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Research paper

Spectrum aware clustering in cognitive radio ad hoc networks

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Abstract

Cognitive radio (CR) is an emerging technology developed for efficient utilization of the radio spectrum. CRN utilizes CR technology and enables the unlicensed users also referred as secondary users (SUs) to access free portions of the licensed spectrum in an opportunistic manner. To support scalability and stability in distributed CRNs also referred as cognitive radio ad hoc networks (CRAHNs), SUs are often organized into smaller groups known as clusters. Spectrum aware clustering is considered as the key technique to overcome numerous is-sues associated with the dynamic nature of CRAHNs. This article focuses on clustering in CRAHNs and presents a comprehensive review of various spectrum aware clustering algorithms presented in the literature. The article highlights notable clustering metrics and includes the description of cluster formation and maintenance process. The article also renders potential research gaps in existing research works and discusses open challenges and issues that need to be addressed for efficient clustering in CRAHNs.

Keywords: *Ad Hoc Networks; Cognitive Radio Network; Spectrum Aware Clustering; Survey.*

1. Introduction

Recent upsurge and technological advancements in wireless communications lead towards the spectral congestion and scarcity problem where several licensed bands are underutilized and unlicensed bands are overcrowded. Cognitive radio (CR) is an emerging wireless technology that copes with the spectrum congestion and scarcity problem and strives to improve the quality of wireless communication through opportunistic utilization of the underused licensed spectrum [1] [2]. CR network (CRN) employs CR technology and enables the unlicensed users also referred as secondary users (SUs) to dynamically access the free portions of the licensed spectrum when not in use by the licensed users. In CRNs, PUs own prior license to operate over the allotted licensed spectrum. SUs can exploit the unused portions of licensed spectrum or freely available licensed channels when not in use by the incumbent PUs, and vacate or switch to some other unused channels whenever the PUs reappear on their allotted bands [3]. SUs can also stay in the same band by altering their transmission parameters to avoid interference to the PUs. For opportunistic utilization the unused licensed channels, SUs perform four spectrum-aware operations namely spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility [4]. Spectrum sensing enables the SUs to scan the surrounding radio environment and to discover currently unutilized licensed channels. Spectrum decision allows the SUs to analyze the observed available channels as per QoS requirements and to identify the most significant band for their communication. Spectrum sharing function ensures proper coordination among the SUs' transmission so that available channels are shared in an efficient manner without or with a minimum number of collisions. Spectrum mobility enables the SUs to resume the unfinished transmission by switching the ongoing transmission to a new route or to a different available licensed channel with minimum degradation in QoS.

CRNs can be broadly classified into infrastructure CRNs and infrastructure-less CRNs as shown in Fig. 1 [5]. Infrastructure CRN consists of a central entity or a CR base-station, which is responsible for managing all spectral-related activities. SUs are usually within one or two hops away from the CR base-station and communicate with each other through the CR base-station. Infrastructure-less CRN also referred as or CR ad hoc network (CRAHN) consists of specialized mobile SUs that perform spectral managerial decisions based on locally sensed surrounding information and communicate with one another in a multi-hop manner independent of any central controller or CR base-station. SUs perform spectrum sensing periodically to sense the surrounding environment and access the currently underutilized licensed channels for their communication. In CRAHNs, SUs may have a different set of available licensed channels owing to the dependency of channels' availability on the PUs activity. Moreover, sensed available channels of SUs also change with time. Hence, CRAHNs environment is extremely dynamic in nature. Absence of common control channel (CCC) or CR base-station and the mobility of SUs further enhance the dynamicity of the network [6].

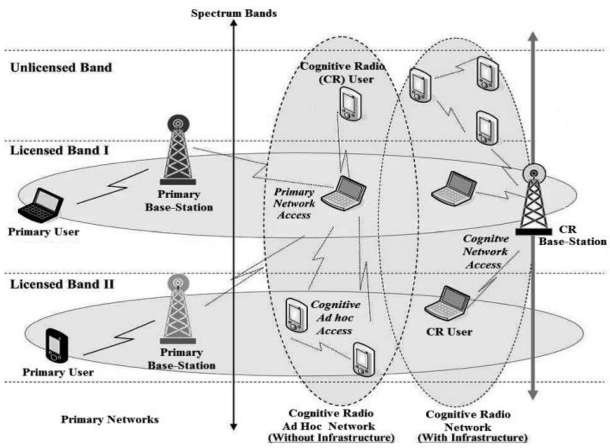

Fig. 1: Cognitive Radio Network Architecture.

