferences. Intra –flow interference occurs when the links belong to same data flow and inter-flow interference occurs when the links belongs to different data flows. The interferences can lead to degradation of end to end performance. So flow detection along with channel selection should be taken into account while finding quality based routes.

5. Throughput

Dynamic spectrum networks enable fast deployment of new wireless technologies. There are many approaches which attained end to end utilization with maximum throughput. SPEAR[30],a high throughput multi-hop routing protocol in dynamic environment, integrate spectrum discovery with channel assignment by exploiting local spectrum heterogeneity The paper [41] explains a routing metric and a routing protocol to achieve higher throughput efficiency, by allowing the CR users to opportunistically transmit according to the spectrum utility.

SAMER [13] tries to find a high throughput path by opportunistically utilizing high throughput links and guaranteed a path’s long term stability. Both PU and SU are considered by SAMER to quantify channel availability. Each SU estimates the period of time during which a channel is not used by U or SU and can be used. So two neighboring nodes can estimate different channel availabilities, the channel availability for a particular link will be the smaller of the two values. SAMER calculates the link matric which is based on ETT [38], where ETT is one of the popular routing metrics for traditional wireless mesh networks. SAMER calculates the throughput based metric for each link as a product of channel availability, link bandwidth and loss rate.

In MRSA [28], final path is selected based on available route bandwidth capacity metric. The path with maximum bandwidth capacity is selected. A similar approach is followed in SPEctrum Aware Routing protocol (SPEAR) [30].

2.1.1.2. Node Based

1. Mobility

In multi-hop CRNs, each node is equipped with a single cognitive transceiver with capabilities of spectrum awareness and configurability. Mobility is defined as the movement of the cognitive node over the spectrum. The channel availability for data transmission is dynamic in cognitive radio networks which vary over time and space. As explained in [25], there are more channel switches if the SU movement increases and PUs are static. So to smoothly perform the routing, the routing schemes and algorithms should be aware of the mobility of the nodes. Also energy efficiency of the nodes plays an important factor as nodes have to monitor the spectrum which consumes energy. Implementing DSA techniques is very challenging due to high fluctuation in channel availability as changes appear due to primary user’s activity and node mobility[51].As shown in [27], the energy consumption increases as a result of rerouting due to unpredictable movement of nodes. The channel access time decreases as mobility increases, which lead to increase in number of channel switches. It proposes a tree based algorithm along with channel selection algorithm. The routing tree is maintained by a static metric which calculates and assigns the priorities based on the number of SUs already assigned these channels.

To smoothly perform routing, the interrupted node should promptly find an available channel to continue its transmission to its next hop. If there is no free channel, then path repair or rerouting happens.

2. Threshold Energy

When considering a network with mobile node deployment, energy conservation is inevitable since mobile nodes are often battery powered. In AODV based routing protocols, flooding of RREQ control messages cause energy consumption. The nodes have to forward the request packets even though they may not be chosen as part of the route later.[72]discuss the different challenges of routing phases in which the energy consumption factor plays an important part. In protocols based on Global Positioning System (GPS) [44], in which GPS is embedded at each node, route is selected based on physical location of SU. So it contributes in reducing the node’s energy consumption by controlling the flooding of the routing control packets. In NDM protocol [56], routes are selected for secondary users based on the remaining energy at each node along the route. Total remaining energy is calculated at all nodes and then path is selected with maximum total remaining energy.

3. PU Interference

There is a complex relation between PUs and SUs systems. In dynamic environment, interference is generated along a multi-hop path through secondary users. The SUs have to leave the channel when PU appears. So, optimal channel assignment along with spectrum awareness should be taken into account to minimize the interference. Random PU activities cause diversity in PU behavior. Many clustering mechanisms have been shown to reduce the routing overhead as A SU member can associate to new SU cluster head in case of interference. The interference from primary users can easily be detected by SUs with passive sensing techniques. Routing in CRNs is classified on the basis of contextual information used for taking the route decisions which include the primary user activity and repair management [63].

