

Classification of Routing Protocols Based on Routing Metrics in Cognitive Radio AD HOC Networks



Shiraz Khurana, Shuchita Upadhyaya

Abstract: Cognitive radio ad hoc networks are opportunistic networks, which utilize licensed spectrum. The spectrum assigning authority has divided the spectrum in to two regions: licensed and unlicensed. The unlicensed bands are clogged while licensed bands are underutilized. So unlicensed traffic needs to be shifted to unused licensed portion of the spectrum. Henceforth, Cognitive Radio Networks are proposed. These networks were having an infrastructure just like base station in cellular network. Cognitive radio ad hoc network are special wireless ad hoc networks having cognitive capability. In these networks, devices are able to adapt according to the environment. These devices are designed to operate in different frequency ranges. Routing data in this kind of network is a bit challenging due to its different nature. This paper discusses these challenges in detail. Later a detailed discussion is presented on the existing approaches used to handle these challenges. A clear & concise analysis of every approaches is preformed which leads to identification of merits & demerits of each of these approach. Lastly, identification of various routing metrics which need to be considered while designing a new routing protocol for cognitive radio ad hoc networks has been made.

Keywords: CRAHNs, routing metric, Multichannel, Multipath

I. INTRODUCTION

In the initial days of spectrum assignment, allocation of spectrum has done statically on long term basis for various frequency bands. With increasing demand for wireless devices, the regulatory authorities have started to reassign some of these bands which were used by legacy system. In today's world, even this reassignment is not able to manage things properly. One study by Spectrum regulatory authority given by federal communication commission (FCC) highlighted that, the encumbrance on various spectrum bands is uneven & statically assigned bands are used within bounded geographically areas over a limited period, and the average utilization of such bands varies between 15-85% [1]. In unlicensed bands the status is totally opposite, especially in the ISM band (e.g. 400-700 MHz).

The number of devices running at the same time are immense (e.g. it includes devices operating in wireless local area network, sensor network, mesh network, personal area network, body area network etc.). This is becoming a bottleneck in the performance of unlicensed bands.

Cognitive radio network is projected to handle this uneven distribution, for wireless devices if they can have cognitive capability, by altering its operating parameters (like in current frequency, user's behavior & network state). Then it can work efficiently over a wide range of spectrum. These spectrum agile devices are known as cognitive radio devices (in early literature it was called as software defined radio).

These devices can access the vacant spectrum portions that are not utilized by licensed users. These vacant spectrums are also known as spectrum holes. Figure 1 shows spectrum holes positions at various frequencies at time t. If some unlicensed user wants to access licensed users spectrum, it needs to identify the spectrum holes available at that time.

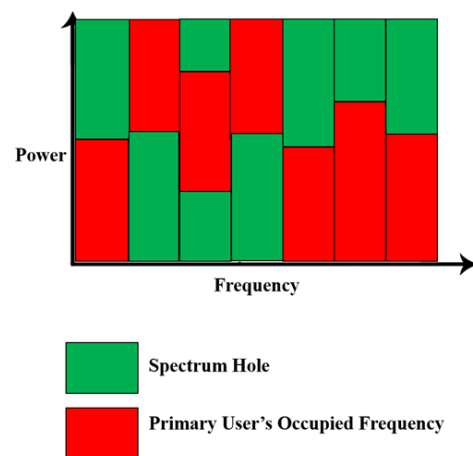


Figure 1: Spectrum Holes at time interval t

If some unlicensed user wants to access licensed users spectrum it need to identify the spectrum holes available at that time. Based on the kind of access to spectrum, these devices are divided into two categories: Primary Users (PUs), who have legitimate access to the spectrum in licensed category. These users having first priority in using the licensed spectrum. When PU is not using the spectrum, in that case, spectrum is considered as free, and it is available to be used by next category of devices known as Secondary Users (SUs). The SUs are the ones who are going to use the spectrum opportunistically.

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The goal of SU is to communicate with other SU by using the licensed spectrum when it is not being used by PU & without interfering with any other SU or PU. This flexibility of switching spectrum dynamically comes with lots of complexities in designing different sorts of protocols for communication at each layer.

In literature, research work performed in the field of CRN focuses on two separate subzones. The first zone mainly focuses on physical and MAC layers, where the main goal is to sense the spectrum, looking for some spectrum hole (the part of spectrum, which is available for communication), minimizing interference between communicating nodes and improving channel efficiency. The other zone generally focuses on Network and Transport Layer. The focus of which is on creation of new routing protocol and suggesting changes to the existing protocol used. This paper is engrossed on this zone.

There is further division in CRN. First one has a centralized infrastructure support and various mobile nodes communicate with the help of this central backbone known as Cognitive Radio Network with Infrastructure. The second one has various network nodes joining hands in an ad hoc manner to create Cognitive radio Ad hoc Network (CRAHN) [3]. Routing in CRAHNs cannot be done based on the fundamentals of traditional wireless networks, because there are many unique challenges involved in CRN. Therefore, we need to design new protocol standards.

In this paper, first, the routing challenges confronted in CRAHNs are discussed in detail, which are different from classical ad hoc networks and then a discussion of existing work in the literature is presented. Later a detailed analysis is presented as to how these approaches handle these challenges. A clear & concise analysis of every approach is preformed which leads to identification of merits & demerits of each of these approaches. Lastly, identification of various routing metrics, which need to be considered while designing new routing protocols for cognitive radio ad hoc networks are identified.

The remaining portion of the paper is as follows: Section II discusses the challenges encountered in routing of packets in CRAHNs. In Section III, classification of existing routing protocol is presented based on routing metrics. Section IV highlights the advantages and shortcomings of each of these approaches. Section V identifies some important routing metrics that need to be considered while designing a routing protocol for CRAHNs. Section VI elucidates the conclusions.