To support stability, scalability and facilitate cooperative tasks in CRAHNs, SUs are often organized into smaller groups through clustering. Clustering is a topology management scheme which logically organizes the network nodes (i.e. SUs) into smaller groups known as clusters. Each formed cluster usually consists of a cluster head node, cluster member nodes, and gateway nodes. Cluster head acts as a central coordinator and is responsible for controlling and managing all activities of the cluster. Cluster member nodes associate themselves with one or more cluster heads and communicate regularly with their cluster head. Gateway nodes act as a bridge and interlink two or more clusters. Fig. 2 illustrates an example of clustering in CRAHNs. Here, SUs are organized in smaller groups to form three clusters (i.e. C1, C2, and C3). Each cluster consists of a cluster head, member SUs and may have intermediate SU or gateway SU between two clusters. CH1, CH2, and CH3 are the cluster head of the cluster C1, C2, and C3 respectively. IN1 interlinks cluster C1 and C2, and IN2 interlinks cluster C1 and C3.

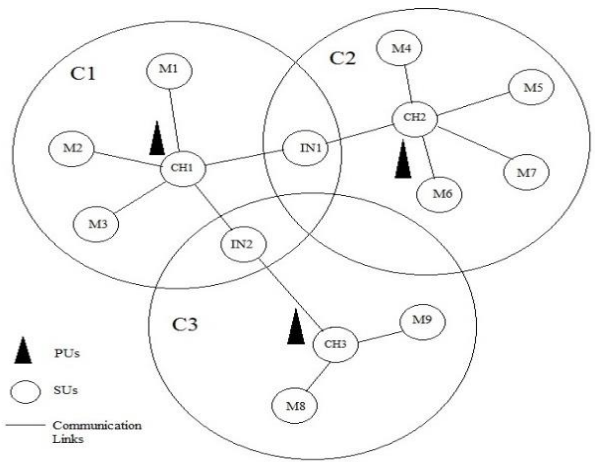

Fig. 2: Clustering in CRAHN.

In CRAHNs, clustering is considered to be the most effective topology management scheme since it is capable to handle and resolve numerous issues associated with the dynamic nature of the network. Typically, clustering in CRAHNs brought about the following major advantages [7].

- Clustering improves the network stability via minimizing the effect of local changes on the network-wide performance.
- Clustering enhances the scalability of the network via minimizing the communication overhead and parallelism.
- Clustering effectively handles and facilitates cooperative tasks among SUs which further aid to improve the network performance.

Several clustering algorithms have been devised in the literature to partition a large CRAHN into smaller groups or clusters. These algorithms are spectrum aware and utilize the surrounding radio environment information of the SUs to form clusters. Typically, existing spectrum aware clustering algorithms form clusters based on the following metrics:

- Availability of channel: Cluster formation based on the similar availability of channels ensures a higher availability of common channels (CCs) among SUs.
- Channel quality and signal strength: Cluster formation on the basis of the channel quality and signal strength minimizes the number of clusters, and also reduces the inter-cluster and intra-cluster interference.
- Location of SUs: Geographically closed SUs may have similarly available channels and have similar characteristics of white spaces. Therefore, the formed cluster consists of a higher availability of CCs among SUs.
- Number of neighbors: Cluster formation on the basis of the number of neighboring nodes minimizes the intra-cluster distance and the overhead incorporated with intra-cluster communications.
- Number of hops: SUs can form two type of clusters namely single-hop cluster and multi-hop cluster. Single-hop: Member SUs exchange information with the cluster head in a single hop. Cluster formation based on single-hop results in larger number of clusters. Multi-hop: All member SUs exchange information with its cluster head in more than one hop (i.e. two hops or more). Cluster formation based on multi-hop results in lesser number of clusters.

The ultimate objective of spectrum aware clustering is to enhance the network-wide performance via the establishment of local CCCs within the cluster, enhancement on cluster stability for strengthening the intracluster and intercluster connectivity, enhancement on the energy efficiency of SUs, and the intensification of cooperative tasks among SUs.

This study focuses on spectrum aware clustering and presents a comprehensive review of various spectrum aware clustering algorithms devised for CRAHNs. In this study, we highlight notable clustering metrics, explain the steps involved in the cluster formation and maintenance, identify potential research gaps in existing clustering algorithms, and discuss open challenges and issues for future research works.