4. SU Interference

As node interference can be divided into two parts: inter routing and intra routing. In intra routing investigations, assumptions are adopted for routing schemes which can provide best end to end network performance. The paper [27] improves the performance of CR-CR interference channels and investigates how to coordinate multiple nodes using different interference management techniques. It also takes into account the SU interference. The paper [68] describes a routing metric that minimizes the SU interference to the PUs.

5. Resource Management

For decades, research has been done to maximize the use of wireless resources in cognitive environment. A cognitive network has a promise of providing flexible and intelligent environment which can improve resource management and network performance. [60] proposes a cognitive resource management technique that can allocate by learning and adapting to specific radio transmission environment. The mechanism applies the cross layer approach and intelligently allocates resources according to traffic demands, traffic priorities, link capabilities, and link qualities.

6. Power Consumption

Some routing protocols are based on consumed power to perform transmissions among nodes. In CRNs, SUs have to continuously sense the presence of PUs. So it is a challenging issue during dealing with mobile devices as they have limited battery. This applies in CRNs as well as in traditional ad-hoc networks.

In [68],a dedicated interface called common link control radio(CLCR) is used to sustain cognitive radio related functions. The paper assumes a free space propagation model for the transmission power of nodes which increases with the distance. A power aware routing protocol [21] is proposed which is based on routing metric based on battery power consumption. In minimum weight routing protocol (MWRP)[48],the link weights are defined as the transmission power required to reach the receiver over a certain interface based on a free space propagation model.

2.1.1.3. Other Metrics

1. End to End Delay

As with less hop distance in which nodes have long transmission range, can lead to more SU interference and performance decreases due to more link failures. So hop count along with spectrum awareness is necessary to improve end to end delay. During transmission, channel unavailability at a single node leads to link breakage is a serious issue to be solved when end to end delay is considered. There are many well defined procedures proposed to avoid rerouting which is very costly as it increases end to end delay. Channels available at different nodes are of different bandwidth, propagation characteristics and available for unequal times due to channel heterogeneity. [63]. A cross layer framework is proposed for spectrum assignment and routing [64]. Backup channel mechanism enables cooperative channel switching which proves to be an efficient solution for minimizing the end to end delay and the problems created due to channel heterogeneity [69].Neighboring nodes can switch to a single channel in a cooperative manner. This enables a transmitting node to find the same set of neighbors on a different channel with the condition that the neighbors can also tune to the same secondary channel.

CRP [68] aims to minimize the end to end delay without any interference to PUs and also allows a level of performance degradation and provides PU protection by selecting relay nodes. It calculates the rebroadcast delay by calculating the cost function based on local information. CRP is based on the cost delay mapping and can be easily implemented via minor modifications. In [67], effective transmission time (ETT) is used. The metric captures the transmission delays on a link by taking the expected number of retransmissions into account. The work in [65, 66] combines delay based on channel switching time and multi-flow interference. The DORP protocol [14, 70] includes the queuing delays. In SEARCH [22], the selected path is one which minimizes the end to end delay. The greedy location based metric which includes the cost of the channel switching time between paths on different channels along with the path delay on each channel.

The packet transmission delay of the flow via a node to the destination is reflected by the path cost metric proposed in Urban-X[29].The work in [71] gives a statistical model for end to end delay by considering the impact of interference and dynamic spectrum access, including spectrum access and retransmission delay.

2. Probabilistic Functions

With reference to the metrics belonging to the third class [1], the works propose to measure the quality of route in terms of different probabilistic functions. The expressions of the metrics account for different metrics components like Link availability probability block probability, Conditional block probability, Expected link utilization, Expected link interference for mobile networks. However, some are described for static networks also.

