IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received January 5, 2018, accepted February 6, 2018, date of publication February 21, 2018, date of current version May 9, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2807781

RARE: A Spectrum Aware Cross-Layer MAC Protocol for Cognitive Radio Ad-Hoc Networks

NAFEES MANSOOR[1], (Member, IEEE), A. K. M. MUZAHIDUL ISLAM[1], (Senior Member, IEEE), MAHDI ZAREEI[2], (Member, IEEE), AND CESAR VARGAS-ROSALES[2], (Senior Member, IEEE)
[1]Department of Computer Science and Engineering, University of Liberal Arts Bangladesh, Dhaka 1209, Bangladesh
[2]Escuela de Ingeniera y Ciencias, Tecnologico de Monterrey, Monterrey 64849, Mexico

Corresponding author: Nafees Mansoor (nafees@ieee.org)

This work was supported in part by the SEP-CONACyT Research Project under Grant 255387 and in part by the School of Engineering and Sciences and the Telecommunications and Networks Focus Group at the Tecnologico de Monterrey.

ABSTRACT This paper proposes a spectRum Aware cRoss-layEr (RARE) medium access control protocol for cognitive radio ad-hoc networks. The RARE protocol initially splits the network into clusters, where cluster formation is defined as maximum edge biclique problem. Besides, in order to maintain the integrity of the cluster-based network, super-frame structure, and topology maintenance protocols are also presented in this paper. Moreover, RARE also integrates a delay-aware routing protocol, where the routing protocol is defined as a weighted graph problem. It is anticipated that clusters in RARE adapt themselves dynamically with respect to spectrum availability and nodes mobility. Furthermore, the routing protocol in RARE is expected to select stable paths while ensuring faster data delivery from a source node to the destination. Simulation is conducted to evaluate the performance of the proposed RARE protocol, where it is found that RARE outperforms existing approaches by maintaining a lesser number of clusters and a steady number of common channels. The simulation results also show that route selection in RARE proves to be more stable with the lowest packet transmission delay compared with the other approaches.

INDEX TERMS Cognitive radio networks, ad-hoc networks, cluster-based network, MAC protocol, routing protocol.

I. INTRODUCTION

With the advancement of microelectronics, a rapid development in wireless technologies has been observed over the past few years. It is also anticipated these future technologies will upturn the living standard with ease and comfort. It is also observed that this exceptional advancement has triggered an escalating demand for new radio spectrum [1]. However, these technologies might suffer from the spectrum scarcity issue as spectrum is a finite precious natural resource and most of the spectrum bands have been allocated [2]. On the contrary, the existing command-and-control based spectrum allocation method utilizes radio spectrum inefficiently [3]. Thus, Cognitive Radio Network (CRN), a concept coined by J. Mitola III, is expected to utilize radio spectrum efficiently [4]. Moreover, CRN is also considered to be an intelligent and self-organized communication system that has the ability to adjust its functionality depending on the network environment [5], [6].

In CRN, two types of users are identified, namely Primary User (PU) and Secondary User (SU), where PU is the licensed user of the spectrum and SU is the unlicensed user [7]. Thus, in CRN, SU opportunistically operates on the licensed spectrum whenever the spectrum is free. On the other hand, based on the infrastructure support, CRN is classified into two types, namely infrastructure-based CRN and infrastructure-less CRN. The infrastructure-less or ad-hoc form of CRN is also referred as Cognitive Radio Ad-hoc Networks (CRAHNs). CRAHN has been receiving profound research interest over the last few years due to its flexible and dynamic features [8]. Meanwhile, clustering is a widely practiced scheme to scale down ad-hoc networks, where cluster-based networks exhibit various advantages compares to flat networks [9]. In cluster-based networks, nodes are divided into logical groups, where adjacent nodes in the same geographical location are associated based on grouping criteria. The grouping criteria usually reflect on network's characteristics and application requirements.

This article presents a spectrum aware cross-layer MAC protocol for CRAHNs named RARE. The initial form of this work is published in [10] and [11], where the concentration is mostly in the network architecture. However, a comprehensive form of the whole idea, which includes both MAC and Network layers, is presented in this article. The article also presents several new algorithms and results for the proposed RARE protocol.

Routing protocol of a network determines how messages from a source node can be forwarded to the destination node. Routing protocols also include mechanisms for route discovery and route maintenance. However, the stochastic behavior of the spectrum makes routing in CRAHN more intriguing. Moreover, network performance is degraded with the abrupt failure in communication as an additional delay is imposed to discover new routes. Hence, an efficient routing protocol in CRAHN needs to identify stable routes as well as to ensure faster data delivery from sender nodes to the destinations. Hence, the proposed RARE protocol begins with a clustering mechanism where the network is logically divided into clusters or groups. Every cluster comprises a cluster-head where cluster-heads are relatively more stable nodes with incumbent mechanisms for route discovery and maintenance. Moreover, the proposed RARE protocol ensures faster data delivery from the sender node to the destination node by considering delay as the routing metric.

Thus, RARE firstly divides the network into clusters, where cluster formation scheme is defined as a maximum edge biclique problem. Clustering scheme in RARE introduces a parameter called Cluster Head Determining Factor (CHDF) to select the cluster-leader/ cluster-head. Here, CHDF value of a node is associated with the number of free sensed channels and number of neighboring nodes. The proposed clustering scheme attempts to maintain a higher number of reserved channels in each cluster that reduces re-clustering issue for changing spectrum availability. Besides, to shrink the re-clustering issue for nodes' mobility, auxiliary cluster-head in each cluster is considered. This auxiliary cluster-head takes control of a cluster when the existing cluster-head moves out. Thus, each cluster in the proposed RARE protocol consists of Cluster Head (CH), Secondary Cluster Head (SCH), Cluster Member (CM) and Forwarding Node (FN). A super-frame structure is also presented in this article that adopts the proposed clustering scheme. Moreover, in order to maintain the integrity of the proposed clustering method, node joining and node leaving protocols are also developed and presented in this article.

In the proposed RARE protocol, the cross-layer design is established by fusing the Network Layer with the MAC Layer. Thus, the proposed RARE protocol integrates a delay-aware routing protocol, which aims to ensure end-to-end faster data transmission with route stability. Additionally, the proposed routing protocol is defined as a weighted graph problem, where delay is considered as the routing metric. Hence, to calculate a link weight, three types of delay are considered, namely switching delay, back-off delay and queuing delay. In CRAHN, a route or a path can be comprised of multiple links, where a link is defined as the connector of two relaying nodes. To ensure faster data delivery to the destination, RARE selects the routing path that provides least cumulative link weights.

Simulation results and analytical analyses demonstrate that the proposed RARE outperforms other recently developed MAC protocols by upholding reduced clusters with sufficient common channels in each cluster. RARE also stays ahead from other protocols by showing better performance in terms of end-to-end delay and overhead.

Thus, key contributions of this article can be summarized as follows:

- RARE, a spectrum aware clustering scheme, is proposed for CRAHNs. In the proposed scheme, a set of free common channels resides in every cluster which enables smooth shifting among channels. Each cluster comprises an SCH to combat the re-clustering issue triggered by CH mobility or varying availability of the spectrum.
- To maintain the integrity of the proposed RARE, Node Move-In protocol is presented that deals with the new node's joining process. Furthermore, Node Move-Out protocol is also developed to deal with the leaving process of any existing node.
- A delay-aware routing protocol for the proposed cluster-based network is developed to ensure faster data delivery from the sender node to the destination node. Hence, delay is considered as the routing metric for the proposed RARE protocol.

The rest of the article is organized as follows. In Section 2, a brief discussion on recently developed MAC protocols for CRAHN is presented. A network model for the proposed RARE protocol is discussed in Section 3. The proposed clustering scheme is described in Section 4. In Section 5, Design challenges for routing protocol in CRAHN are highlighted. Next, the proposed routing protocol is presented in Section 6. In Section 7, simulation results and discussions are presented. The article finishes in Section 8 where conclusion and future works are discussed.

II. EXISTING MAC PROTOCOLS IN CRAHN

Over the past few years, cognitive radio network has been receiving a lot of attention among the communication researchers. The recently developed MAC protocols meet various essential issues for the concrete implementation of cognitive radio networks. In this section, different recently proposed MAC protocols for CRAHN are discussed.

The self-organized network MAC protocol for CRAHN presented in [12] splits the network into groups, where a broker agent is used to negotiate with the PU. One of the major problems in this protocol is the re-grouping issue since groups need to be reformed with the appearance of PU. Furthermore, neighbor discovery process and group maintenance are absent in the protocol. Affinity propagation message-passing technique is exercised for clustering in [13], where cluster size can be large in the protocol. Cluster with a large number of members triggers latency in intra-cluster communication. In addition, this protocol considers nodes to be unmoving that leads re-clustering issue once nodes are mobile.

Similar to [13], this MAC protocol tends to construct clusters with a large number of members, while the number of free channels shared by all nodes is quite fewer (often equal to 1). Again the re-clustering issue is dominant for the protocol with the appearance of PU.

MAC protocol presented in [14] categories nodes based on degree, where the degree is obtained from network statistics. This protocol allows clusters to have 2-hop communication. However, all nodes in the network require having full network information. Moreover, once nodes are mobile, the re-clustering issue is acute. An ID-based centralized clustering mechanism for CRAHN presented in [15] recovers failed links locally, where the original routes are kept intact. The protocol considers static control channel where re-clustering is critical with changing spectrum availability and mobile nodes. A Partitioning MAC protocol for CRAHN that mutually disjoints the network into clusters is presented in [16]. However, clusters in this approach can have a huge number of members that increases latency in intra-cluster communication. Although the clustering method is relatively steady for changing spectrum availability, the re-clustering issue is critical for nodes' mobility for [16]. Untied nodes based distributed clustering is presented in [17], where the protocol is grounded on combined weight metric (spectrum history, distance, instantaneous state and effect of interferences). Re-clustering needs to be performed with the presence of the PU, as the proposed clustering scheme is not fully based on spectrum agility. Moreover, the clustering mechanism in [17] fails to support mobility of the nodes.

A cluster formation algorithm based on available channels, physical location, and spectrum occupancy history is proposed in [18]. The proposed MAC constructs a reasonable number of clusters for the network. However, the number of common channel per cluster reduces with increasing network size in the architecture, which increases the re-clustering probability for varying spectrum availability. Moreover, the re-clustering issue for mobility of nodes is also a deficit of [18]. A distributed cluster agreement algorithm called Spectrum-Opportunity Clustering (SOC) is presented in [19] where clusters are formed based on common idle channels. This MAC protocol provides a desirable balance between common channels and cluster size, however, the protocol can produce a huge number of clusters. Moreover, re-clustering for mobile nodes is another shortfall for SOC. Clustering scheme considering radio link availability is presented in [20] where cluster-heads are determined based on node's degree, number of hops and channel switching. MAC protocol in [20] considers node's mobility; however, re-clustering for varying spectrum availability is a critical issue. One of the widely conversed cluster-based MAC protocol for CRAHN is CogMesh in [21]. This MAC protocol constructs clusters based on a particular local channel called master channel. Control channel assignment may alter the existence of heterogeneous channel condition that leads to inconsistency in the network. Furthermore, CogMesh practices licensed spectrum for control messaging for in-band signaling, where PU signal may interfere. Although this protocol considers nodes' mobility, however, no mechanism is presented to reduce the re-clustering issue for mobile nodes.