Rest of the paper includes the following sections. Section 2 presents an overview of diverse clustering algorithms, explains cluster formation process along with the pros and cons. Section 3 discusses open challenges and issues that need to be addressed while clustering in the dynamic environment of CRAHNs, and at the last, conclusions are drawn based on the study.

2. Literature review

This section briefly overviews and renders the fundamental concept and working principle of state-of-the-art spectrum aware clustering algorithms presented to facilitate the stability, scalability, and cooperative tasks among SUs in CRAHNs.

Chen et al. [8] presented a cluster based framework named as CR based mesh network (Cogmesh) for decentralized CRNs. Cogmesh involves clustering in two different phases i.e. setup phase and optimization phase. In the setup phase, each SU listens on one of its idle channels to hear the beacon messages sent from other cluster heads. If the SU receives the beacon messages within the pre-defined time interval then it sends a request message to the cluster head to join the cluster. Otherwise, the SU declares itself as a cluster head and forms cluster on that channel and request the neighboring SUs to join the newly formed cluster. If the SU does not hear any beacon but receives a neighbors' message then it switches to next channel and attempts to detect any other single-hop cluster head. If the SU still fails to join any cluster then it declares itself as a cluster head. In optimization phase, clusters are merged in a manner such that there is at least one channel commonly available among all member SUs. Cogmesh adapts to the change in network topology and radio environment, however, it suffers from frequent re-clustering and maintenance issues and incurs a large control overhead.

Asterjadhi et al. [9] presented a distributed clustering algorithm named as COMBO that utilized the spectrum availability information to form clusters in CRNs. In COMBO algorithm, each SU calculates a weighted priority on the basis of minimum availability of CCs with k-hop neighbors, k-degree of connectivity and its identity (ID), and exchanges its weighted priority with the k-hop neighbors. The SU having the largest weighted priority among the k-hop neighbors forms a cluster and sends the cluster information to its k-hop neighbors. All neighboring SUs that overhear a higher weighted priority value associate themselves with cluster head. In case, if any SU does not hear any request then it forms a new cluster and becomes the cluster head of the newly formed cluster. The algorithm is automatically terminated whenever each of the SU either becomes a cluster head or a member. Since combo aims at maximizing the number of CCs, it results in a larger number of small-sized clusters.

Baddour et al. [10] utilized affinity propagation mechanism and presented a clustering algorithm that forms clusters on the basis of available channels and node degree of the SUs. In the presented algorithm, SUs exchange their available channels and node degree information with the neighboring SUs. Each SU then calculates a metric s(i,n) that measures the similarity level between a pair of SUs (i.e. SU_i, SU_n) in terms of the number of common channels between them. Each SU computes and further exchanges the responsibility r(i, k) and availability a(i, n). Here, r(i, k) refers to the suitability of SU_k to be the cluster head for SU_i and a(i, n) refers to the suitability of SU_n as a cluster head for SU_i from the perspective of SU_i and SU_n. All those SUs having r(i, i)+a(i, i)>0 become the candidate for cluster head, and the SU which has maximum node degree within the single-hop neighbors become the cluster head. Simulation results showed that the presented algorithm results in lesser number of clusters in the network and a higher availability of CCs in the formed clusters.

Zhang et al. [11] employed group-wise constrained approach and presented a distributed clustering algorithm that organizes networks nodes into single-hop clusters. In the presented algorithm, each SU forms a disjoint cluster, which consists of only one node (i.e. each SU represents an individual cluster). Merging operation is then performed where nearby clusters are merged that have at least one CC between them. The merging operation is continued until the number of clusters reduces to the predefined number, the value of which depends on the number, density and the transmission range of the SUs. As more energy is consumed by cluster heads, the responsibility of cluster head is circulated among the member SUs to save energy of cluster heads. The presented algorithm consumes lesser energy and results in lesser number of clusters.