In coolest path[62],for a SU link, a channel's temperature is defined as the fraction of time during which the channel is not available due to PU activity in the neighborhood of any of the two SUs. Also Coolest path is defined which provides three definitions of the path temperature based on link temperature:(i)*accumulated temperature*, sum of the link temperatures of the path, (ii) *highest temperature,* the maximum link temperature of the links

In [61], the authors propose a probabilistic metric that calculates the probability of PU interference at a given SU for a given channel. The metric can determine the most probable path which satisfy a given bandwidth demand D in which N nodes that operate on a maximum of M orthogonal frequency bands.

3. Hop Count

Hop count is used as the main routing metric which is used to select among the candidate paths. It is a indicator of faster transmission delay as it consume less networking resources because it passes through lower number of nodes. For example SAMER[13] takes a two tier routing approach which balances between short term opportunistic gain(hop count) and long term optimality(higher spectrum availability).In SEARCH[22]hop count is a filtering metric. It compares the hop count used in the original route formation to the number of hops used in the current path which differs as due to route maintenance based on PU's activity, periodically. If the difference is above threshold, there is a need of new route formation.

The work in Multipath Routing and Spectrum Access (MRSA)[28] uses hop count as a tie broker. The new route is preferred only if it has low hop count and final route is selected based on available route bandwidth capacity metric. The work in Urban-X [29] avoids routing loops so the routes are limited to have maximum number of hopes. SPEAR [30] also uses hop count metric as a tie broker. The hop count in [45, 46, 47] is used as a filter for selecting secondary users.

III. Route Procedure and Recovery

3.1. Route procedure

Most of the work on routing in cognitive radio networks has been done on techniques and channel assignments for distance minimization [8, 54, 55, 57, 60, 58, 64], while a link state protocol is required to select the best possible channels at each nodes and best route as well [52].Spectrum decision and routing are based on local coordination, so on demand routing and spectrum assignment scheme is used for exchanging local information between the cognitive nodes and multi-frequency scheduling. CAODV [52] is a modified version of AODV, forwards packet without requiring a dedicated control channel and avoids active primary users regions during routing. In DSDV, routing procedure is followed as:

1. Route Discovery: Initially when a node wants to start transmission, it sends RREQ message on all available channels to all its neighbors. Each neighboring node which receives the route request message then forwards to all its available channels and can also save the information about the route discovery for a specified time for route establishment and maintenance purposes.
2. Route Reply: In this phase, route reply is sent back either by destination or any node which has the route entry for the destination node. Routes are established and channels are selected based on link metric, flow requirement and with the aim to increase network capacity of wireless network by exploiting the channel diversity. Channel assignment is done that must satisfy the goal of improving the capacity of network and also interference avoidance.

3.2. Route Recovery

Due to the dynamic spectrum and mobility, there are frequent path breaks which led to frequent channel switches. So route recovery is essential and the routing schemes should be able to maintain routes during different routing failures like channel

Metric	Channel Stability	Link cost and delay	Common Control Channel	Flow control	Throughput
[33],[65]		✓			
SAMER[13]			✓		✓
[20]				✓	
[25]	✓				
[67]		✓			
SEARCH[22]	✓	✓			
STOD-RP[24]	✓	✓			
DORP[70][14]	✓	✓			
Coolest path[9]	✓				
[26]	✓				
SMR[45]		✓			
NDMR[46]		✓			
NDM_AODV[47]		✓			
[71]		✓			
OLT[47]		✓			
Gymkhana[43]	✓				
[41]					✓
[64]	✓		✓		
[51]			✓		
[42]			✓		
SPEAR[30]					✓
URBAN-X[29]		✓			
MRSA[28]					✓

Table 1: Channel based routing metrics used by routing protocols in CRN

switches, SU mobility etc. which can lead to reduction in route maintenance cost. Route recovery in cognitive radio networks is very challenging, as SU has to leave channel due to PU appearance. This local change at a particular node affects the end to end delay and needs a well-defined route management procedure [52]. The sudden appearance of a PU in a given location may render a given channel unusable in a given area, thus resulting in unpredictable route failures, which may require frequent path rerouting either in terms of nodes or used channels. In this scenario, effective signaling