From the literature, it is observed that recently developed MAC protocols meet several critical concerns for the concrete development of CRAHN. However, a robust cluster-based MAC protocol for CRAHN considering spectrum awareness and nodes mobility with a feasible trade-off between the number of clusters and number of shared channel per cluster is still due [22]. Thus, in order to alleviate the shortcomings of the existing protocols, this article introduces RARE, a spectrum aware cross-layer MAC protocol for CRAHN. The following section discusses the network model, which is considered for the development of the proposed RARE protocol.

III. NETWORK MODEL

In this paper, an ad-hoc network that comprises of self-organized CRs is considered, where the CRs have sensing ability to utilize the free spectrums in a distributed manner. Both PUs and SUs coexist in the network, where the SUs are location aware. Each CR has the computational capability to calculate the CHDF and also aware of the CHDF values of the neighbors. In the network, radio spectrum is distributed into non-overlapping orthogonal channels with distinctive channel ID for each channel. SUs only utilize PUs' licensed spectrum once PUs' transmission is absent. Depending on the physical position, channel availability varies from node to node.

In CRAHN, SU observes its local radio environment to identify the presence of PU's transmission and accordingly recognizes the current spectrum availability. In the proposed RARE, it is assumed that CRs use energy detector based spectrum sensing method to identify the spectrum availability. This is because, implementation of energy detector, which is a non-coherent detector, is simple. Energy detector is also considered to be an optimal detector of unknown signal where noise power is known. Thus, efficiency of energy detector depends on the strength of the received signal, noise characteristics of the receiver, and sensing duration.

The clustering mechanism proposed in this article is independent of any precise PU activity model. The Semi-Markov ONOFF model is considered to offer an analytical performance evaluation of the proposed clustering scheme, where the Semi-Markov ON-OFF process is modeled on any channel for the PU traffic. Busy (ON) or idle (OFF) are the two states that have been considered for any channel [23]. The length of the busy or idle period is anticipated to be an autonomous random variable. This hypothesis is anticipated to be proper as the spectrum bands are licensed to PUs that operate autonomously. Hence, SU only operates on the free available channels and SU has to vacate channels wherever PU's transmission is sensed. It is also assumed that there exists a global common control channel in the network.

In the proposed RARE protocol, a simple interference avoidance model is assumed to avoid interference between PUs and SUs. It is also assumed that every CR is equipped

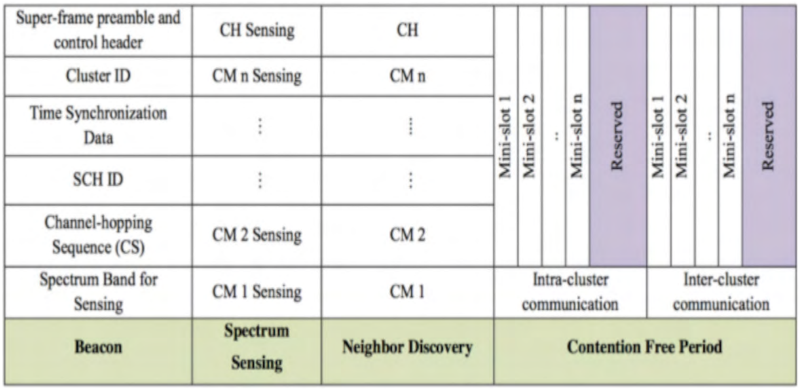


FIGURE 1. Proposed MAC Super-frame Structure.

with two transceivers, where one transceiver is used for control and the other one is used for data transmission. The transmission range for all of the radios is considered to be equal. Due to stochastic nature of the spectrum, spectrum uncertainty can be defined in terms of the spatial variance, where the available channel set for each node varies based on the geographical location. Thus, clustering for CRN needs to consider the spatial variance of the spectrum. However, if there is no common channel between two radios, no communication can take place. Thus, there exists a communication link between two radios if and only if the radios are in each other's transmission range and share at least one common channel between them.

In the proposed protocol, every cluster consists of a leader node called Cluster-Head (CH), where the CH coordinates both intra-cluster and inter-cluster communications. Once the network is clustered, each cluster has its own control channel. Moreover, a node that is situated at the border of two neighboring clusters is termed as FN. Since any FN can hear beacons from both clusters, CH uses FN for inter-cluster communication. However, due to a sudden appearance of PU, the common channel of a cluster can become inaccessible. In such scenario, CH fails to communicate with the member nodes on the existing common channel. Thus, cluster reformation is essential where a new common channel is required to be identified for the new cluster. It is considered that all the previous nodes may not reside in the new cluster, as the new common channel may not be exhibited in the accessible channel lists of all previous members. Therefore, the new cluster may have a new member set. Other previous members that failed to reside in the new cluster either form new cluster(s) or join other cluster(s). Thus, with the sudden appearance of PU, the cluster structure changes where number of clusters may also change in the network. This scenario is termed as the re-clustering effect in this article.

In CRAHN, if a node moves from one location to another, there is a high possibility that the mobile node may experience different channel availability. Therefore, both neighborhood and set of accessible channels of the mobile node may change. Moreover, the mobile node may also get disconnected from the current cluster once the common channel of that cluster becomes inaccessible to the mobile node. Hence, the node may stray from the cluster due to mobility, which requires the node to either form a new cluster or to join existing cluster. In case of CH's mobility, CH gets disconnected from the cluster and the member nodes. Afterwards, those member nodes try to get connected with other clusters or to form new clusters. Hence, a mobility of the CH may affect the performance of the network, since this phenomenon disrupts the structure of the cluster and triggers the re-clustering process.

Based on the network model, the proposed MAC protocol and maintenance protocols are discussed in the following sections.

IV. THE PROPOSED CLUSTERING SCHEME IN RARE

This section of the article discusses the proposed clustering scheme in the RARE protocol. A super-frame structure is also presented in this section that adopts the proposed clustering scheme. Moreover, in order to maintain the integrity of the proposed MAC, maintenance protocols are developed and highlighted in this section.

A. SUPERFRAME

In RARE, the proposed clustering scheme is performed in a distributed manner. Hence, channel access time in each cluster is separated by a synchronized series of super-frames. The proposed MAC super-frame structure has four main periods namely, beacon period, spectrum sensing period, neighbor discovery period and data period (Figure 1). During the beacon period, CH initiates the beacon message which contains cluster ID, time synchronization information, SCH ID, control and resource allocation information of the cluster. Following the beacon period, a spectrum-sensing period is initiated. After each spectrum-sensing period, every node in the network updates its Accessible Channels List (ACL). Following the spectrum-sensing period, the neighbor discovery period is initiated which is a contention access period. Neighbor discovery and cluster formation phases are fused in the super-frame as they are highly associated. During the neighbor discovery phase, nodes need to alter different channels to discover neighbors. Once neighbors are discovered, nodes share ACLs and neighbors' list among themselves. The proposed super-frame ends with the contention free data period, which is divided into two parts; intra-cluster communication period and inter-cluster communication period. Details of the 4 major periods of the proposed super-frame are discussed in the following sub-sections.

1) BEACON PERIOD

The proposed super-frame is initiated by a CH and starts with super-frame preamble and control header. Before transmission CH needs to determine the status of the channel (busy or free) using a Distributed Coordination Function (DCF). Once, CH finds the medium to be free for a time interval equivalent to DIFS (DCF Inter-Frame Space), transmission takes place. If CH finds the channel to be busy, it defers the transmission till the completion of the existing transmission. Next, CH waits an added DIFS interval and generates a uniform random back-off interval. Beacon also contains cluster ID, time synchronization information, secondary cluster head ID, Channel-hopping Sequence (CS) and sensing band for the cluster.

Cluster ID field contains the unique ID of the cluster where time synchronization information is used to determine the location, proximity or speed of the nodes. As SCH is selected by the CH based on the CHDF value, CH puts the SCH ID in super-frame to notify every member. Since every cluster consists of a set of common channels, which are chosen by the CH. CH also generates a CS to access these channels. During transmission, if the PU suddenly shows up, CH immediately stops the beacon on that channel and tunes to the next channel from CS. Other nodes of the cluster also tune to next the channel if they do not receive the beacon for a pre-specific time. Thus the CH keeps its routine actions to safeguard the interference with PUs. CH also adds the spectrum band for sensing in the super-frame.

2) SPECTRUM SENSING PERIOD

Following the beacon period, nodes start the spectrum-sensing process to identify unused spectrum. Nodes need to have updated information about the free channels before transmission. Grounded on the spectrum band, nodes in the network start sensing the spectrum independently to check the channel status. After each sensing period, nodes in the cluster update their ACLs. A synchronized spectrum-sensing period reduces the probability of false alarm and misdetection problems. During the sensing period, if any node senses the presence of the PU on the current control channel, it shifts to the next channel from CS, and sends control channel occupancy status to the CH. CH stops the beacon on that channel and tunes to the next channel based on CS. Other members also tune to the next channel if they do not receive beacon for a pre-specific time.

3) NEIGHBOR DISCOVERY PERIOD

Neighbor discovery is a contention access period that starts after sensing period. Neighbor discovery and cluster formation phases are fused in the super-frame, as they are highly associated. In order to join the network, node needs to discover the neighboring network topology, which is performed during this phase. Once node senses the free channels and prepares ACL; it needs to arrange the channels in a sequential order. Based on the sequence, node alters among the channels to discover neighbors. If PU signal is identified, node hops to next channel of the sequence. It is assumed that the channel stopover time of a node is long enough to discover all the neighboring nodes that are operating on that particular channel. The neighbor discovery process is presented in Section IV-B.

4) CONTENTION FREE PERIOD

The proposed super-frame ends with the contention data free period where the CRs use predefined time-slots to transfer packets. In clusters, all available channels can act as data channel as there is no specific channel allocated for data transmission. Each node of a cluster occupies a mini-slot and uses that slot for data transmission. Mini-slots are assigned by the CH where CH reserves some slots for future usages.