II. CHALLENGES OF ROUTING IN CRAHNS [3]:

- A. Protection to PUs Transmission:** This is an important challenge that differentiates between classical ad-hoc networks & CRAHNs. PUs are the licensed users that have priority in using spectrum. The transmission of PUs must be saved at any cost. If SUs are using spectrum of PUs and it later wants to use its spectrum again, it is allowed immediately. The SU must abandon its transmission on that channel until or unless PU itself surrenders that channel.
- B. Diversity of channels:** The channels, which are available for data transmission is highly dependent on PU's channel utilization & mobility of SUs. A channel that is free from PU's activity will be selected for transmission more than exceedingly utilized channel.

Different bandwidth channels may be available for transmission between two nodes as well. Therefore, it is very hard to manage this sort of mixed channel scenarios.

C. Combination of various operating environments: Two SUs can exchange information only if they have at least one common channel between them. Every SU has different power capabilities & many channels. All channels may have different data rates & transmission range. A low power SU & a smaller bandwidth channel in a route can be a bottleneck. Therefore, there is a combination of various operating environments which hard to manage.

D. Switching & Back off Delay: PUs will have the ownership of the spectrum. Whenever the PUs want to access the spectrum, they must be able to use it without any delay. This introduces two kinds of delays in transmission of SUs. In case, SU switches to another frequency, then a switching delay will be there: it is the time SU takes to adjust its parameter to another frequency and again tuning the other node to be on the same frequency so that transmission starts again. In case, SUs decide to wait on the same frequency, till PU finishes its transmission, consequently SU can continue its transmission on the same frequency. The waiting time is known as back off time or back off delay. In this case, data must be held up into some buffer. There is another case in which SUs can still use the same frequency; for that, it has to reduce its transmission power so that it does not cause any interference with the PUs. But this case is not so popular.

E. Availability of Spectrum: The availability of spectrum is very dynamic in CRAHN. The main task of cognitive radio devices is to determine the spectrum holes and out of these holes, which one is selected for transmission needs to be determined carefully. It is always better to assign some weight to different channels based on their availability from PUs utilization.

F. Deafness issue in transmission: When a channel is not available for transmission, then the current node must choose some other channel to transmit information. Now if neighbor node is not synchronized to switch to same channel (new one), then it cannot receive data. This is known as deafness problem. It can be solved in many ways: one solution is that the current node first advertise new channel on Common Control Channel (CCC) so that neighbour node can switch to the new advertised channel. Other solution is that current node can transmit on all the available channels, correspondingly the neighbor node can receive the data & will reply on the selected channel. However, this solution is costlier.

III. CLASSIFICATION OF ROUTING PROTOCOL BASED ON METRIC:

In this section, we discuss different routing protocols that have been developed for CRAHNs. As shown in figure 2, we have classified routing protocols based on the metric they use for route formulation. In [4], some routing metrics for CRAHNs have been overviewed. In this paper, a reassessment of the metric is carried out with some additional metrics followed by a description.

The routing protocol based on these metrics and a comparative assessment of these routing protocols based on their merit, demerit and other criteria. This includes:

- Hop count based
- Delay based
- Transmission count based
- Energy based
- Link & Channel stability based
- Location based
- Combined metric & Multimeric based

The following subsections discuss the route establishment process of the surveyed protocol in the above-mentioned categories in detail.

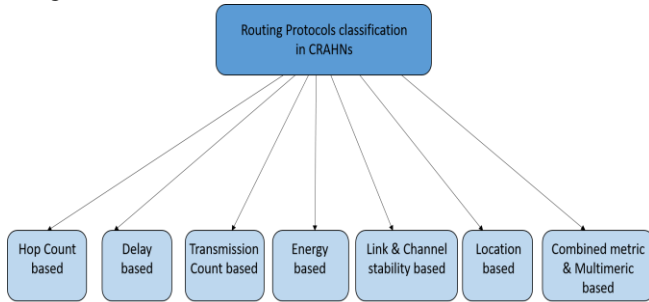


Figure 2: Classification of Routing Protocols based on Metric

A. Routing Protocol Based on Hop Count

This section gives a brief summary of routing protocols for CRAHNs by using hop count as a metric. Hop count metric is used in classical ad hoc networks as a valuable parameter, while it faces multiple different challenges in CRAHNs.

a) Cognitive Ad hoc On demand Distance Vector

CAODV proposed in [5] by Cacciapuoti et al. for CRAHNs is a modified version of AODV protocol [6]. It is a distributed protocol which avoids regions of primary user’s activity altogether. Nodes, which are operating in PU’s activity zone, never participate in route formation and packet delivery. It does not require any dedicated common control channel to broadcast control information. It assesses the quality of any available channel by means of RREQ and RREP packets. It also minimizes the route cost by performing a joint path and channel selection at each forwarder. The proposed work exploits the presence of multiple available channels to improve the overall performance. In this, routing decisions are made at physical, MAC and network layers. Merit of this protocol is that it primarily focuses on avoiding any disturbance to Primary User (PU), while maintaining end-to-end connectivity. The demerit is that it does not consider the diversity in available channels. CAODV assumes that all channels are of same bandwidth, which is not practical in real world scenario. The hop count is used as filter between multiple routes with same sequence number. CAODV also uses route maintenance procedures in case there is some issue with route due to node mobility or PU appearance. It sends route error packets back & forth.

b) Joint path and spectrum diversity routing protocol

In [7] the author have proposed a joint path & spectrum diversity protocol. As the activity of PUs varies in time, frequency and space domain, cognitive users (CUs) can switch dynamically to different spectrum and paths in the presence of PU. The proposed work specifically handles this issue by using Dual Diversity routing protocol for Cognitive Radio Ad hoc Network (D2CARP). This is a distributive protocol and it utilizes the local knowledge about network topology. It exploits the next hop routing concept and makes decision about multiple paths by minimum hop count.