Metric	Mobility	Threshold Energy	PU Interference	SU interference	Resource Management	Power Consumption
[36],[65]				✓		
[51]	✓					
[25]	✓					
MWRP[48]						✓
[72]		✓				
[27]				✓		✓
STOD-RP[24]	✓					
CRP[68]			✓			
[60]					✓	
NDM_AODV[47]						✓
[71]				✓		
[34]	✓					
[63]			✓			
NDM[56]		✓				✓
[44]		✓				✓
[21]						✓
CRP[68]	✓		✓			

Table 2: Node based routing metrics used by routing protocols in CRN

procedures are required to restore ‘‘broken” paths with minimal effect on the perceived quality. The route discovery procedure is very similar to link state routing algorithms where this newly introduced weight is used.

A Spectrum-Tree base On-Demand routing protocol (STOD-RP) is proposed in [24] which simplifies the collaboration between spectrum decision and route selection by establishing a “spectrum-tree” in each spectrum band. The formation of the spectrum-tree addresses the cooperation between spectrum decision and route selection in an efficient way. The routing algorithm combines tree-based proactive routing and on-demand route discovery. Moreover, a new route metric which considers both CR user’s QoS requirements and PU activities is proposed. In addition, their work provides a fast and efficient spectrum-adaptive route recovery method for resuming communication in multi-hop CRNs.

The work presented in [26] presents an algorithm for handoff scheduling and routing in multi-hop CRNs. One of the main contributions of this work is the extension of the spectrum handoff to a multi-link case. Following a classical approach, the problem of minimizing latency for spectrum handoff across the network is shown to be NP hard and a centralized and a distributed heuristic algorithm has been developed. The centralized algorithm is based on the computation of the maximum non-conflict link set. With this approach, the algorithm iteratively assigns new channels to links. For route recovery and to address the starvation problem, an aging based prioritization scheme is utilized.

Routing protocol which chooses the best effort route between the source-destination pair for multi-hop communication is called single path routing. Single path routing is not the best solution where the network topology is highly dynamic like CRNAs and where the network resources are limited. Multipath routing is introduced as an alternative to single path routing for its potential to address issues such as route failure and recovery, and network congestion.

IV. Discussion

Table 1 summarizes the different channel based routing metrics used for single hop and multi-hop routing. Different routing protocols combine more than one metric to achieve different goals or to break ties when numbers of routes are equal under the primary metric. Table 2 shows the node based routing metrics adopted by different routing protocols. Also it compares the different routing techniques based on metrics. Table 3 summarizes the other metrics used by routing protocols in CRN.

Metrics	End to end delay	Probabilistic Functions	Hop count
[36],[65]	✓		
SAMER[13]			✓
[51]		✓	
[69]	✓		✓
SEARCH[22]	✓		✓
CAODV[20]			✓
Coolest path[9]		✓	
[61]		✓	
SMR[45]			✓
NDMR[46]			✓
NDM_AODV[47]			✓
[71]	✓		✓
[1]		✓	
SPEAR[30]			✓
URBAN-X[29]	✓		✓
MRSA[48]			✓
CRP[68]	✓		✓

Table 3: Other routing metrics used by routing protocols in CRN

V. Conclusion

Through available spectrum bands in CRNs with multi-hop communication are different for each hop; spectrum sensing information is required for topology configuration in CRNs. The dynamic spectrum changing pattern of devices enabled with cognitive radio capabilities makes routing a challenging issue. In this paper, we have discussed the routing schema and different routing metrics used in routing protocols to optimize performance and minimize interference for CR users. Intrinsic properties and performance of the routing protocols for CRNs are presented. Finally we have presented route management to provide efficient routing to CR users in a dynamic environment.

The discussions provided in this survey strongly advocate spectrum-aware communication protocols that consider the spectrum management functionalities. The cross-layer design requirement necessitates a rethinking of the existing routing protocols developed for CRNs. Many researchers are currently engaged in developing the communication technologies and protocols required for CRNs. However, to ensure efficient spectrum-aware communication, more research is needed along the lines introduced in this survey.

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