Moreover, the contention free period is divided into intra-cluster communication period and inter-cluster communication period. During intra-cluster phase, a node transmits packet within the cluster on the assigned mini-slot. Leaving process of the CH, FN and CM are considered in the protocol. When CH wants to leave the cluster, it notifies all CMs regarding the movement and requests the SCH to take charge. On the other hand, if an FN wants to leave, the FN informs its parent CH about the movement. CH then checks with other members and appoints new FN that gives the finest connectivity to the neighboring cluster. Moreover, CH removes mini-slot of the leaving FN from inter-cluster communication period. In case of the movement of a CM, the moving-out CM informs the CH and CH removes assigned mini-slot for that particular CM from the intra-cluster communication period. CH also notifies the neighboring CHs that a node is approaching. The neighboring CH initially treats the approaching node as member node and assigns mini-slot from reserved slots. Thus, this scheme ensures connectivity of any mobile node in the network. On the other hand, packets are transmitted between neighboring clusters in inter-cluster communication period. When CH wants to send packet to the neighboring CH, CH uses the FN as the relay node to forward the packet to the desired CH.

B. NEIGHBOR DISCOVERY

In order to join a network, a CR needs to discover neighbors in the network. Through neighbor discovery, a CR node can discover its neighboring nodes and/or neighboring clusters, and exchange control information. Once a node identifies available free spectrum and prepares the ACL, the node

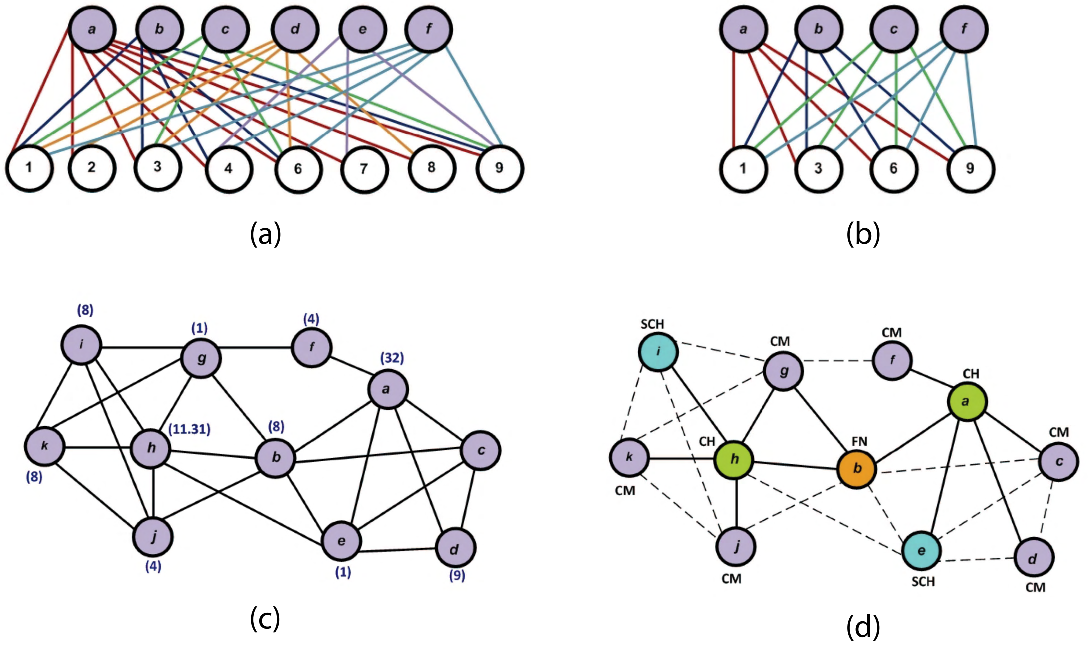


FIGURE 2. (a) Bipartite graph constructed by node CR_a, (b) Maximum edge biclique graph of node CR_a, (c) Nodes with CHDF value, (d) Proposed cluster-based network.

arranges the channels in a sequential order for its neighbor discovery purpose. Based on the sequence, the node starts channel hopping to hear beacon. A sequential hopping of the sensed channels for the neighbor discovery purpose is considered in which a CR uses the global common control channel to obtain a common time reference. During neighbor discovery, a channel stopover time is defined as the total duration a node stays on any channel before hopping to the next channel from the ACL. It is considered that channel stopover time is long enough to discover all the neighboring nodes on the same channel.

Upon receiving a beacon, a CR node sends a HELLO message to the CH and waits for the REPLY message. Later, neighboring CH sends back the REPLY message once the HELLO message is received. While transmitting the HELLO message, the CR node also starts a timer to set the maximum waiting time to receive the reply. CR retransmits the HELLO message if the timer expires or CR fails to receive the REPLY message. Retransmission mechanism is used in the neighbor discovery phase of the proposed protocol in order to achieve data transmission reliability. However, it is considered that the total duration of all retransmissions and the corresponding timers for any particular HELLO message cannot exceed the channel stopover time. In the neighbor discovery phase, if the CR manages to receive beacon from any neighboring cluster and receives a REPLY message, the CR node starts the node joining process, which is discussed later in the Topology Management Section. However, if there is no received beacon from any cluster, the node starts the cluster formation process, which is discussed in the next section.

C. CLUSTER FORMATION IN RARE

Grounded in spectrum availability, the proposed clustering mechanism divides the network into logical groups. Once neighbor discovery is accomplished, the node generates its neighbor list and exchanges ACL with 1-hop neighbors. The proposed clustering scheme aims to reduce the number of clusters and also focuses on the construction of clusters with maximum common channels. By considering the definitions in Table 1, cluster formation process of the proposed MAC protocol is shown in Algorithm 1. The proposed cluster formation scheme is defined as a maximum edge biclique problem, where the scheme attempts to include maximum nodes and the maximum number of common channels in each cluster.

Initially, based on neighbor list N_i and ACL C_i, every CR_i constructs an undirected bipartite graph G_i (A_i, B_i, E_i) where $i = 1, 2, 3,$ ę, n. A graph $G(V, E)$ is called bipartite if vertices set V can be split into two disjoint sets A and B, where $A \cap B = V$, such that all edges in E connect vertices from A to B. For a node CR_i, $A_i = CR_i \cap N_i$ and B_i=C_i, where, C_i is the ACL of CR_i. An edge (x, y) exists between vertices $x \in A_i$ and $y \in B_i$ if $y \in C_i$, i.e., channel y is in the *ACL* of CR_i. A bipartite graph G_i(A_i, B_i, E_i) constructed by CR_a is shown in Figure 2(a). The set of vertices A_a corresponds to the 1-hop neighbors N_a=b, c, d, e plus a, while the set of vertices B_a corresponds to the accessible channels list of CR_a, which is C_a=1,2,3,4,6,7,8. Here, vertex a of A_a is connected to all vertices in B_a, since B_a=C_a. The maximum edge biclique graph of a node can be constructed from the bipartite graph of that particular node. In Figure 2(b), the maximum edge biclique graph of CR_a is presented, which is constructed

TABLE 1. Symbols used in the cluster formation and cluster maintenance algorithms.

j, k, x, y, N	Positive integer (e.g. 1,2,3,...)
CR_x	Any Cognitive Node
CR_j	Joining Node
CR_k	Leaving Node
CR_N	Any Neighbor of CR_x
CH_x	Neighboring CHs of CR_x
FN_x	Neighboring FNs of CR_x
CM_x	Cluster member of CH_x
ACL_x	Accessible Channel List of CR_x
N_x	Neighbor List of CR_x
G_{px}	Bipartite Graph of CR_x
G_{cx}	Maximum Edge Biclique Graph of CR_x
$CHDF_x$	CHDF value of CR_x
$CR_{x,y}$	Link that connects CR_x and CR_y
ID_x	ID of CR_x
CM_l	Non Member Neighbor Node of a leaving node CH_k

from bipartite graph of node *a* in Figure 2(a). CR_a forms its maximum edge biclique graph with neighboring CR_b, CR_c and CR_d and channels (1, 3, 6). Thus, every individual node in the network constructs own maximum edge biclique graph.

The main objective of the proposed clustering scheme in the RARE protocol is to allocate the maximum number of idle channels for intra-cluster communication with a reduced number of clusters. To carry out this objective, a parameter called Cluster Head Determining Factor (*CHDF*) is introduced. *CHDF* concentrates on two parameters; number of neighboring nodes and number of common channels, where values of these two parameters are obtained from the maximum edge biclique graph. Every cognitive node in the network computes *CHDF* based on Equation 1, which is shown below,

$$CHDF_i = \sqrt[c_i]{c_i^{N_i}} \tag{1}$$

where, C_i is the number of idle common channels for CR_i and N_i is the number of neighboring nodes of CR_i that are obtained from the maximum edge biclique graph of CR_i. Even though both number of neighboring nodes and number of common idle channels are considered in the calculation of the CHDF, however, more importance is given on common idle channels. This provides more robustness for intra-cluster communication, as a higher number of reserved channels provides more flexibility for channel switching and reduces re-clustering issue for changing spectrum availability. The root operator is used in Equation 1 to downsize the magnitude of the CHDF value.

Thus, a cognitive node in the network calculates CHDF value independently (as shown in Figure 2(c)) and exchanges the calculated CHDF value with 1-hop neighbors. The proposed cluster scheme is presented in Figure 2(d). The Node with higher *CHDF* comparing with its neighbors forms the cluster and becomes CH. If the *CHDF* value of a node CR_i is lesser than its neighbor, CR_i joins the neighboring node as CM that has the highest *CHDF*. Once clusters are formed, CH prioritizes other CM based on CHDF for the SCH selection. CM with the highest CHDF becomes the SCH for the cluster. The SCH receives control of the cluster if current CH moves out and shrinks the possibility of re-clustering.

The logical structure of the cluster follows star topology, where the CH is the center node of the star and there are no logical connections to the cluster members. Thus, every communication within a cluster is accomplished via the CH, as CMs cannot transmit packet among each other directly. Once the cluster is formed, CH determines and maintains a list of operating frequencies for the cluster. CMs then check neighbor list to find the existence of other clusters in the neighborhood. If located, CM informs the CH regarding the presence of other clusters. Next, CH assigns CM as FN if the CM provides better connectivity with the neighboring cluster, where the better connectivity consideration is grounded on CHDF value. FN can either have a direct communication link with the neighboring CH or use the neighboring FN to communicate with the neighboring CH. In other words, two neighboring CHs can have one FN or two FNs between them. There is no logical connection between any CM with the FN. Thus, the proposed MAC protocol reorganizes ad-hoc network and divides the network into clusters. As shown in Figure 2(d), a cluster consists of CH, SCH and CMs.

However, in a dynamic environment, nodes can join and/or leave cluster any time. Thus, to maintain the logical topology of the proposed cluster-based network, cluster maintenance protocols are developed and discussed in the following section.

D. TOPOLOGY MANAGEMENT IN RARE

To maintain the logical topology of the proposed cluster-based system, two cluster maintenance protocols are developed, namely Node Move-In and Node Move-Out. When a node requests to join any existing cluster, Node Move-In protocol is used, while Node Move-Out protocol is used when a node wants to leave the network. In the following subsections, maintenance protocols for the proposed network are discussed.