This work assumes that the entire band considered for routing are free from PU usages, that part is done by sensing module. The benefits of jointly exploiting path and spectrum diversity in CRAHNs are also explained.

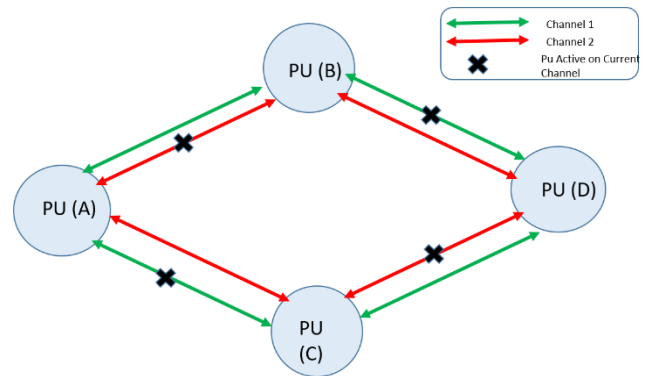


Figure 3: joint path & spectrum diversity

Joint path and spectrum diversity allows CUs to switch dynamically among different paths and channels for communicating with each other in the presence of frequency and space domain dependent PU activities. Figure 3 shows joint path and spectrum diversity: There are two different channels in which PU is active. From Node (A) to Node (B) channel 1 is available while channel 2 is used by PU. From Node (B) to Node (D) channel 2 is available. Similarly, from Node (A) to Node (C) Channel 2 is available and from Node (C) to Node (D) channel 1 is available. So all nodes are under PU activity range. As no complete path is available between a source to destination at the same time, so we need to you use both path and spectrum diversity. Path diversity cannot counteract PU activity that varies in frequency domain whereas spectrum diversity cannot counteract PU activity that varies in space domain. It supports multipath and multichannel routes. It broadcasts route request messages to all neighbors to identify the route between source to destination. The best route selection criterion is Hop Count. Since it broadcasts RREQ to all the available channels, it consumes more resources. The proposed work is compared with CAODV [5] & proved to be better on experimentation in NS2. The performance analysis is examined using the following parameters: packet delivery ratio, route overhead, delay, & hop count.

c) Fault-Tolerant Multi-Path Multi-Channel Routing Protocol

Che-arón et al. [16] proposed a reactive on demand routing protocol, which exploits spectrum and path diversity while determining a path between source to destination. It creates multi-channel and multipath route between source and destination. At each SU, it creates two routing tables, one for primary route and another one is for backup route. While creating routes, it will store multiple channel entries in the primary routing table. The backup routing table will be used only in case primary route has failed. In addition to that, it provides fast and efficient route recovery in the presence of path failure during data delivery in CRAHNS. The failure may be due to one of the following reasons: primary user activity, node mobility & failure and link degradation. The algorithm identifies the reason of path failure over a primary transmission route. Based on the reason of failure, different route recovery mechanism will be instigated. A backup path is created to ensure that data transmission is not hampered in case of path failure. The backup path is selected based on cause of failure. In case link failure is due to PU appearance then the current node cannot transmit data packet to the next hop node on the current channel. Hence, it will select alternate channel from the primary routing table. If the data is not delivered due to node mobility or node failure then backup path will be utilized, and a new backup path will be created. The current work is compared with D2CARP [7] and simulation results shows that the proposed protocol has an edge over it in terms of average throughput and average end to end delay.

B. Routing protocols based on delay

In this section, routing protocols which use delay as a metric are discussed. In CRAHNS, delay can be of following types:

1. Switching delay: this kind of delay is observed when a node needs to switch channels or path to transfer information to other nodes.
2. Backoff delay: this delay is faced in MAC layer while trying to solve hidden terminal problem or when a SU waits for PU to finish its transmission so that it can continue on the same band.
3. Queuing delay: this delay is observed at a node when the channel capacity is no longer able to handle the requested data rate.

These are the major delays, which are observed in CRAHNS. The protocols which make routing decisions based on delay metric are described as follows:

a) Path and spectrum diversity with optimized path selection

In [8] the authors proposed a joint path spectrum diversity based routing protocol with an optimized path selection for CRAHNS. During path establishment, it avoids Primary User (PU) region and makes transmission path less vulnerable to the PU activities. It provides efficient route recovery mechanism in the presence of path failures resulting from PU activity. The path selection criterion favors a path with small delay and low interference to PUs. Firstly, it divides the whole transmission area into two

regions: *in_PU_region* & *out_of_PU_region*. The nodes which are operating in *in_PU_region* do not participate in any route establishment any further. Only those nodes which are operating in *out_of_PU_region* are allowed to participate in route establishment. Thereafter delay parameter comes into practise, which uses the expected path delay (EPD) routing metric for path decisions. The EPD metric takes account of the effect of packet loss and link delay, which is proposed and implemented. In this work, the EPD metric is defined as: the expected time it takes a probe packet to travel from source to destination.

$$EPD(\text{path}) = \sum_{\text{link } k \in p} ELD(k)$$

Where path *p* constitutes all the links *k*. For a link *k* it can be determined as:

$$ELD(k) = ETX(k) * (RTT(k)/2)$$

Where ETX(*k*) is expected transmission count of a link *k* or number of sent ETX probe packet. RTT(*k*) is the time interval between sending RTT probe packet and receipt of acknowledgement.