Huang et al. [12] presented a clustering algorithm which divides the network into smaller multi-hop clusters based on the channel availability and node degree of the SUs. In the presented algorithm, clusters are formed on the basis of the node importance degree $D_{i,m}$ which is calculated as follow:

$$D_{i,m} = \frac{n_{i,m}}{1 + H_{i,m} + S_{i,m}}$$

where $n_{i,m}$ is the number of one hop and two-hop neighbors of SU_i on the channel, $H_{i,m}$ refers to the average number of hops from all one-hop and two-hop neighbors to SU_i, and $S_{i,m}$ refers to the average channel switches when different channels have been chosen by a SU with the neighboring SUs. SUs calculate and exchange $D_{i,m}$, and the SU having the maximum $D_{i,m}$ is selected as a cluster head. All other SUs associate themselves with the cluster heads having maximum $D_{i,m}$. Through simulations, it is shown that the presented algorithm results in lesser number of clusters in the network, exhibits a higher a number of CCs between neighbor clusters, and minimizes the clustering overhead.

Li and Gross [13] considered channel availability and node degree as clustering metrics and presented a clustering algorithm that provides continuous connectivity among cluster heads, and connectivity among the cluster head with its members. In the presented algorithm, SUs exchange the information of available channels for each neighboring SU. Each SU calculates and further exchanges two-tuple metrics (P, G). P is spectrum connectivity degree and refers to the total number of CCs between SU_i and each neighboring SUs. G is local connectivity degree and refers to the number of CCs among the SU and its entire neighboring SUs. The SU who have least P value is selected as a cluster head. In case, if two SUs have the same P then the SU having higher G becomes the cluster head. All non-cluster head SUs associate themselves with cluster heads and become member SUs. In case, if member SU is located in more than one cluster then the SU associates itself with cluster head that maximizes the number of CCs in the cluster. Through simulations, it is shown that the presented algorithm results in lesser number of formed clusters, higher number of CCs, and higher number of CCs with neighboring clusters.

Bradonjic and Lazos [14] considered channel availability as clustering metrics and presented a clustering algorithm that attains a trade-off between the cluster size and the number of CCs in a cluster. In the presented algorithm, SUs exchange the local information of available channels with neighbor SU, and construct a bipartite graph G(X∪Y,Z) which consists of two sets of vertices X∪Y, and each edge e ∈ Z connects X and Y. Here, X refers to the SU_i and its neighbors, vertices Y refer to the available channels of SU_i, and each e specifies that SU_i ∈ X has an available channel y ∈ Y. Based on three different clustering criteria namely maximum node biclique (MNB), maximum edge biclique (MEB) and maximum one-sided edge cardinality biclique (MECB), each SU constructs a biclique from the bipartite graph. SUs then calculate and further exchange the weight $w_i = Q^*(A, B)$. All those SUs who have maximum w_i among their neighbor SUs become the cluster heads. Rest of the SUs associate themselves with the cluster head which is one hop away and has highest w_i among neighbor cluster heads. Simulation experiments proved that the proposed algorithm results in lesser number of clusters in the network and a higher number of common channels in a cluster.

Li et al. [15] utilized channel quality, signal strength, and channel availability as clustering metrics and presented a clustering algorithm for static or quasi-static CRNs. In the presented algorithm, SUs exchange the information of available channels and compute a reserved value (RV) on each connected link with neighboring SUs. Calculated RVs are then exchanged with the neighboring SUs. SUs then add the RV of each connected link and generate an aggregated RV (ARV). The SU having maximum node degree or minimum node ID among neighboring SUs become the cluster head. All other SUs associate themselves with the cluster heads that have connected links with the least ARV. Through simulations, it is shown that the presented algorithm results in lesser number of clusters with the higher number of CCs, exhibits lesser clustering overhead, and minimize the number of re-clustering.

Ozger and Akan [16] utilized channel availability, geographical location of SU and node degree as clustering metrics, and proposed an event-driven spectrum aware clustering (ESAC) algorithm that forms temporary single-hop clusters upon the detection of a specified event. Temporarily formed clusters are maintained until triggering event is terminated. In ESAC, all those SUs which detect an event are assigned as the eligible node (EN) for clustering. Each EN then assigns its neighbors that are nearby to the sink and are at a greater distance from the event, as eligible nodes. All newly assigned eligible SUs further attempt to discover their next-hop EN till the sink node has been discovered. An eligible node with the maximum weight among its single-hop neighborhood is then selected as a cluster head. The cluster head then sends a request message to one-hop neighboring SUs to join its cluster as members. Through simulations, it is shown that ESAC maximizes the number of neighboring SUs with CCs and also exhibits lesser energy consumptions as compared to other clustering algorithms.