1) NODE MOVE-IN

The Node Move-In protocol defines the joining process of a node where the node is not associated with any cluster. Hence, the node initiates the joining process once it identifies beacon from any neighboring CH. While joining, a node can join an existing cluster or form a new cluster. By considering the definitions in Table 1, the node joining process is shown in Algorithm 2.

When a node wants to join, it first identifies the free available channels and prepares the ACL. Next, the new node, annotated as CR_j, scans for beacons by hopping over the channels in ACL for a given period sequentially. Channel scanning time, also known as scanning interval, is chosen such a way that it outstrips the period of the longest super-frame. Thus, if there is a neighboring cluster on the current channel, new node can capture the beacon during the scanning period. From the received beacon, CR_j recognizes probable

Algorithm 1 (Cluster Formation)

```
START
$CR_i$ starts sensing and prepares $ACL_i$
$CR_i$ broadcasts $ACL_i$ and $N_i$ to $CR_N$
$CR_i$ constructs $G_{pi}$ and $G_{ci}$ based on $G_{pi}$
$CR_i$ calculates $CHDF_i$ and shares $CHDF_i$ with $CR_N$
if $(CHDF_i > CHDF_N)$ then
    $CR_i$ declares itself as CH and constructs cluster
    $CR_i$ selects SCH based on CHDF from the $CM$
else if $(CHDF_i < CHDF_N)$ then
    if $(|N| > 1)$ then
        if $(|CHDFhighest| > 1)$ then
            $CR_i$ requests $CR_N$ to join as CM where $ID_N$ is minimum
        else
            $CR_N$ with highest $CHDF_N$ is selected
            $CR_i$ requests $CR_N$ to join as CM
        end
    else
        $CR_i$ requests $CR_N$ to join as $CM$
    end
if $(ID_i < ID_N)$ then
    $CR_i$ declares itself as CH and constructs cluster
else
    $CR_i$ requests $CR_N$ to join as CM where $ID_N$ is minimum
end
END
```

Algorithm 2 (Node Move-In)

```
1  START
2  $CR_j$ starts spectrum sensing
3  $CR_j$ prepares $ACL_j$
4  $CR_j$ prepares $CR_N$
5  $CR_j$ broadcasts $ACL_j$ and $CR_N$
6  $CR_j$ constructs $G_{pj}$
7  $CR_j$ constructs $G_{cj}$ based on $G_{pj}$
8  $CR_j$ calculates $CHDF_j$
9  $CR_j$ shares $CHDF_j$ to $CR_N$
10 if $CR_j \in CR_N$ then
11     if $(j > 1)$ then
12         if $((ACL_j \cap ACL_{CH}) > 2 \wedge$ mini-slot is available$)$ then
13             $CR_j$ joins $CH_j$ as CM
14         $CH_j$ rejects join request from $CR_j$
15         $CR_j$ tries to join other CH
16         if $(CH_j$ fails to join any cluster$)$ then $CH_j$ forms new cluster and becomes CH
17         ;
18         else if $(CHDF_j > CHDF_{CH})$ then
19             if $(CR_N == CH_N)$ then
20                 $CR_j$ becomes new CH
21                 $CH_j$ becomes new SCH
22             else if $(CH_N \subset CR_N)$ then
23                 $CR_j$ calculates new CHDF for $CR_{Nnew} = CH_N$
24                 if $(CHDF_{jnew} > CHDF_{CH})$ then goto 26
25                 ;
26             goto 14
27         goto 14
28     else
29         goto 14
30     end
31 else if $(FN_j \in CR_N)$ then
32     if $(j > 1)$ then
33         select $FN_j$ with highest CHDF
34         $CR_j$ forms new cluster and becomes CH
35     else
36         $CR_j$ forms new cluster and becomes CH
37     end
38 else
39     $CR_j$ forms new cluster and becomes CH
40     $CR_j$ selects CM with highest CHDF as SCH
41 END
```

neighboring nodes and prepares neighbor list CR_N. Afterwards, CR_j broadcasts neighbor and channel lists to CR_N. Upon receiving the broadcast message from CR_j, neighboring nodes CR_N also broadcast their ACLs.

Once the broadcast message from the neighbor is received, CR_j constructs the bipartite graph G_{pj} and the maximum edge biclique graph G_{cj}. Next, CR_j calculates CHDF value $CHDF_j$ based on the maximum edge biclique graph. Afterward, CR_j broadcasts and shares $CHDF_j$ with neighbors CR_N. CR_j first checks the existence of any CH in the neighborhood and attempts to join the cluster. However, if CR_N contains multiple CHs, CH with the highest CHDF value is selected by the new node. However, if the highest CHDF value is identical for multiple neighboring CHs, CH with least ID is selected.

Next, CR_j compares $CHDF_j$ with the selected cluster head's CHDF value. If selected CH possesses higher CHDF, CR_j attempts to join the cluster as CM. Thus, CR_j sends join request to the CH. To join the cluster, CR_j needs to share n channels (where $|n| > 2 \wedge n \subseteq ACL_{CH}$ with the CH. It is considered that to join a cluster, a joining node needs to retain not less than two common channels with the CH. This consideration ensures the existence of at least one backup channel, which provides stability in intra-cluster communication. CH may turn down the join request if CR_j fails to share the required number of channels or no reserved mini-slot exists in the super-frame for CR_j. Otherwise, the CH assigns a mini-slot for CR_j from the reserve slots and later assigns a mini-slot for intra-cluster communication. CR_j may become the FN if it provides better connectivity than existing FNs, where better connectivity consideration is based on the CHDF value. If the selected CH rejects the join request, joining node CR_j tries to join other cluster using the above-mentioned process.

Moreover, if CR_j fails to join any cluster, CR_j forms a new cluster.

On the other hand, if the CHDF value of CR_j is higher than the cluster head's CHDF value, CR_j compares its neighboring node set, CR_N with the selected cluster head's neighboring node set CR_N. The neighboring node set of a selected CH is the CM list. CR_j can have connections with all the member nodes if these two sets are identical, where $CR_N = CH_N$. Hence CR_j becomes the new CH and existing CH becomes the SCH. Moreover, if $CH_N \subset CR_N$, where the CM set is a subset of the neighbor set, joining node needs to calculate its CHDF based on a new neighbor set CR_{Nnew}, where $CR_{Nnew} = CR_N$ With the new CHDF value, joining node CR_i compares $CHDF_{j_{new}}$ with the selected cluster-head's CHDF. If $CHDF_{j_{new}}$ is higher than $CHDF_{CH}$, CR_j becomes the new CH and existing CH becomes the SCH.

Again, if $CH_N \not\subset CR_N$, CR_j joins the cluster as CM. If CR_j provides better connectivity than existing FN with the neighboring cluster, CR_j becomes FN. However, a joining node CR_j can declare itself as CH and form a new cluster once it fails to find or join an existing cluster.

2) NODE MOVE-OUT

The Node Move-Out protocol deals with the leaving process of any existing node of the network. Leaving process of CH, FN and CM are the three movements that are considered in Node Move-Out protocol. Hence, if the received signal strength indication (RSSI) of the beacon starts to decrease and CM or FN has no record about the CH movement, CM or FN considers itself as the moving node and initiates the leaving process. The Node Move-Out process of a leaving node CR_k starts with a broadcast leaving message for the neighbors CR_N. While leaving, node CR_k first checks its neighbor list. If an FN is leaving, then the neighbor list of the leaving node CR_N may contain multiple CHs. Moreover, if the leaving node is an FN, node CR_k can have one CH and one or more FN in the neighbor list.

Thus, if $CR_k \in CR_N$,where k>1 refers the leaving node CR_k is a FN and directly connected with multiple CHs. Next, CR_k informs the parent cluster-head CH_k about the movement. If CH_k finds any member node from the neighboring cluster, it requests that member node be the FN and maintain the connection. If multiple CMs from the same cluster are placed in CH_N, CM with highest CHDF is selected. CM forwards this message to the parent CH and once approved, CM becomes the new FN and connects the two clusters. CH_k allocates mini time-slot for the new FN for inter-cluster communication.

If CH_k fails to get a direct connection with neighboring cluster, CH_k sends message to its cluster member CM_k to check for the existence of other clusters in their neighbor list CM_N. Again if l>1, CM_l with higher CHDF value is selected. Here, two kinds of scenario are considered; one is the neighbor of CM_l is a CH and the other scenario is the neighbor node of CM_l is a CM. For the first case, CM_l becomes the FN and connects two clusters. And in the second scenario, two member nodes from the two clusters become the FNs and connect the two clusters.

Again, if $CH_k \in CR_N \wedge FN_k \in CR_N$, where k=1 refers that the leaving node CR_k is a forwarding node which has connection with one CH and FN(s). Thus, the leaving FN informs the parent cluster-head CH_k and forwarding node FN_k about the movement. If CH_k finds any CM from the neighboring cluster in its neighbor list, it sends request to CM to act as an FN to maintain the connection. CM forwards the request to the parent CH and once approved, CM becomes the new FN. CH_k allocates mini time-slot for the new FN for inter-cluster communication. If CH_k fails to get direct connection with the neighboring cluster, CH_k sends message to its cluster member CM_k to check for the existence of the cluster in the neighbor list CM_N. Again if k>1, CM_k with higher CHDF value is selected. Here, two kinds of scenario are considered; one is the neighbor of CM_k is a CH and in the other scenario, neighbor node of CM_k is a CM. For the first case, CM_k becomes the FN and connects two clusters. However for the second, scenario, two CMs from the two clusters become the FNs.

However, if the leaving node CR_k is a cluster-head, the leaving CH informs all CMs about this movement and assigns the SCH as a new CH. Based on the CHDF value, a new SCH is selected by the new CH. FN node(s) informs the neighboring cluster about the movement. Again, if $CH_k \in CR^F_N N_k \notin CR_N$, where k=1 refers that the moving out node is a CM. Thus, the leaving CM informs the parent cluster-head CH_k about the movement. Next, CH_k first checks whether the leaving node is an SCH or not. If the leaving node is an SCH, CH_k selects another node as SCH from the CMs and removes mini time-slot of the leaving node from the intra-cluster communication phase. CH_k also informs the neighboring cluster about the leaving node and potential joining scenario. The host cluster treats the approaching node as a CM and defines a timeslot for that particular node. With this consideration, a mobile node remains connected with the network.

V. DESIGN CHALLENGES FOR ROUTING PROTOCOLS IN CRAHN

The dynamic changes of spectrum availability due to the stochastic behavior of the PU, routing protocols in CRAHN become different from other traditional ad-hoc routing protocols and triggers addition design challenges [24]. It is anticipated that the performance of a routing protocol is highly affiliated with identifying and considering these challenges [25], [26]. Hence, some key design challenges for routing protocols in CRAHN are recognized and discussed in this section.