$$ETX(k) = 1 / ([1 - P_f(k)] * [1 - P_r(k)]) \\ = 1 / (d_f(k) * d_r(k))$$

Where *P_f* and *P_r* are the probabilities of packet loss in forward and reverse direction. *d_f(k)* and *d_r(k)* are the forward and reverse delivery ratio. This algorithm also maintains multiple channels in case some channel or complete link of the path is unavailable due to PU appearance or mobility of SU. It selects a path with low delay & less interference to the PUs. It is a multipath and multi-spectrum routing protocol. The proposed work is compared with D2CARP [7] & from performance analysis it is proved that ED2CARP has better results with respect to average throughput, average end to end delay, average jitter & packet loss.

b) Minimum channel switch routing

In [18] a routing algorithm is proposed which includes a channel selection strategy to minimize switching delay. The algorithms prefer to choose a path that will have least number of channel switches per hop, while making a path between a source to destination. The proposed work is compared with shortest path routing (SPR) which is based on minimum hop count. It uses an edge weight concept to represent switching information. If both neighboring nodes operate on the same licensed channel then weight 0 is assigned otherwise weight 1 is assigned. The algorithm tries to choose that channel which is most common among all the nodes, in terms of availability. To access all local spectrum information and to perform route discovery & maintenance, it assumes to use common control channel. The proposed work [18] shows lower percentage of switches per hop.

c) A delay-centric parallel multi-path routing protocol for cognitive radio ad hoc networks

Shihong zon et al. [25] developed a routing protocol for cognitive radio ad hoc network named DPMR (delay centric parallel multipath routing).

Firstly analysis of multi-hop CRAHNs for end-to-end delay using queuing theory is performed, considering spectrum availability and link data rate. It is formulated as min max optimization problem with the objective of minimizing end-to-end delay. The problem is then solved by a gradient-based search method. Once multiple parameters are available for routing metric calculation, 3 dimensional (3D) conflict graphs are generated which helps in route selection. Then a delay centric parallel multipath routing protocol is specified, that uses multiple paths at the same time.

C. Routing Protocol based on Transmission count

Transmission count refers to the number of data transmission or retransmission required to transmit data from source to destination successfully. When a node sends one packet to another node, after receiving data the receiving node sends acknowledgement after which the transmission is considered as successful. In wireless transmission, this metric is used as a quality measure for a path.

a) A new Spectrum Path Diversity Routing Protocol based on AODV

Bahareh et al. [9] proposed a protocol with slight amendment in D2CARP [7] and CAODV [5]. It is a dual diversity protocol, which uses path and spectrum diversity. To deal with PU activities Expected transmission count (ETX) has been used as routing metric, further it has different channel selection strategies. The complexity of this protocol is a bit higher, but it claims to have better throughput and packet delivery ratio as compared to D2CRAP.

b) AP_CR: An Anypath Routing Protocol

Chao et al. proposed a dynamic forwarding selection scheme based routing protocol in [10], with the objective of delivering data with least number of transmissions between two nodes. A set of intermediate nodes are formed into a set called forwarding set. Each node will be assigned some priorities within the set, whenever a packet needs to be forwarded. A node must do it only when no other higher priority node has not done that. PU occupancy issue is resolved to a very good extent as there are many forwarding node as backup. It is also a kind of opportunistic routing. Packet loss is also minimized because there will always be some node from the set which is ready to deliver the packet. The cost is associated with the node itself. This cost will determine whether a node will be included in the forwarding set or not. Benefits includes: data transmission is less vulnerable to PU activities by providing a set of multiple candidate forwarder. This algorithm will perform better in case of frequent channel switching. The overall advantage is that it minimizes the number of transmission required for data transfer. Inadequacy is that every node has to keep track of the entire band to estimate availability probability of them.

c) SACRP: Spectrum Aggregation-based Cooperative Routing

In [11] ping et al. have proposed a cooperative routing protocol based on spectrum aggregation concept named SACRP. Physical and MAC layer have been designed in SACRP & further two different classes of algorithm have been proposed. Class A focuses on achieving higher throughput by selecting a relay node that provides higher capacity than the direct link. Class B focuses on reducing end-to-end delay by reducing hop count & expected transmission count (ETX). The simulation results shows that under cooperative scheme the protocol works better in terms of throughput & end-to-end delay as compared to non-cooperative scheme.

D. Routing protocol based on Energy

In CRAHNs, all the nodes are mobile and battery operated. As compared to classical ad hoc network, the energy requirement is severe in case of CRAHNs. There are many channels & path switching that consume energy. The following literature discusses the protocols, which use energy as a metric.

a) Energy and Interference Aware Cooperative Routing

In [12], Shuyu et al. proposed two different routing algorithms; the first one is to find out shortest path between source & destination by minimizing the total transmission power required. It further suggests that a relay node can be added to reduce total transmission power although it may increase the hop count. It determines total transmission power of a link & between source & destination.

Second algorithm targets one of the most neglected research area in CRAHNs: protection to primary receiver. Similar work is performed in [22]. It suggests providing protection to primary receivers by selecting next hop node that has minimum overlap area of secondary user with primary transmitter. It calculates total fractional overlap area for n^{th} path. The proposed work assumes that CR user employ energy detection technique for primary signal detection to identify whether a channel is busy or idle. If total received energy E is more than σ Threshold, it means channel is not available for utilization. Detection of primary user in k^{th} channel is determined with some probability. There may exist some false alarm & miss detection as well. Higher the value of probability of detection (P_d) more the protection to other users. Lower the value of false alarm (P_f) better the efficient utilization of the channel. It is calculated as follow:

$$P_{sw}^k = P_b^k (1 - P_d^k) + P_i^k (1 - P_f^k)$$

Where P_b^k means channel is busy and CR user miss to detect, P_i^k means channel is idle and no false alarm is generated. The simulation results show that the proposed cooperative algorithm to save up to 30% of transmission power & interference probability to primary receiver is improved by 6% in comparison to Non-Cooperative routing.