Shah et al. [17] presented a spectrum-aware cluster based energy-efficient multimedia (SCEEM) routing algorithm that provides energy efficient routing and supports the QoS by minimizing the number of the SUs in route establishment process. In SCEEM algorithm, SUs that have a higher number of CCs or higher spectrum rank are grouped to form a cluster. The group members having the highest spectrum energy rank is elected as the cluster head. Cluster heads employ the TDMA approach within the cluster and utilize the CSMA technique for inter-cluster medium access. SCEEM algorithm consists of information sharing phase where SUs exchange their available channels via broadcasting the information message on a pre-assigned control channel. In SCEEM algorithm, SUs calculates their spectrum energy rank and compute the relative spectrum availability rank with neighboring SUs. The SUs then compare their rank value with the rank value of neighboring SUs, and the SU having the highest rank is declared as a potential cluster head (PCH). If a PCH does not receive any cluster head message within a threshold time then it declares itself as a cluster head and informs the neighbors to join the cluster via broadcasting cluster head request messages.

Saleem et al. [18] presented a novel clustering algorithm that utilizes the channel quality metric for cluster formation. The channel quality metric of a channel is measured in terms of the likelihood of the channel to be in the off state at a specified time. SUs exploit the channel capacity metric and rank their available channels. This algorithm consists of two phases namely cluster formation phase and cluster maintenance phase. Cluster formation phase comprises of cluster head election, node joining and gateway election steps. In cluster head election, the SU having maximum availability of channels is selected as a cluster head. In node joining step, a non-clustered SU is associate itself with the cluster head having the highest rank. In gateway election step, each member SU detects the presence of neighboring clusters on each of its available channels, and become a gateway node by sending a gateway request message to its cluster head. Cluster maintenance phase involves merging and splitting steps where two different clusters are merged and split on the basis of the number of CCs per cluster.

Zareei et al. [19] exploited available information of the neighbor nodes and presented a distributed clustering algorithm that forms clusters on the basis of availability of channels, and power and speed of the SUs. In the presented algorithm, a new metric named as CHEV has been introduced which is used to identify the SU which has the maximum number of neighbors and CCs and has maximum energy and minimum speed. This algorithm consists of maximum vertex biclique graph (MVBG) construction phase and cluster head election phase. In MVBG phase, each SU builds a neighbors list and constructs an undirected bipartite graph and maximum vertex biclique graph. In cluster head election phase, CHEV of each SU is calculated and the SU having the maximum CHEV is selected as the cluster head. Each member node determines the presence of other CHs and informs the cluster head about the newly detected neighbors. After receiving this information, CH assigns the member node (have highest CHEV) as a gateway node with each identified cluster for inter-cluster communication.

Zhang et al. [20] presented a graph cut based distributed clustering algorithm with the aim to minimize the number of inter-cluster CCs and maximize the number of intra-cluster CCs. The algorithm models the network as a weighted undirected graph based on the local topology and computes the SU similarity metric. The SU similarity metric is calculated by the aid of two components namely the ratio of common channels and relative position similarity. In this algorithm, each SU constructs a weighted graph G(V, E), where V and E refer to the neighbor set and link set of the SU and calculates the weight of link with the aid of the SU similarity metric. Each SU utilizes the constructed weighted graph and formulates the clustering process as a graph cut problem in a manner such that the graph cut of $(X, \bar{X})$ should minimize the cut(X) and maximize U(X) where $X \subseteq V$ are SUs belonging to the same cluster and $\bar{X}$ are removed SUs. Next, SU broadcasts the cluster information through its available channels and compares its cluster utility with received clusters utility information. If the SU detects a cluster having better clustering information then it replaces its cluster with the detected cluster.

Ozger et al. [21] considered physical proximity, available channels, and relative position of the SU to the sink node and presented mESAC clustering algorithm that forms clusters in two different stages namely eligibility corridor determination phase and cluster head selection stage. Eligibility corridor determination stage determines the corridor between the event and the sink by changing the status of the nodes that belong to the same region. In this phase, eligibility clustering request messages are sent by event detecting nodes to neighbors that are one-hop away through a common control channel. The node which is closer to the sink becomes an eligible node. The eligible nodes again send the messages to the non-eligible one-hop neighboring nodes until the request message reaches the sink node. In cluster head selection stage, eligible nodes are grouped in the event to the sink corridor as per the availability of the spectrum and only the appointed nodes are eligible to form the clusters. In this phase, a weight is assigned to all eligible nodes on the basis of node degree, availability of channels, remaining energy, distance with sink, and speed of the node. At last, the eligible node having the highest weight becomes the cluster head.