In CRN, primary users are considered to have higher priority in using the spectrum for transmission over secondary users. Thus, once an SU identifies the presence of the PU's transmission, SU needs to seize the transmission immediately and switches to another channel. Moreover, while communicating with a neighboring node, a secondary radio may require switching the channel due to the spatial variance of

Algorithm 3 Node Move-Out

```
1  START
2  $CR_k$ broadcasts LEAVE MESSAGE to $CR_N$
3  if $(CH_k \in CR_N)$ then
4      if $k > 1$ then
5          $CR_k$ informs $CH_k$ regarding leaving
6          while $(CH_k)$ do
7              if $((CM_l \notin CH_k) \wedge (CM_l \in CH_N))$ then
8                  if $(l > 1)$ then
9                      $CM_l$ with highest CHDF is selected
10                     $CH_k$ requests $CM_l$ to be FN
11                     $CM_l$ forwards request message to $CH_l$
12                     $CM_l$ becomes FN
13                 else
14                     goto 10
15                 end
16             else
17                 $CH_k$ sends message to $CM_k$ for other cluster in $CM_N$
18                 if $(CH_l \in CM_N)$ then
19                     $CM_k$ forwards request message to $CH_l$
20                     $CM_k$ becomes FN
21                 else if $(CM_l \in CM_N)$ then
22                     $CM_l$ forwards request message to $CH_l$
23                     $CM_k$ becomes FN
24                     $CM_l$ becomes FN
25                 continue
26             end
27         end
28     else
29         if $(FN_k < CR_N)$ then
30             goto 6
31         else
32             if $(CR_k$ is SCH$)$ then
33                 $CR_k$ selects new SCH from CM
34             else
35                 $CR_k$ leaves the cluster
36             end
37         end
38     end
39 else
40     $CR_k$ informs all CM
41     SCH becomes CH
42     new SCH is selected based on CHDF from $CMs$
43 end
44 END
```

the spectrum [27]. Therefore, routing protocol for CRAHNs has to consider the channel switching time, where the channel switching time is defined as the required time to tune the radio to the new channel. Moreover, the routing scheme should also cater delays due to queuing and back-off [28]. In CRAHN, the back-off delay is caused by multi-flow interference in a channel, where queuing delay is grounded on the output transmission capacity of a node on a particular channel. One of the fundamental tasks of CR is to analyze spectrum in its vicinity and to determine the available channels. Thus, a routing protocol in CRAHN has to consider the future activity of the PU to reduce route interruption time. Hence, to measure the stability of a route, the protocol needs to consider spectrum availability.

In CRAHN, recognizing the design challenges for routing protocol is dependent on the network objectives [29]. However, it is expected that the aforementioned challenges need to be addressed in designing an efficient routing protocol for cognitive radio ad-hoc network. Moreover, it is anticipated that such routing protocol may select stable paths with reduced delay. Hence, the proposed RARE protocol identifies the appropriate nodes as CHs and FNs, where these nodes provide maximum route stability. Thus, delay-aware routing in the RARE protocol for CRAHN is discussed in the next section.

VI. THE DELAY-AWARE ROUTING PROTOCOL IN RARE

The proposed routing protocol in the cluster-based network determines the route from any sender node to the destination node. The selected route in RARE needs to ensure faster data delivery to the destination since multiple paths are anticipated from sender to the destination. Hence, path that ensures lesser delay is selected by the proposed routing protocol to deliver the message. It is expected that the proposed clustering scheme identifies stable nodes as CHs and FNs. Moreover, in RARE, the intermediate nodes or the relaying nodes of a route are also the CHs and the FNs. In the protocol, delay is considered as the routing metric where three types of delay are considered, namely switching delay, back-off delay and queuing delay. Hence, the total Link Delay (δ_T^L) is defined as the arithmetic sum of these delays, which is expressed as follows,

$$\delta_T^L = \delta_T^S + \delta_T^B + \delta_T^Q \tag{2}$$

where, T is an intermediate link, which is positioned on the path from the sender node CR_s to the destination node CR_d. The total delay of link T can be expressed by δ_T^L where δ_T^S is the switching delay, δ_T^B is the back-off delay and δ_T^Q is the queuing delay of link T.

The proposed delay-based routing protocol in RARE is presented in this section where the routing metric is presented in the following sub-section. Route discovery, selection, and maintenance algorithms are later discussed in the subsequent sections.

A. ROUTING METRIC

As discussed earlier, in the proposed RARE protocol nodes that experience similar free channels are grouped into same clusters. Intermediate nodes are required to relay the message in a multi-hop network when a sender node is not directly connected to the destination node. In such situation, any intermediate node may need to switch from one channel to another to forward the message to its next hop. Thus, if a node requires channel switching to deliver the message to its next hop, time required for this switching purpose is considered to be a non-zero value. In this paper, the channel switching time is termed as Switching Delay (δ^S), where δ^S depends on the relative positions of the two channels in the channel set. Thus, if any node CR_i forwards message to the next hop CR_j, where CR_i needs to switch from ath channel of ACL_i to bth channel, the switching delay can be defined as follows,

$$\delta^S_{i,j} = k * |a - b| \tag{3}$$

here, k is considered to be a positive real number where k is determined by the tuning delay of two neighboring channels for a particular step size. For instance, tuning delay is considered to be 10 ms for a step of 10 MHz [26].

In the network, a CH waits for a random time before it broadcasts the beacon. CH uses the random back-off time to avoid collision when multiple neighboring cluster-heads intend to use the same channel. Moreover, because of the back-off period for the beacon message, other mini-slots in the super-frame are also delayed. Thus, for N_i contending nodes on a given channel C_i with a contention window size wc_o and p_c be the probability of collision, δ^B for CR_i can be determined by the following equation,

$$\delta^B_i = \frac{1}{(1 - p_c)\left(1 - (1 - p_c)^{N_i - 1}\right)} wc_o \tag{4}$$

In the cluster-based network, data traffic flows through the intermediate CHs and FNs, where neighborhood density plays an important role in the traffic flow. This is because; the message may require remaining in the queue for a longer period if the message passes through a dense area. Thus, queuing delay is defined in terms of neighborhood density, where the neighborhood density refers to the number of 1-hop neighbors of a node. Let, N_i be the number of neighboring nodes of CR_i where data rate of CR_i is DR_i and packet size is P. Then, Queuing Delay of upcoming packets (δ^Q) for CR_i can be determined by the following equation,

$$\delta^Q_i = \frac{PN_i}{DR_i} \tag{5}$$

Therefore, based on Equation 2 and considering the results from (3), (4) and (5), delay $\delta^L_{i,j}$ of the link that connects CR_i and CR_j can be expressed as follows,

$$\delta^L_{i,j} = \delta^S_{i,j} + \delta^B_{i,j} + \delta^Q_{i,j} \tag{6}$$

The path delay or route delay is defined as the cumulative sum of link delays for all the links in the route. Thus, considering a route r from a sender CR_s to the destination CR_d, the path delay δ^P_r can be expressed as follows,

$$\delta^P_r = \sum_{i,j \epsilon P_{th} s,d} \delta^L D_{i,j} \tag{7}$$

TABLE 2. Symbols used in the routing protocol.

N, k	Positive integer (e.g. 1,2,3,...)
CR_s	Sender Node
CR_d	Destination Node
CH_s	Cluster Head of CR_s if CR_s is a member node
CR_k	Any node in the network
CR_N	Neighbour of CR_k
$RReq$	Route Request Message
$RRep$	Route Reply Message
$CR_{k,N}$	Link that connects node CR_k with node CR_N
$Path$	Two dimensional Path Array
$Size\_Path$	Size of Path Array
Min_Delay	Minimum Delay
$RErr_{i,j}$	Error message to state broken link between node CR_i and CR_j
$DErr_{i,j}$	Error message for unreachable destination CR_d from CR_i

B. ROUTE DISCOVERY AND SELECTION

The proposed routing protocol in RARE starts with the route discovery process, where the sender node discovers all possible routes to the destination node. By considering the definitions in Table 2, the route discovery process is presented in Algorithm 4.

In the proposed routing protocol, when a node wants to send packets to any other node of the network, the sender node needs to discover all possible routes to the destination node. Thus, the sender broadcasts route request message to all its 1-hop neighbors. However, if the sender node is a CM, instead of broadcasting the route request message, the sender node sends a route request to its CH. Later, CH broadcasts the route request message to its 1-hop neighbors.

Considering the route discovery process in RARE, the CHs and the FNs carry out the route discovery process. Thus, any intermediate CM remains inactive during this discovery process. Hence, if a CM receives the route request message, that member ignores the message if the node is not the destination. However, if the route request is received by any CH or FN, the particular CH/FN initially checks the existence of the destination node in its neighborhood. If the destination node is not found in the neighborhood, CH/FN becomes a relay node and rebroadcasts the route request message to all its 1-hop neighbors. This process continues till the request message reaches the destination node.

On the other hand, if relay node finds the destination node in its neighbor list, the relay node calculates its switching delay to communicate with the destination using Equation 3. Afterwards, the relay node calculates its back off delay using Equation 4 and queuing delay using Equation 5. Next, the relay node adds all these three delays to come up with the link delay for the link that connects the relay node with the destination node. Next, relay node adds this link delay with the path delay, where the initial value of path delay is set to be zero. Afterwards, the relay node generates a route reply message where the message contains the path delay (*path_delay*) value and IDs of the two nodes associated with this link. The relay node forwards this route reply message to the neighbor node that previously broadcast the route request message.

Upon receiving the route reply message, any node relay node in the path calculates the link delay and adds this link

Algorithm 4 Route Discovery Algorithm

```
1  START
2  if ($CR_s$ == $CM$) then
3      $CR_s$ forwards $RReq$ to $CH_s$
4      $CH_s$ broadcasts $RReq$ goto 8
5  else
6      $CR_s$ broadcasts $RReq$
7      $Path\_Delay = 0$
8      while ($RReq$) do
9          $CR_k$ receives $RReq$
10         if ($CR_k$ != $CM$) then
11             if ($CR_d \epsilon CR_N$) then
12                 $CR_k$ calculates $Link\_Delay$ using Eq. 7
13                 $Path\_Delay=Path\_Delay + Link\_Delay$
14                 $CR_k$ sends $RReq$ with $Link$ and $Path\_Delay$
15                 while ($CR_k$ != $CR_s$) do
16                     $CR_k$ calculates $Link\_Delay$ using Eq. 7
17                     $Path\_Delay=Path\_Delay + Link\_Delay$
18                     $CR_k$ sends $RReq$ with $Link$ and $Path\_Delay$ to $CR_N$
19                     $CR_N$ becomes $CR_k$
20                 end
21                 if ($CR_k$ == $CR_s$) then
22                     $CR_s$ calculates $Link\_Delay$ using Eq. 7
23                     $Path\_Delay=Path\_Delay + Link\_Delay$
24                     $CR_s$ stores $Path$ with $Path\_Delay$ in $Path$
25                 else
26                     break
27                 end
28             else
29                 $CR_k$ broadcasts $RReq$
30                 $CR_N$ becomes $CR_k$
31             end
32         else
33             break
34         end
35     end
36     if ($Size\_Path > 1$) then
37         $Selected\_Route = Route\_Selection\_Algorithm$
38         $CR_s$ sends message to $CR_d$ using $Selected\_Route$
39     else
40         $CR_s$ sends message to $CR_d$ using Path
41     end
42 end
43 END
```

delay value to the received path delay. The relay node updates the route reply message by replacing the new path delay with the existing path delay and by adding the link in the existing path. Later, the relay node sends route reply message to the neighbor node that previously broadcast the route request message. This process continues till the sender node receives the route reply message. Once the sender node receives the route reply, sender node calculates the link delay and adds it with the received path delay. Next, sender node updates the Path array by adding the path delay and the full path, where the full path contains the entire links from the source sender node to the destination. This route discovery process is continued until all the paths from the source node to the destination node are obtained. Thus, the algorithm identifies all the possible paths from the sender node to the destination node and stores these paths along with the path delay in the Path array.