b) Energy Aware Multipath Routing Protocol

Kamruzzaman et al. propose an energy aware on demand multipath routing protocol for CRAHNs [13]. The work considers residual energy of each CR user & protection to PU transmission as one of the major objectives. It tries to provide robust & high throughput routing which involves not only multipath route selection but also spectrum assignment in energy constrained CRAHNs. It assumes the availability of common control channel (CCC). Further, it undertakes to combine available channel (l) along with time slot t, It is denoted as (l,t). For each channel slot, the channel can take one of the stated states: occupied (by either CU or PU), free (not in use by PU and CU both) and scheduled (to be used by CU in Future). The objective is to maximize the utility function:

$$U_k = (mE_{res,k})/HC_k$$

Where $mE_{res,k}$ is minimal residual path energy & HC_k is hop count in the k^{th} route request.

c) Spectrum and Energy Aware Routing

[14] Discusses a Spectrum and Energy Aware Routing Protocol (SER). It is a joint route and spectrum selection protocol. The proposed SER protocol will select only those nodes that are above a threshold & diverting traffic to nodes which have better energy utilization, so that overall network energy is optimized. The throughput can also be optimized by diverting the traffic to less utilized channels. It uses common control channel (CCC) for exchanging route establishment packets. At the MAC (Medium access control) layer, proposed work has divided each frame. In Figure 2, there is a sensing window, an ad hoc traffic indication window followed by communication window. The Ad hoc Traffic Indication Message (ATIM) window is contention based. During control channel, it uses CCC. In communication window, a channel is divided into time slots in addition to route selection. Three types of slots are taken: occupied, free & tentatively assigned to transfer actual data.

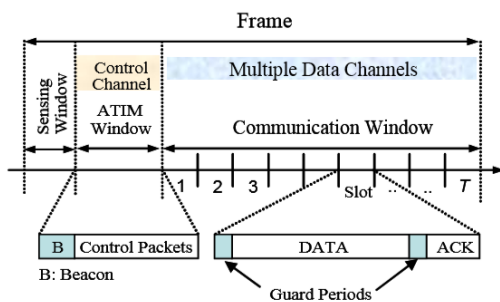


Figure 2: MAC layer frame structure

It uses residual energy & hop count as metric. The evaluation is conducted on custom simulator written in C language to show effectiveness and applicability of their work.

d) Energy-Efficient and Robust Multipath Routing

In [15] Singh et al. proposed, an on-demand multipath routing protocol by considering energy efficiency. The metric used in this protocol is residual energy and channel stability. A combined metric by using residual energy & route stability is generated to identify robust multipath,

which are energy efficient as well. A common control channel is assumed to be available for exchanging all control packets. In this, two paths are designated as primary and secondary path. The secondary path will be used only when primary is not available. When both of the paths are not available only then route establishment process will be initiated. The selection of next hop node will be based on residual energy. The channel assignment is based on most stable channel, in terms of access duration. At destination, when all the route request are received, it is sorted according to energy efficiency and stability and then primary and secondary routes are selected. The proposed work is compared with other existing work in the literature. Results proves the applicability and betterment of their work in terms of throughput and energy efficiency.

E. Routing protocols based on Link & Channel Stability

In classical ad hoc networks, all nodes communicate on the same frequency. However, this is not the case with CRAHNs. In CRAHNs, there is diversity in channel availability so link and channel stability is a very important factor while designing routing protocols. Two nodes in CRAHNs can communicate only when both nodes are operating on a common channel. The remaining part of this section discusses routing protocol based on link and channel stability.

a) Gymkhana

Gymkhana protocol as proposed in [17] is mainly based on stability of network links. It is a distributed protocol, which uses a mathematical framework called Laplacian spectrum of graph, which allows to identify those network paths which fall in blue zones (the effect of PU is minimum in this zone) and red zones (zone where PU may be very active). The main purpose of this protocol is to avoid red zones & focus more on blue zones, so that the links available are highly stable. To evaluate path connectivity, it uses following steps:

- 1) Identification of key parameters from origin to destination on all the candidate paths using an AODV protocol approach.
- 2) To denote the presence of PU, a mathematical structure has been used on a given path & a graph is generated.
- 3) Based on the graph generated in step 2 & associated second smallest eigenvalue in Laplacian matrix the path connectivity is measured. The eigenvalues are calculated as the difference between graph's degree matrix and adjacency matrix.

These results are prime factor in evaluating the connectivity of CRAHN's. It is assumed that each SU has the capability of measuring list of available channels & primary user activity factor (a_p) on those channels. Just like AODV, RREQ is broadcast on all available channels. At each hop, two different lists are prepared the list:

$$L_k^a = \{ID_k^a\},$$

Where L_k^a contains node id for all the nodes encountered in path k.

$$L_k^b = \{I_k^n\}$$

L_k^b contains influence vector of all the nodes encountered in path.