Xiaoyan et al. [22] considered the available channels, geographical position, and database statistics and proposed an improved clustering algorithm for centralized CRNs with an aim to improve the network throughput and maintain the clusters' stability. In this clustering algorithm, SUs establish wireless connections with potential neighbors, and only the cluster member can directly communicate through the available channels. The gateway nodes are the SUs that relay the traffic between clusters and connect two different clusters. The clustering algorithm requires two rounds of neighbor discovery and cluster formation involves three steps. In the first step, SU find out their neighbors and compute the reserved value by the aid of three parameters namely channels' capacity, degree of stability and quality of each connected link, where channels' capacity is estimated via Shannon's formula, degree of stability refers to the number of CCs between two SUs and quality refers to the sum of the CCs'. SUs compute channels' capacity, stability degree and quality, and then rank each link on the basis of the capacity rank, stability rank and quality rank of the link. SUs then compute the reserved value which is a weighted sum of the three rank values. In the second step, SUs exchange the reserved values of links and control information with the neighboring SUs. After receiving the neighbors' reserved values, each SU adds the reserved values (sent and received) of the same link and utilize the updated reserved values to form clusters according. In this step, the SU which has the most 1-hop neighbors or with the lowest node ID is selected as CH and the channel which either is the CC among all cluster members or has the minimum frequency is elected as CCC. In the third step, formed clusters are initialized and the cluster members hear the cluster formation beacon from cluster head on the CCC.

Dutta et al. [23] presented a novel clustering algorithm where SUs are required to sense and collect the available as well as underuse PU channels and gather the information about neighboring SUs using HELLO packets. In this clustering algorithm, all SUs are also required to maintain a set S that contains the identities of the neighboring SUs. The important parameters used for cluster formation include the signal to interference and noise ratio (SINR) and the expected transmission time (ETT). SUs compute the difference in SINR with their neighboring SUs and the SUs that have the SINR and ETT difference within the predefined threshold values are placed in the same cluster, and the SU having minimum SINR is elected as the cluster head. SUs having the SINR and ETT difference outside the predefined thresholds are marked as outliers and do not join any cluster. The SU which is elected as CH broadcasts the CH declaration message. The neighboring SUs that receive the declaration message then compare the SINR and ETT with CH and join the cluster with the smallest value otherwise declares themselves as the gateway (GW).

Li et al. [24] proposed a novel clustering algorithm named as ROSS that forms clusters on the basis of the proximity of available spectrum of the SUs in their neighborhood. In ROSS, clusters are formed in two phases namely cluster formation phase and membership clarification phase. In the cluster formation phase, the proximity of available channels of the SU and the cluster heads are determined by the aid of the individual connectivity degree (ICD) and neighborhood connectivity degree (NCD). Each SU utilizes the ICD and NCD and calculates the connectivity vector, and compares its connectivity vector with neighboring SUs. The SU having lowest ICD becomes a cluster head. If two SUs having the same ICD then the SU having the highest NCD becomes the cluster head and the other SU becomes the member of CH. Moreover, if two SUs have the same NCD then the SU having smallest ID becomes the CH. After clusters are formed, there might be a situation where a SU be a member of two or more clusters. In membership clarification phase, the SUs belong to more than one cluster are exclusively added with only one cluster and also removed from the other clusters. The SU is moved to the cluster that results in the increase of common channels in the claiming clusters. Kumar and Singh [25] presented a localized clustering algorithm named as weight-based clustering (WCL) that partitions the network into single hop clusters on the basis of the availability of channels, the speed of the SUs and the interference level of the PUs. In WCL, each SU computes a weight w and further exchanges its computed weight with one hop neighboring SUs. The weight w_i of the SU_i is calculated as follow:

$$w_i = \alpha c_i + \beta p_i + \lambda / v_i^2$$

where c_i and v_i refer to the number of available channels and the speed of the SU_i respectively, p_i is the interference level of the PUs, and α, β and γ are predefined scaling factors which are calculated on the basis of the environment of CRNs. WCL involves the cluster formation in two phases namely cluster head selection and cluster formation phase. In cluster head selection phase, each SU sets a timer t_1 and broadcasts its weight w on each of its available channel. On receiving the broadcast messages from the neighbors, each SU verifies that it has received the higher weight or not. If a SU does not receive a higher weight within t_1 then it declares itself as a cluster head. Next, the cluster head node set a timer t_2 and sends a cluster head message to its neighboring SUs on the CCs and upon expiry of t_2, the cluster head terminates the cluster formation process. In cluster formation phase, the SUs that have received a higher weight attempt to join the cluster via sending a join message to the respective cluster head. Through simulation, it is shown that WCL algorithm maximizes the stability and scalability, and minimizes the communication overhead.