Next, the path selection process starts where the sender node selects the routing path (Algorithm 5). If the sender node receives multiple routes, sender node selects the path that provides the least delay as the routing path. Later, sender node uses this selected route to send the message to the destination node. However, if sender node discovers only one path during route discovery phase, sender node uses that particular route to send the message to the destination node.

C. ROUTE MAINTENANCE

For the proposed route maintenance algorithm (Algorithm 6), two types of disruption are considered, namely link failure and destination failure. When a link in the routing path is broken, then predecessor node of the broken link sends the route error message to the sender node. Upon receiving the route error message, sender node first removes the current route entry from the Path array. Afterwards, the sender node removes all the routes that contain the broken link from the Path array. Next, the path selection process starts where the sender node identifies a new routing path using the Route Selection Algorithm (Algorithm 5). Later, sender node uses this new route to send a message to the destination node. However, if sender node fails to find an alternative route in the Path array, sender node requires identifying new routes to the destination node, where the route discovery is performed using Algorithm 4.

On the other hand, the destination failure may occur because of the movement of the destination node or any other malfunction at the destination node. In such case, neighboring node of the destination sends the destination error message to the sender node. Upon receiving the destination error message, sender node starts route discovery process (Algorithm 1) to identify new routes to reach the destination node. The following section discusses the performance of the proposed RARE in the simulation environment.

VII. SIMULATION RESULTS AND DISCUSSION

Simulation results of the proposed RARE protocol are presented in this section, where the performance of RARE is evaluated and compared based on the simulation results. NS2 is considered as the simulation tool where each experiment is executed for 150 seconds and average results

Algorithm 5 Route Selection Algorithm

```
START
$Min\_Delay = Path[1,1]$
$flag=1$
for $i=2:Size\_Path$ do
    if ($Path[i,1] < Min\_Delay$) then
        $Min\_Delay=Path[i,1]$
        $flag=i$
    else
        Break
    end
end
return $Path[flag,2]$
END
```

Algorithm 6 Route Maintenance Algorithm

```
START
if ($link_{i,j} \in Path_{s,d}$) AND ($RErr_{i,j}$) then
    $CR_i$ notifies $CR_s$
    $CR_s$ removes the entry of the current route from Path
    $CR_s$ removes all the entries that contain $link_{i,j}$ from Path
    if ($Path \neq \phi$) then
        $CR_s$ calls Route Selection Algorithm
    else
        $CR_s$ calls Route Discovery Algorithm
    end
else
    Break
end
if ($link_{i,d} \in Path_{s,d}$) AND ($DErr_{i,d}$) then
    $CR_i$ notifies $CR_s$
    $CR_s$ calls Route Discovery Algorithm
else
    Break
end
END
```

of 100 runs are considered. In the simulation environment, proposed network is populated with randomly positioned SUs and PUs where other network configurations are presented in Table 3. Both topological and routing performances of RARE are evaluated and compared in this section. Hence, the performance of the proposed clustering protocol is discussed in Section VII-A and performance of the proposed routing protocol is presented in Section VII-B.

A. PERFORMANCE EVALUATION OF THE PROPOSED CLUSTER FORMATION SCHEME

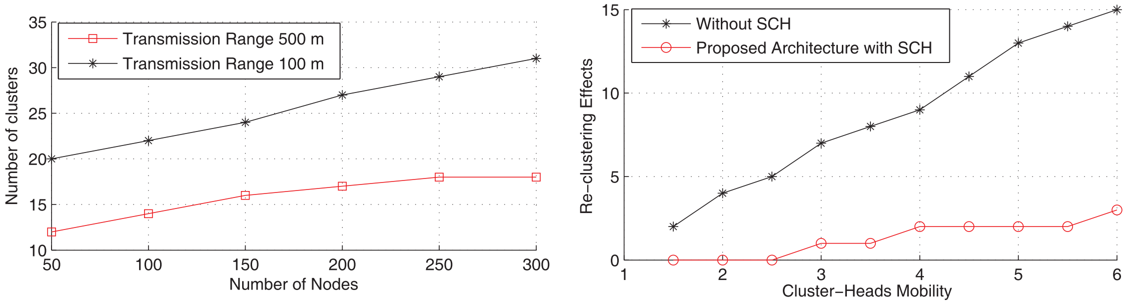
Performance of the proposed cluster formation scheme along with the cluster maintenance protocols are presented in 3 and 4, respectively. The efficiency of a cluster-based network can be investigated through total number of clusters in the network, where lesser number of clusters is preferable. Moreover, a stable clustering scheme also requires to reduce the chances of the network to be re-structured for nodes mobility. Hence, performance metrics of the clustering scheme are defined over number of constructed clusters and number of re-constructed clusters. Moreover, performance of proposed maintenance protocols is measured based on completion time. Furthermore, the proposed clustering scheme are compared with four existing schemes namely, cluster-based approach [18], SOC approach [19], node contraction approach [20] and CogMesh [21]. As presented in 5, clustering performance of these protocols are compared and analyzed based on number of clusters and number of common channels in each cluster.

TABLE 3. Simulation environment for RARE protocol.

Simulation Area	10 km^2 (square kilometers)
Number of SU	50 to 300 nodes
Number of Channels	10 Channels
Transmission Range of PU	1000 meters
Transmission Range of SU	100 meters, 500 meters
Network Bandwidth	1 Mbps
Packet Size	512 bytes
Packet Rates	100 packets/sec to 800 packets/sec
Initial Energy of SU	10 Joules
Tuning Delay	10 ms

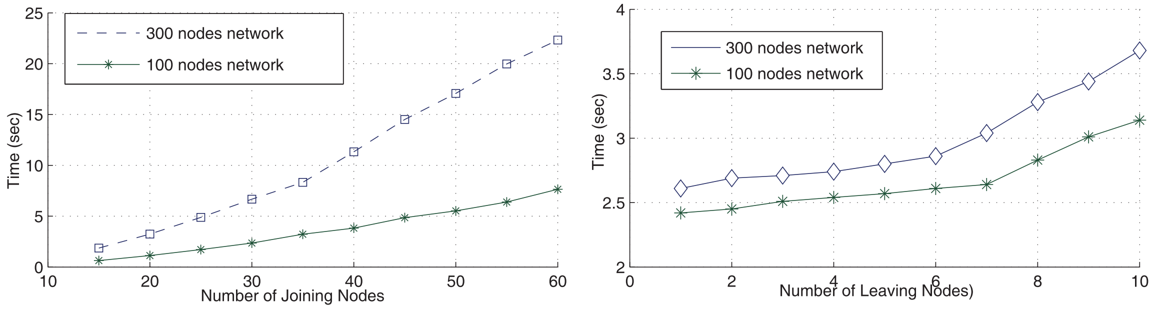
Figure 3(a) investigates the performance of the proposed cluster formation scheme based on number of constructed clusters and checks the impact of radio transmission range and network size over these clusters. Thus, two scenarios are considered where the radio transmission ranges are considered to be 500 meters and 100 meters. It is observed from the figure that the proposed scheme constructs a lesser number of clusters with the radio transmission range of 500 meters than the radio transmission ranges of 100 meters for all different size networks. This is because, when the transmission range of a node is increased, the coverage area of that particular node also increases. Thus, when cluster-heads have longer transmission range, clusters cover the larger area in the network. Therefore, higher transmission ranged nodes results a lower number of clusters in the network.

The proposed clustering scheme uses SCH to reduce the re-clustering effect where re-clustering phenomena are triggered by cluster-head's mobility. Therefore, simulation is conducted to measure the re-clustering effect for cluster-based networks with SCH and without SCH (Figure 3(b)). Here, to illustrate the re-clustering effect in a network of 300 nodes, the number of moving out CHs varies from 1 to 10. Here, the re-clustering effects are quantified as the number of newly constructed clusters with new member sets. From Figure 3(b), it can be seen that the proposed protocol with SCHs has lesser effect on the re-clustering issue. This relates to the explanation given in the earlier section, that is, if cluster-head moves out from a cluster, SCH takes charge of the cluster to maintain the intra-cluster connectivity without re-clustering. However,



(a) (b)

FIGURE 3. **(a) Node Vs Cluster.(b) Re-clustering effect vs CH's mobility.**



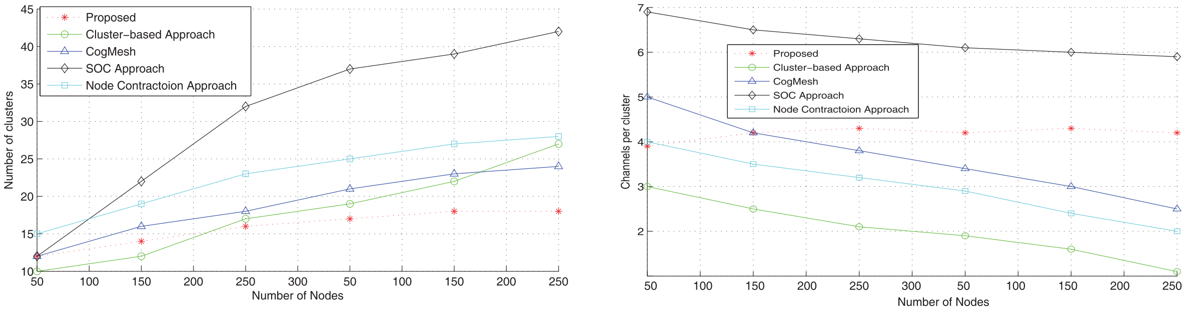
(a) (b)

FIGURE 4. **Performance evaluation for (a) Node Move-In. (b) Node Move-Out.**

from the figure, it is also observed that the proposed protocol has some re-clustering effects, since there may exist some SCHs who may not be directly connected with all the CMs. In such cases, once the SCH becomes the CH, all the existing member nodes may not reside in that particular cluster and may show the re-clustering effects. Nevertheless, Figure 3(b) shows that the proposed protocol with SCH significantly reduces the re-clustering effect triggered by the movement of the CHs.