The proposed work creates a virtual graph V_k for each of the k paths. Further, it has generated eigenvalue for the laplacian matrix based on this virtual graph. The virtual graph will have two kinds of edge between two consecutive nodes. If two consecutive nodes are operating on the same channel, then there is horizontal edge. If it is operating on different channel then there will be vertical edge. Each edge will have associated weight based on two factors: activity of PU on that channel and cost of switching from a channel to another. This ultimate objective of the proposed work is to maximize utility function.

$$U_k = ((\lambda 2)_k / (\lambda 2)^{clear_k}) * 1 / H_k$$

where H_k is the number of hops in k^{th} path, $(\lambda 2)_k$ the second smallest eigenvalue of L_k^c (laplacian matrix) can be used to evaluate the degree of connectivity in V_k , of path k , $(\lambda 2)^{clear_k}$ is the second smallest eigenvalue of L_k^c when all the primary activity factors are equal to 0, that is when there are not PUs influencing nodes of the path k .

b) Multipath Routing Protocol

Multipath routing is considered as better bandwidth utilization by discovering multiple paths between a source and destination. The importance of multiple path routing is enlarged in case of diversified channel environment and sudden primary user appearance. The protocol mentioned in [19] discovers route through multiple paths. The proposed work (MPR) considered channel stability as a metric before actual route formation. MPR discovers multiple path in single route discovery. The protocol selects the most stable route between source and destination. The protocol also ensures disjoint and loop free delivery as well. It calculates channel availability probability based on previous history. Therefore, a list of channels with corresponding state probability of channel is stored at each node. The calculation of probability is not only on a current channel, but also on adjacent channels as well (considering co-channel interference). After this calculation, the node needs to assign a channel for route discovery phase. It selects the most stable channel from the set of available channels. The channel stability metric is exchanged with other nodes in Route Request packet. In route reply packet, flow id is assigned as a label to identify the flow. The remaining portion is similar to AODV [6] protocol. It records multiple paths in the same routing table.

The proposed work has comparative analysis with CAODV [5], with respect to packet loss, route discovery frequency, route discovery latency and average delay.

F. Routing protocol based on geographic location of nodes

The routing protocol which depends on geographic location of the nodes falls under this category. The local information regarding the geographic location is shared among nodes. Usually it is performed through GPS. The source node needs to predict the location of destination in advance. Correspondingly it can route packets towards the

destination. In the remaining part of this section the protocol which uses this kind of approach are presented.

a) SEARCH

SEARCH [24] proposes, a geographic forwarding based spectrum aware routing protocol for CRAHNS that avoids the region of PU activity. It is a distributed protocol designed for multi-hop CRAHN, which jointly considers spectrum and path diversity. The present work operates in two different modes, greedy mode and PU avoidance mode. This protocol predicts the location of the destination in advance & based on that calculates the neighboring node that leads to destination one by one. Optimal paths are found by geographical forwarding on each channel. It employs a greedy approach on each channel to reach the destination. In between, if there is appearance of Primary User (PU), the algorithm switches its mode from greedy to PU avoidance mode. The distinguishing feature is to evaluate when to circumvent PU region and when to change the channels. The next hop node must be in focus region. The focus region is a sector of a circle (an arc) centered on the line that connects a current node with the destination and of an angular range of 2θ . If there is no node in the focus region further, then this node is called decision point & PU avoidance phase is started. It then attempts to find alternate path. This information from different channels are then combined at the destination in a series of optimizations to find a valid path between a source to destination. The major objective is to minimize the hop count and end-to-end delay.

b) A Location-Aided Routing Protocol for Cognitive Radio Networks

Launch [21] proposed by Habak et al. is a location based protocol for routing in cognitive radio network. It propose to achieve minimum route setup delay, handles primary user's heterogeneity & secondary user's mobility. This always prefers stable route over shortest route. The protocol is distributive in nature & uses common control channel. It further assumes that each SU is capable of adjusting the signal strength to optimize energy consumption & uses two transceivers. It uses location of nodes for route discovery, packet forwarding and route maintenance. This paper proposes a novel routing metric, which is based on location in addition to that, this tends to lock available channel. Launch uses a greedy approach to find the route from source to destination, its preference is to select the more stable route that is free from PU activity rather than close to destination. Other than greedy forwarding, it also considers lowest expected delay. The current work is equated with other existing literature by making a comparison in terms of varying the number of SUs, number of PUs and node mobility.

G. Combined metric or multimeric

There are many protocols, which use only a single metric to determine the route.

Whereas there are some protocols which either combine multiple metrics together or use multiple metric at the same time. In this section, some of these protocols are discussed.

a) CRP[22]

It is a distributed joint route and spectrum selection routing protocol. It provides protection to PU receiver. In addition to that, it allows creation of multiple classes of flows based on requirement. The protocol assumes to have a common control channel. This allows all the routing control packets to be transferred to this channel. The presence of PU transmitters can be detected by CR user while sensing the network, but PU receivers are not detected by CR user in transmission medium. Therefore, there might be interference with them. In this paper, Chowdhury et al. [22] propose a solution to this problem by selecting the node, which has least overlap area with primary user transmission radius.

In other words, the node which will have higher initiative will be selected as next node. Another thing which is suggested is to divide the network flow into two classes: "Class 1": which prefers to have least end to end delay while meeting minimum PU interference avoidance. "Class 2" on the other hand will have higher protection to PU, while sacrificing some performance. The route establishment is completed in two stages: first, is spectrum selection and second is next hop selection. The following metric are used for CR route and spectrum selection:

(i) Probability of bandwidth availability, (ii) variance in the number of bits sent over the link, (iii) spectrum propagation characteristics (iv) PU receiver protection (v) spectrum sensing consideration. These metrics are collectively used to determine class 1 and class 2 routes. The proposed work in [22] is compared with existing literature and it performed better in end-to-end CR performance, PU receiver protection & route maintenance.

b) Route Selection for Multi-hop using Reinforcement Learning

In [20] Aqueel et al. proposed three different routing schemes out of which two are based on Reinforcement Learning (RL) concept and one is based on Spectrum Leasing (SL) concept. The main difference between SL and RL is: In SL secondary user will receive information about the activity area of PU in advance, called as spectrum occupancy map. The source node will select its neighbor for a specific route between source and destination that offers the highest minimum channel available time. RL based technique do not have any spectrum occupancy map in advance. One algorithm does it by using traditional RL based scheme while another calculates average Q value. It selects a route that has been selected for transmission in the past maximum number of times. The experimentation has been performed on two different types of topologies, a 6-node network and a 10-node network. Evaluation is performed on real testbed using software radio peripheral and GNU radio units. The protocol has been compared with exiting work in literature & superiority of the work has been proved in terms of route selection, throughput and packet delivery ratio.