3. Open challenges and issues

In CRAHNs, clustering is extremely challenging since extreme dynamic environment results in loss of connectivity among the cluster heads and the cluster members, and frequent re-clustering and cluster maintenance impose additional overheads. This section briefly highlights open challenges and issues that should be handled in the future works for efficient clustering in CRAHNs.

- Static or quasi-static network: Existing clustering algorithms generally consider a static or quasi-static network and assume that the network topology does not change or undergoes little changes with respect to time. However, the assumption itself is impractical since the environment of CRAHN is of highly dynamic in nature. Thus, the design of efficient clustering solution for CRAHNs having highly dynamic environment is still open.
- Heterogeneity in channels: Existing clustering algorithms usually consider the available channels of all SUs to be of similar type and exclude some important characteristics such as channel quality, bandwidth, QoS requirement etc. In a real environment of CRAHNs, characteristic of each of the available channel can be different as available channels are located on different frequencies and also may have different bandwidths. Thus, the heterogeneity in channels should be considered while forming clusters.
- Diversity in transmission range: Existing clustering algorithms form clusters while assuming the similar transmission range of the SUs. However, in real time, the transmission range of each SU may differ since the transmission range is affected by several parameters such as dynamics in PUs activity, congestion, and collisions, hidden terminal problem etc. Hence, heterogeneity in the transmission range of the SUs needs to be addressed while cluster formation.
- Maintenance: Most existing clustering algorithms are focused on the cluster formation process in cost and time effective manner. However, maintenance of the cluster is much more challenging than the cluster formation since maintenance needs to be performed whenever topology changes occur. Moreover, maintenance requires a number of complex operations to be performed such as splitting and merging of two or more clusters, migration of cluster head from one cluster to another, addition or deletion of member nodes from the cluster etc. Thus, in addition to cluster formation, clustering algorithms should be capable to maintain the formed cluster in minimum cost.
- Security: Most of the existing clustering algorithms assume the SUs to be legitimate and trustworthy. However, SUs are susceptible to various types of security threats and attacks. For example, a malicious SU may degrade the performance of the network after becoming the cluster head. Hence, security measures should be incorporated along with the clustering formation procedure.

4. Conclusion

In this study, we presented a comprehensive review of prominent spectrum aware clustering techniques devised in the literature to enhance the stability, scalability and facilitate the cooperative tasks among the SUs in cognitive radio ad hoc networks. We have analyzed and discussed the fundamental concept and basic steps involved in cluster formation of some recent clustering algorithms. It has been observed that most clustering algorithms employed one or more clustering metrics and aimed at strengthening the overall performance of the network with the global objective of a minimizing the number of clusters and maximizing the number of CCs in a cluster. From the study, we have concluded that spectrum aware clustering algorithm should form cluster such that it results in lesser number of clusters in the network and a higher number of CCs, consumes lesser energy, exhibits lesser inter-cluster and intra-cluster communication overhead, and is free from frequent re-clustering and maintenance issues.

References

[1] Federal Communications Commission (2002), Spectrum policy tasks force report. ET Docket No 02-135.

[2] Haykin S (2005), Cognitive radio: brain-empowered wireless communications. *IEEE Journal on Selected Areas in Communications*, 23, 201-220.

[3] Akyildiz I, Lee W, Vuran M & Mohanty S (2006), NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey. *Computer Networks*, 50, 2127-2159.

[4] Akyildiz I, Lee W, Vuran M & Mohanty S (2008), a survey on spectrum management in cognitive radio networks. *IEEE Communications Magazine*, 46, 40-48.

[5] Akyildiz I, Lee W & Chowdhury K (2009), CRAHNs: Cognitive radio ad hoc networks. *Ad Hoc Networks*, 7, 810-836.