To illustrate the node-joining scenario, randomly positioned new nodes ranging from 10 to up 100 are considered in Figure 4(a), where simulation execution time is considered as the evaluating factor. Figure 4(a) depicts that with the increasing number of new nodes, the time took for joining the network increases in both networks. The reason is that when the number of joining nodes is increased, more individual nodes are required to be joined with the network. Since in every joining session, a new node requires executing certain steps to accomplish the joining process, so the increased number of joining nodes increases the cumulative joining sessions, which eventually increases the total time taken for joining purpose. Furthermore, it is observed from Figure 4(a) that for any number of new nodes, shorter joining time is required when the nodes are joining in the 100-nodes network, than in the 300-nodes network. This is because, in a fixed area, node density is higher for the network comprising 300 nodes than the network comprising 100 nodes. Thus, when a new node attempts to join a higher dense network, the joining node finds more neighboring nodes as compared to a low dense network. As discussed earlier, after sensing the spectrum, a new node needs to discover its entire neighboring nodes and requires accessible channel lists of all the neighbors. Therefore, a particular new node requires a longer time to discover all its neighboring nodes in a higher dense network than to discover all its neighboring nodes in a lower dense network. Moreover, the node may find more neighboring clusters in a high-density network than a lower dense network. Therefore, checking with more clusters requires a longer time than checking with a lesser number of clusters. Thus, considering time periods, a new node requires a longer time to join in a higher dense network than to join a lower dense network.

Performance evaluation of the proposed Node Move-Out protocol is presented in Figure 4(b), where Figure 4(b) depicts that with the increasing number of leaving nodes, the time required for the leaving purpose increases in both networks. Since the cumulative time for leaving process increases with increasing number of leaving nodes, thus, with increasing number of leaving nodes, simulation execution time is also increased in both scenarios. Moreover, it is also observed from the figure that with the increasing number of leaving nodes, both networks show similar growth in the execution time. This is because, a node-leaving process in the proposed Node Move-Out protocol can be expressed as a local process, where a network-wide update is not required. Hence, similar growth in the simulation execution time is observed in the figure for both networks.



(a)

(b)

FIGURE 5. **Performance comparison of the proposed cluster formation scheme in RARE with other approaches.**

Performance comparison of the proposed clustering scheme with other approaches in terms of the number of clusters is depicted in Figure 5(a). This figure illustrations the relation between numbers of nodes and number of clusters for these approaches. It can be seen that as the number of nodes increases, number of clusters also increases in all approaches. However, when the node's number upturns to 300, proposed architecture gives 19 clusters where cluster-based approach, SOC approach, node contraction approach and CogMesh create 24 clusters, 42 clusters, 28 clusters and 27 clusters, respectively. Thus, as indicated in Figure 5(a), the proposed clustering protocol constructs a lesser number of clusters as compared with other approaches. This is because; the higher number of neighboring nodes is one of the major considerations for a CH selection process in the proposed scheme. Performance comparison of the proposed protocol with the other protocols in terms of a number of common channels per cluster is shown in Figure 5(b). It is shown that SOC approach has the highest number of common channels per cluster than others. Meanwhile, the proposed clustering scheme upholds a stable number of common channels per cluster while other three schemes have a declining number of common channels per cluster as the number of nodes increases.

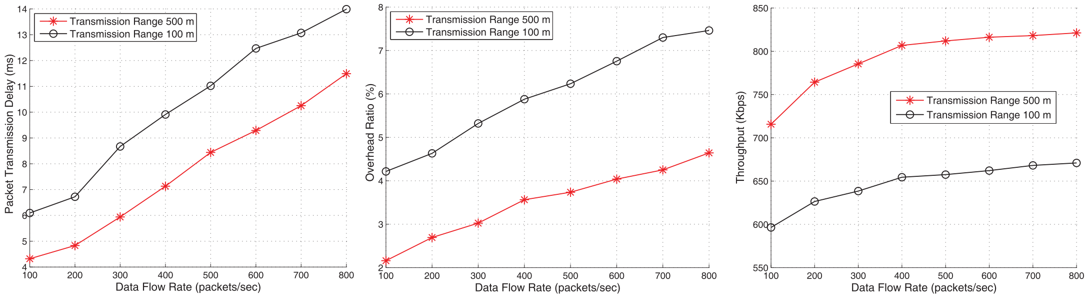
B. PERFORMANCE EVALUATION OF THE PROPOSED ROUTING SCHEME

Routing performance of the proposed RARE protocol is evaluated and compared in this section. Performance of the routing protocol in RARE is evaluated in two different network models where the performance metrics are packet transmission delay, throughput, and overhead ratio (Figure 6). Varied packet rates are considered to evaluate the performance of the protocol for different traffic load. Moreover, simulation results of the proposed routing protocol are compared with two other established routing protocols namely, the cluster-based approach [18] and CogMesh [21]. The comparative study is conducted based on packet transmission delay and overhead ratio.

From Figure 6(a), it is observed that the packet transmission delay is lesser in a network with radio transmission range of 500 meters than in the network with radio transmission range of 100 meters for all different traffic loads. This is because, when radio transmission range in a network is longer, a lesser number of intermediate nodes is engaged to forward the data in the network, which results in lesser data processing sessions. Moreover, it is also observed from Figure 6(b) that the overhead ratio is lesser in a network with radio transmission range of 500 meters compared to the network with radio transmission range of 100 meters for all different traffic loads. As the number of intermediate nodes is comparatively higher when radio transmission range is 100 meters, more control messaging is required for routing the packets from source to destination. Therefore, with increased control messaging, a network with radio transmission range of 100 meters has more network overhead ratio than that of a network with radio transmission range of 500 meters.

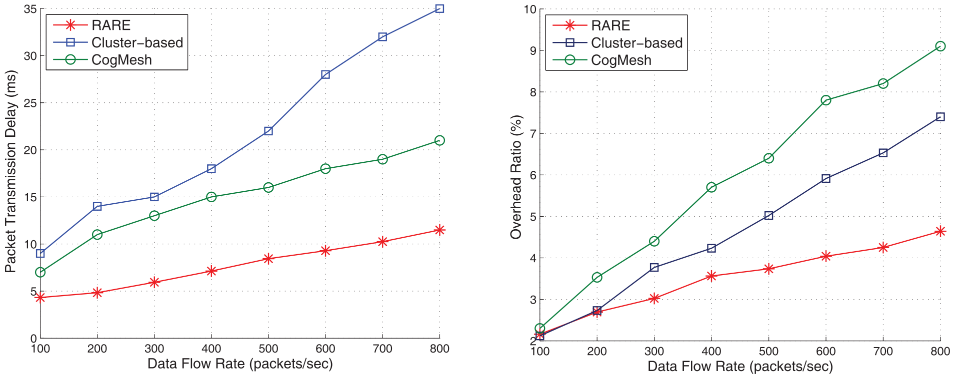
Figure 6(c) depicts that, for all different data flow rates, throughput is better in the network with the radio transmission range of 500 meters. The reason is that a network with longer transmission ranged nodes, source node finds a lesser number of intermediate nodes to relay the packets to the destination. Therefore, in reduced hop count, both overhead and delay are also reduced (Figure 6(a) and Figure 6(b)). Hence, throughput in the longer transmission ranged network gets better compared to that of a shorter transmission ranged network. It is also found that throughput does not linearly increase with the increased data rate in both networks. This is because increased data rate means increasing number of packets per second which may increase the queuing delay at the intermediate nodes. Therefore, data packets require a longer time to be delivered to the destination. Thus, the throughput increases slowing in higher traffic rate.

Performance comparison of the proposed routing scheme with other protocols in terms of packet transmission delay and overhead raion is depicted in Figure 3. This figure also attempts to define the behavior of these routing protocols for different traffic loads. From the Figure 7(a), it is observed that the packet transmission delay increases with increasing data flow rate in all three protocols. The reason is that when a higher number of packets propagates, the source node and the intermediate nodes need longer time to forward the



(a) (b) (c)

FIGURE 6. Performance evaluation of the routing protocol in different network models.



(a) (b)

FIGURE 7. Performance Comparison of the proposed delay aware routing protocol with other protocols.

packets to next hops, which increases the cumulative packet transmission delay. Therefore, the packet transmission delay increases with increasing data flow rate in all three architectures. On the other hand, compared to these two protocols, the proposed routing protocol shows better performance in terms of packet transmission delay for all different traffic loads. This is because; the proposed routing scheme takes the delay as the dominant factor for route selection.

Figure 7(b) depicts that the overhead ratio increases with increasing data flow rate in all three protocols. However, compared to the other two protocols, the proposed routing protocol shows better performance in terms of the overhead ratio for all different traffic loads. That is because; CogMesh and the cluster-based approach require more intermediate nodes for transmitting data packets to the destination node from the source node than the proposed cluster-based network. Moreover, the proposed protocol buffers the data packets and routing packets at each node more efficiently since route selection is more stable in RARE. The reason is that the proposed RARE effectively identifies the CHs and FNs of the cluster-based network and later ensures only these nodes for all routes in the network. Therefore, the proposed protocol finds the optimal path efficiently as compared to other two approaches; hence data delivery cost is minimum.

VIII. CONCLUSION AND FUTURE WORKS

In this article RARE, a spectrum aware cross-layer MAC protocol for CRAHN, is presented. In RARE, clusters are formed based on the parameter called CHDF. The proposed protocol attempts to maintain the number of clusters lesser while ensuring a stable and suitable number of common channels per cluster. The suitable number of common channels makes the proposed clustering scheme more robust to varying spectrum availability. The protocol also introduces secondary cluster head in each cluster, which reduces the re-clustering issue for mobile nodes. From the simulation results, it is observed that the proposed MAC protocol upholds a stable number of common channels per cluster in different scenarios that shrinks the re-clustering issue for varying spectrum availability. Furthermore, the proposed scheme constructs a lesser number of clusters compared to other approaches, as the higher number of neighboring nodes is one of the major considerations for a cluster head election in the proposed scheme. Thus, less number of clusters leads the backbone to be smaller, which results in efficient and reliable communication. On the other hand, a delay aware routing protocol for RARE is presented, where delay is considered as the routing metric for the protocol. In the proposed protocol, link weight is calculated based switching delay, back-off delay and queuing delay. Conclusively, in the simulation environment, it is observed that the proposed protocol performs better than other recently developed protocols. This study will lead to the development of the rendezvous algorithm for neighbor discovery.

REFERENCES

[1] J. Mitola and G. Q. Maguire, Jr., "Cognitive radio: Making software radios more personal," *IEEE Pers. Commun.*, vol. 6, no. 4, pp. 13–18, Apr. 1999.