c) QoS/QoE-CAODV

This protocol supplements one metric to the existing work CAODV [5] where no Quality of Service (QoS) provision is defined. The proposed work exploits this shortcoming; it enhances QoS along with adding one metric called Quality of Experience (QoE). QoE includes availability, accessibility, access time, retainability of service; while QoS includes quality of session, throughput, end-to-end delay, and jitter. One major deciding factor is user experience. After deriving QoS parameter for a link, QoE is also calculated. The proposed work is simulated on OPNET simulator and better results have been obtained in terms of mean opinion score, delay variation, end-to-end delay and jitter.

d) MACNRP

In [26] Omar S Ghandour et al. proposed a multipath activity based routing protocol that utilizes channel availability and create multiple paths which are node disjoint. In this protocol, between a source and destination pair, at least two node-disjoint paths are established which are free from PU activity. In addition to that, at least two channels with different frequencies are created to save data transmission from PU appearance. Therefore, in total, four different paths per source destination pair will be there for data transfer. It also divides each frequency channel into a number of timeslots to use it efficiently to allow multiple CUs. It further proposes another modified version of their own protocol, with frequency and timeslot reservation. While evaluating the protocol in OPNET simulator blocking probability analysis is performed. The results are compared with D2CARP [7].

IV. COMPARATIVE ANALYSIS

In this section, we present a comparative analysis of routing protocols that have been proposed for CRAHNS. These protocols have their merits and demerits. Table 1 summarizes all the routing approaches proposed for CRAHNS taking into consideration the substantial aspects that might contribute in the assessment of the approaches/protocols. The intent is to identify the contributing elements that may provide direction for proceeding with the design of efficient routing strategies for

CRAHNs.

Table 1: Comparison of Routing Protocols

Reference name & no.	Routing metric	Use of Common Control Channel	Multichannel or multipath or single channel or single path	Merits	Demerits	Simulation environment	Evaluation criteria
CAODV [5]	Hop count	No	Multichannel	End to end connectivity, PU transmission protected, dynamic CRN, selects shortest path.	High resource consumption, all channels considered are of same bandwidth, Route discovery requires overhead.	NS2	Packet delivery Ratio, hop count, overhead.
D2CARP [7]	Hop count	No	Multipath & Multichannel	Better Packet delivery Ratio, less overhead & delay.	More resource consumption, Intermediate nodes cannot change to different paths, Large routing tables.	NS2	Packet delivery Ratio, delay, overhead, Hop count.
FTCARP [16]	Minimum Hop count	No	Multipath & Multichannel	Backup Route is available, it handles various kind of route failure.	Two separate tables are created at each SU.	NS2	Average throughput, average delay.
ED2CARP [8]	Estimated Path delay	No	Multipath & Multichannel	Overall better performance	No protection to PU receivers	NS2	Packet loss, throughput, end-to-end delay, jitter.
Proposed work [9]	Transmission count	No	Multipath & Multichannel	Throughput and PDR is very good	The protocol is complex in nature	NS2	Routing load, PDR, throughput.
AP_CR [10]	Transmission count	No	Multichannel & Any path	Less link breakage due to PU	More resources are consumed per connection	Custom simulator in C++	No. of transmission, PDR & overhead.
SACRP [11]	Transmission count & delay	yes	Aggregation of channels	Cooperative scheme has efficient utilization of resources	In multiuser scenario there will be collision of control packets	MATLAB	Throughput, end-to-end delay.
MCSR [18]	Switching delay	Yes	Multichannel single path	Number of switches per hop is more	The average hop count for a path is more.	Java based custom Simulator	Average hop count/path, percentage switches per hop, Path transition.
Proposed [12]	Transmission power, Primary Transmitter overlapping area	NO	Single path	reduced Transmission power & protection to PU receivers	Complex procedure	Custom environment	End to end power consumption, interference probability, end-to-end hop count, end-to-end delay.
EOMR [13]	Residual energy, Hop count	Yes	Multipath	Better reliability due to energy efficient paths	Channel slot timing needs to be managed which makes it more complex.	Custom Simulator in C++.	Average throughput, end-to-end delay, energy efficiency.
SER[14]	Maximal minimal residual energy with lower hop count	Yes	Multipath	Better throughput and load balancing	longer route request packet	Custom Simulator in C language	Throughput, end-to-end delay, routing overhead.

Classification of Routing Protocols Based on Routing Metrics in Cognitive Radio AD HOC Networks