[6] Liang YC, Chen KC, Li G & Mahonen P (2011), Cognitive radio networking and communications: An overview. *IEEE Transactions on Vehicular Technology*, 60, 3386-3407.

[7] Yau K, Ramli N, Hashim W & Mohamad H (2014), Clustering algorithms for Cognitive Radio networks: A survey. *Journal of Network and Computer Applications*, 45, 79-95.

[8] Chen T, Zhang H, Maggio G & Chlamtac I (2007), CogMesh: A Cluster-Based Cognitive Radio Network. *Proceedings of second IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks*, Dublin, pp.168-178.

[9] Asterjadhi A, Baldo N & Zorzi M (2010), a cluster formation protocol for cognitive radio ad hoc networks. *Proceeding of European Wireless Conference (EW)*, Lucca, 2010, pp.955-961.

[10] Baddour K, Üreten O & Willink T (2010), A Distributed Message-passing Approach for Clustering Cognitive Radio Networks. *Wireless Personal Communications*, 57, 119-133.

[11] Zhang H, Zhang Z, Dai H, Yin R, Chen X (2011), distributed spectrum-aware clustering in cognitive radio sensor networks. *Proceedings of the IEEE global telecommunications conference (GLOBECOM'11)*, Houston, Texas, pp.1–6.

[12] Huang X, Wang G, Hu F & Kumar S (2011), Stability-Capacity-Adaptive Routing for High-Mobility Multihop Cognitive Radio Networks. *IEEE Transactions on Vehicular Technology*, 60, 2714-2729.

[13] Li D & Gross J (2011), Robust Clustering of Ad-Hoc Cognitive Radio Networks under Opportunistic Spectrum Access. *Proceed-*

ings of IEEE International Conference on Communications, Kyoto, pp.1-6.
[14] Bradonjić M & Lazos L (2012), Graph-based criteria for spectrum-aware clustering in cognitive radio networks. *Ad Hoc Networks*, 10, 75-94.
[15] Li X, Hu F, Zhang H & Zhang X (2013), a Cluster-Based MAC Protocol for Cognitive Radio Ad Hoc Networks. *Wireless Personal Communications*, 69, 937-955.
[16] Ozger M & Akan O (2013), Event-driven spectrum-aware clustering in cognitive radio sensor networks. *Proceedings of IEEE INFOCOM*'2013, Turin, pp.1483-1491.
[17] Shah GA, Alagoz F, Fadel EA & Akan OB (2014), A Spectrum-Aware Clustering for Efficient Multimedia Routing in Cognitive Radio Sensor Networks. *IEEE Transactions on Vehicular Technology*, 63, 3369-3380.
[18] Saleem Y, Yau KLA, Mohamad H, Ramli N & Rehmani MH (2015), SMART: A SpectruM-Aware ClusteR-based rouTing scheme for distributed cognitive radio networks. *Computer Networks*, 91, 196–224.
[19] Zareei M, Islam AM & Mansoor N (2016), Cross-layer mobility-aware MAC protocol for cognitive radio sensor network. *EURASIP Journal on Wireless Communications and Networking*, 160, 1-15.
[20] Zhang H, Xu N, Xu F & Wang Z (2016), Graph cut based clustering for cognitive radio ad hoc networks without common control channels. *Wireless Networks*, 24, 209-221.
[21] Ozger M, Fadel E & Akan OB (2016), Event-to-Sink Spectrum-Aware Clustering in Mobile Cognitive Radio Sensor Networks. *IEEE Transactions on Mobile Computing*, 15, 2221-2233.
[22] Xiaoyan L, Xiao Q, Zhang Y (2017), Clustering Algorithm for Cognitive Radio. *Boletín Técnico*, 55, 491-497.
[23] Dutta N, Sarma HKD & Polkowski Z (2018), Cluster-based routing in cognitive radio ad hoc networks: Reconnoitering SINR and ETT impact on clustering. *Computer Communications*, 115, 10-20.
[24] Li D, Fang E & Gross J (2018), Robust clustering for ad hoc cognitive radio network. *Transactions on Emerging Telecommunications Technologies*, 2018; e3285, https://doi.org/101002/ett3285.
[25] Kumar S & Singh AK (2018), a localized algorithm for clustering in cognitive radio networks, *Journal of King Saud University - Computer and Information Sciences*, 2018, https://doi.org/10.1016/j.jksuci.2018.04.004.