[2] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "A survey on spectrum management in cognitive radio networks," *IEEE Commun. Mag.*, vol. 46, no. 4, pp. 40–48, Apr. 2008.

[3] *Notice of Proposed Rule Making and Order: Facilitating Opportunities for Flexible, Efficient, and Reliable Spectrum Use Employing Cognitive Radio Technologies*, document ET Docket No. 03-108, Federal Communications Commission, 2005, p. 73.

[4] J. M. Iii, "An integrated agent architecture for software defined radio," KTH, Stockholm, Sweden, Tech. Rep., 2000.

[5] N. Mansoor, A. K. M. M. Islam, M. Zareei, S. Baharun, T. Wakabayashi, and S. Komaki, "Cognitive radio ad-hoc network architectures: A survey," *Wireless Pers. Commun.*, vol. 81, no. 3, pp. 1117–1142, Apr. 2015.

[6] M. Zareei, A. K. M. M. Islam, S. Baharun, C. Vargas-Rosales, L. Azpilicueta, and N. Mansoor, "Medium access control protocols for cognitive radio ad hoc networks: A survey," *Sensors*, vol. 17, no. 9, p. 2136, 2017.

[7] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Comput. Netw.*, vol. 50, no. 13, pp. 2127–2159, 2006.

[8] S. Bhandari and S. Moh, "A survey of MAC protocols for cognitive radio body area networks," *Sensors*, vol. 15, no. 4, pp. 9189–9209, 2015. [Online]. Available: http://www.mdpi.com/1424-8220/15/4/9189

[9] G. P. Joshi and S. W. Kim, "A survey on node clustering in cognitive radio wireless sensor networks," *Sensors*, vol. 16, no. 9, p. 1465, 2016. [Online]. Available: http://www.mdpi.com/1424-8220/16/9/1465

[10] N. Mansoor, A. K. M. M. Islam, M. Zareei, S. Baharun, and S. Komaki, "A stable cluster-based architecture for cognitive radio ad-hoc networks," in *Proc. IEEE Region 10 Conf. (TENCON)*, Oct. 2014, pp. 1–6.

[11] N. Mansoor, A. K. M. M. Islam, M. Zareei, S. Baharun, and S. Komaki, "A novel on-demand routing protocol for cluster-based cognitive radio ad-hoc network," in *Proc. IEEE Region 10 Conf. (TENCON)*, Nov. 2016, pp. 632–636.

[12] Q. Zhao, S. Qin, and Z. Wu, "Self-organize network architecture for multiagent cognitive radio systems," in *Proc. Int. Conf. Cyber-Enabled Distrib. Comput. Knowl. Discovery*, 2011, pp. 515–518.

[13] K. E. Baddour, O. Üreten, and T. J. Willink, "A distributed message-passing approach for clustering cognitive radio networks," *Wireless Pers. Commun.*, vol. 57, no. 1, pp. 119–133, 2011.

[14] J.-Z. Zhang, F. Wang, F.-Q. Yao, H.-S. Zhao, and Y.-S. Li, "Cluster-based distributed topology management in cognitive radio ad hoc networks," in *Proc. Int. Conf. Comput. Appl. Syst. Model. (ICCASM)*, 2010, pp. 544–548.

[15] C.-C. Tang, K.-F. Ssu, and C.-H. Yang, "A cluster-based link recovery mechanism for spectrum aware on-demand routing in cognitive radio ad hoc networks," in *Advances in Intelligent Systems and Applications*. Berlin, Germany: Springer, 2013, pp. 601–610.

[16] A. Asterjadhi, N. Baldo, and M. Zorzi, "A cluster formation protocol for cognitive radio ad hoc networks," in *Proc. Eur. Wireless Conf. (EW)*, 2010, pp. 955–961.

[17] A. C. Talay and D. T. Altilar, "United nodes: Cluster-based routing protocol for mobile cognitive radio networks," *IET Commun.*, vol. 5, no. 15, pp. 2097–2105, Oct. 2011.

[18] X. Li, F. Hu, H. Zhang, and X. Zhang, "A cluster-based MAC protocol for cognitive radio ad hoc networks," *Wireless Pers. Commun.*, vol. 69, no. 2, pp. 937–955, 2013.

[19] L. Lazos, S. Liu, and M. Krunz, "Spectrum opportunity-based control channel assignment in cognitive radio networks," in *Proc. 6th Annu. IEEE Commun. Soc. Conf. Sensor, Mesh Ad Hoc Commun. Netw. (SECON)*, Jun. 2009, pp. 1–9.

[20] X.-L. Huang, G. Wang, F. Hu, and S. Kumar, "Stability-capacity-adaptive routing for high-mobility multihop cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 60, no. 6, pp. 2714–2729, Jul. 2011.

[21] T. Chen, H. Zhang, G. M. Maggio, and I. Chlamtac, "CogMesh: A cluster-based cognitive radio network," in *Proc. 2nd IEEE Int. Symp. New Frontiers Dyn. Spectr. Access Netw.*, vol. 1. Apr. 2007, pp. 168–178.

[22] M. Zareei, A. K. M. M. Islam, N. Mansoor, S. Baharun, E. M. Mohamed, and S. Sampei, "CMCS: A cross-layer mobility-aware MAC protocol for cognitive radio sensor networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2016, no. 1, p. 160, 2016.

[23] A. Motamedi and A. Bahai, "MAC protocol design for spectrum-agile wireless networks: Stochastic control approach," in *Proc. 2nd IEEE Int. Symp. New Frontiers Dyn. Spectr. Access Netw. (DySPAN)*, Apr. 2007, pp. 448–451.

[24] M. Youssef, M. Ibrahim, M. Abdelatif, L. Chen, and A. V. Vasilakos, "Routing metrics of cognitive radio networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 1, pp. 92–109, 1st Quart., 2014.

[25] M. Zareei, E. M. Mohamed, M. H. Anisi, C. V. Rosales, K. Tsukamoto, and M. K. Khan, "On-demand hybrid routing for cognitive radio ad-hoc network," *IEEE Access*, vol. 4, pp. 8294–8302, 2016.

[26] S. Krishnamurthy, M. Thoppian, S. Venkatesan, and R. Prakash, "Control channel based MAC-layer configuration, routing and situation awareness for cognitive radio networks," in *Proc. IEEE Military Commun. Conf. (MILCOM)*, Oct. 2005, pp. 455–460.

[27] H. Ma, L. Zheng, X. Ma, and Y. Luo, "Spectrum aware routing for multihop cognitive radio networks with a single transceiver," in *Proc. 3rd Int. Conf. Cognit. Radio Oriented Wireless Netw. Commun. (CrownCom)*, 2008, pp. 1–6.

[28] M. Rahman, "Cognitive radio ad-hoc networks: A routing perspective," Ph.D. dissertation, Dept. Biomed. Electron. Telecommun. Eng., Univ. Naples Federico II, Naples, Italy, 2013.

[29] P. Rawat, K. D. Singh, and J. M. Bonnin, "Cognitive radio for M2M and Internet of Things: A survey," *Comput. Commun.*, vol. 94, pp. 1–29, Nov. 2016.

NAFEES MANSOOR (S'08–M'17) received the B.Sc. degree *(cum luade)* in computer science and the M.Sc. degree in telecommunication engineering from Independent University, Bangladesh, and the Ph.D. degree from Universiti Teknologi Malaysia in 2016, with a focus on communication systems and networks. He is currently an Assistant Professor with the Department of Computer Science and Engineering, University of Liberal Arts Bangladesh. His research interests include cognitive radio network, wireless sensor network, ad hoc network, and artificial neural network. He received the MJIIT Scholarship to perform his Ph.D. research at Universiti Teknologi Malaysia. He was a recipient of best paper awards at the ICAICT 2016, RISP-NCCP 2015, ICEEE 2014, and MJJIS 2013. He was also a recipient of the JACTIM Research Proposal Award in 2012. He is serving as an Associate Editor for the IEEE ACCESS journal.

A. K. M. MUZAHIDUL ISLAM (SM'14) received the M.Sc. degree in computer science and engineering from Kharkiv National University of Radio Electronics, Ukraine, in 1999, and the D.Eng. degree in computer science and engineering from the Nagoya Institute of Technology, Japan, in 2007. He was with various industries in Bangladesh and in Japan. He has started his career as an Academician at Universiti Teknologi Malaysia, Malaysia. Since last year, he has been serving at the University of Liberal Arts Bangladesh as an Associate Professor, where he is also the In-Charge of the CSE Department. He has published over 75 international research publications. His research interests include network achitecture, communication protocol, cognitive radio network, wireless sensor network, IoT, and network security. He is an Advisory Member of ICBAPS2015, Malaysia. He has received Japanese Government Monbusho Scholarship (2002–2006). He was the Communication Track Chair at ICIEV15, ICAEE 2015, and ICAEE 2017 International Conferences. He has served as the Program Chair of ICAICT 2016 International Conference, Bangladesh. He has also served as the Secretariat of ICaTAS 2016 International Conference, Malaysia, and the 7TH AUN/SEED-Net 2014 International Conference on EEE. He is a Chartered Engineer.

MAHDI ZAREEI (S'11–M'17) received the M.Sc. degree in computer network from the University of Science Malaysia in 2011 and the Ph.D. degree from the Communication Systems and Networks Research Group, Malaysia-Japan International Institute of Technology, University of Technology Malaysia, in 2016. He is currently a Post-Doctoral Fellow with the School of Engineering and Sciences, Tecnologico de Monterrey, Campus Monterrey. His research interests include IoT, cognitive radio, energy harvesting, 5G, and wireless sensor network. He is a member of the Mexican National Researchers System, level I. He received the JASSO Scholarship in 2015 to perform part of his Ph.D. research at Osaka University, Japan. He is serving as an Associate Editor for the IEEE Access journal.

CESAR VARGAS-ROSALES (M'89–SM'01) received the M.Sc. and Ph.D. degrees in electrical engineering from Louisiana State University, Baton Rouge, LA, USA, with a focus on communications and signal processing. He was the Director of the Ph.D. Program in information and communications technologies with the Tecnologico de Monterrey, Campus Monterrey, from 2012 to 2016. He is currently the Leader of the Research Group on Telecommunications at Tecnologico de Monterrey. He is the co-author of the book *Position Location Techniques and Applications* (Academic Press/Elsevier). His research interests are personal communications, 5G, cognitive radio, MIMO systems, mobility, stochastic modeling, traffic modeling, intrusion/anomaly detection in networks, position location, interference, routing in reconfigurable networks, and optimum receiver design. He is a member of the Mexican National Researchers System (SNI), level II, a member of the Academy of Engineering of Mexico, and a regular member of the Mexican Academy of Sciences. He is the IEEE Communications Society Monterrey Chapter Chair and the Faculty Advisor of the IEEE-HKN Lambda-Rho Chapter. He was also the Technical Program Chair of the IEEE Wireless Communications and Networking Conference (IEEE WCNC 2011).

• • •