ERM [15]	Energy and channel & path stability	Yes	Multipath	It is suited for mobile networks, energy efficient and reliable	PU's are considered as static	NS2	Network throughput, packet delivery ratio, average energy consumption per bit.
Gymkhana [17]	Link stability	No	Single path	Path connectivity and path length is determined effectively	The mathematical model it employs is very complex.	Mathematical model	Utility function.
MPR [19]	Channel Stability	No	Multipath	Single routing table for multiple paths, single route discovery	Route overhead at each SU is more because of Multiple processing of route reply, Costly because it transfers information on all channels	NS2	Packet loss rate, average delay, route discovery latency & frequency.
Launch [21]	Location, PU activity and delay	Yes	Single path	It uses channel locking mechanism so less number of collisions	No consideration for QoS	NS2	End to end delay, loss ratio
CRP[22]	bandwidth availability, variance in the number of bits sent over the link, spectrum propagation, PU receiver protection,	Yes	Single path	Highly efficient protocol divided into two classes: minimizing end-to-end delay, PU receiver protection.	Complex multimeric computation before spectrum selection and node selection	NS2	End to end delay
Search [24]	Path optimality	NO	Multipath	Route efficiency is very good.	No QoS mechanism is available.	NS2	Path setup delay, end-to-end delay, packet delivery ratio.
DPMR [25]	Spectrum availability and link data rate	Yes	Multipath & multiple channel	Multiple paths are used at the same time so better performance	Bigger routing tables as per channel delay and path delay both parameter need to be stored.	NS2	End to end delay, route discovery overhead, and Packet delivery ratio.
MACNRP [26]	Channel ideality factor	Yes	Multipath	Less probability of collision between CU and PU.	Routing overhead is high.	OPNET	Throughput, delay, number of failed path, overhead and blocking probability.
QOE-CAODV [23]	Quality of experience	NO	Multichannel	The quality of experience metric targets availability, accessibility, access time & retainability of service	all channels considered are of same bandwidth	OPNET 14.5	Mean opinion score, delay variation, end-to-end delay and jitter.
SL,RL [20]	Q value, Highest minimum channel available time	Yes	Multi-hop Single path	Two different approaches are used Spectrum leasing and reinforcement learning	Spectrum leasing assumes advance availability of time & slot of PU usage	NS2, QualNet and real test bed scenario	Average throughput, route breakage, packet delivery ratio

V. ANALYTICAL ASSESSMENT

The surveyed protocols show that extensive effort has been performed in the past for finding different routing metrics for CRAHNS. However, there exists some limitations & snags that still need some insight. In this section, the findings are presented. The metrics that need to be addressed are as follows:

- 1) **Residual Energy:** In ad hoc networks, all nodes are mobile and battery operated. Therefore, energy consumption is an important aspect while designing routing protocols. In CRAHNS, the additional challenge makes the energy requirement even more severe.

- 2) In CRAHNs, the channels availability is dynamic which leads to switching, that consume energy otherwise backoff period consumes energy. Node mobility and failure are also there. Sometimes a low energy node can be a bottleneck for the whole route. The node selection process can influence this metric. So it is suggested to consider this residual energy metric for energy constrained batteries before designing a new protocol.
- 3) **Channel & link Stability:** This is a unique challenge for CRAHNs, which was not a requirement in classical ad hoc networks. In CRAHNs, two nodes can communicate when both of them are in each other's transmission range & must have at least one common channel on which both of them can operate. This requirement is not very easy to attain. Since whenever PUs requires the channel it must be given access and hence SUs must leave the band. While designing an effective algorithm it must consider about this condition. The SUs must choose a channel, which is more stable & will be available for longer duration of time. Fewer interruptions from PU will save energy and give better throughput & performance.
- 4) **Channel Capacity:** In CRAHNs, there will be variety of operating environments. Between two nodes there will be variety of channels with different bandwidths and hence capacity. This capacity parameter can be very important as a lesser capacity channel between a source and destination route will be a bottleneck. It may influence the overall end-to-end delay, packet delivery ratio and throughput. So it is recommended to consider capacity as another significant parameter.
- 5) **Protection to PU receiver:** The concept of CRAHNs states that there should be no disturbance to PUs transmission at any cost. Most of the literature depends on sensing module (irrespective of implemented in hardware or software) to detect the existence of primary transceiver in current area. Once PU transmitter is operating in that area, SUs will change their operating spectrum. However, there is no protection to PU receivers, as their transmission cannot be detected directly. Some of the work discussed earlier does this by implementing overlap area concept [22]. So it is advised to save the primary receiver transmission as well.
- 6) **Mobility of Nodes:** This metric is common with classical ad hoc networks. However, in case of CRAHNs, not only SUs can move but PUs can also be mobile. It makes a double impact on the routing protocols. Usually PUs transmitters are considered as fixed like base station in cellular network while primary receiver can be mobile. Research in CRAHNs need to focus more on this area.
- 7) **Quality of Service and Experience:** Quality of Service (QoS) is the ability to guarantee certain level of performance. QoS includes quality of session, throughput, end-to-end delay, and jitter etc. Resources such as bandwidth & spectrum availability are dynamic in nature. In real time, service there is always a need of certain guarantee of resource availability. While designing a routing protocol, this parameter needs extra consideration. Quality of Experience (QoE) is different but related to QoS. It includes availability, accessibility, access time, retainability of service; this is another important parameter as it relates to user satisfaction.
- 8) **Route Maintenance:** In CRAHNs, the change in route can occur not only because of node mobility but also due to PU appearance. In case of distributed and multi-hop network, this is even more severe. Therefore, route maintenance is very important. After establishing the route, there may be route failure due to many reasons. The protocol must be able to handle this efficiently.
- 9) **Multichannel/Multipath routing:** The channel availability is very dynamic in CRAHNs. Most of the literature focuses on this and it is always suggested to have at least one channel as a backup. The benefits of taking backup channel are:
 - a. Transmission only gets hindered temporarily in case of sudden appearance of primary user on the current channel. Then the node can switch to backup channel to continue the remaining transmission.
 - b. It will get rid of frequent route discovery phases & this will reduce end-to-end delay and improve throughput.
 - c. This will save energy in nodes as well. So it is endorsed to have multichannel, multipath, or both in the routing protocols to be designed for CRAHNs.

VI. CONCLUSION

The current work highlighted the unique challenges in designing routing protocols for CRAHNs. Recent routing solutions to these challenges have been highlighted. The solution approaches are classified according to the routing metrics used. These are hop count based, delay based, transmission count based, energy based, link & channel based, location based and combined metric & multimeric based. Further, a detailed study of merits and demerits of all the proposed work taken into consideration is presented. Finally, some potential findings and routing metrics that require attention are discussed.

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