Clustering in Multi-Channel Cognitive Radio Ad Hoc and Sensor Networks

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The authors investigate the benefits and functionalities of clustering such as topology, spectrum, and energy management in CRAHNs and CRSNs. They also discuss motivations for and challenges of clustering in CRAHNs and CRSNs. Existing clustering schemes are reviewed and compared. They conclude by revealing key considerations and possible solutions for spectrum-aware clustering in multi-channel CRAHNs and CRSNs.

Abstract

CR enables dynamic spectrum access to utilize licensed spectrum when it is idle. CR technology is applied to wireless ad hoc and sensor networks to form CRAHNs and CRSNs, respectively. Clustering is an efficient topology management technique to regulate communication and allocate spectrum resources by CR capabilities of nodes in CRAHNs and CRSNs. In this article, we thoroughly investigate the benefits and functionalities of clustering such as topology, spectrum, and energy management in these networks. We also overview motivations for and challenges of clustering in CRAHNs and CRSNs. Existing clustering schemes are reviewed and compared. We conclude by revealing key considerations and possible solutions for spectrum-aware clustering in multi-channel CRAHNs and CRSNs.

Introduction

Excessive demand for wireless communications has resulted in spectrum scarcity. Although unlicensed spectrum bands are overcrowded, licensed ones are not efficiently utilized. Cognitive radio (CR) stands as a promising solution to overcome this problem by enabling dynamic spectrum access (DSA) for secondary users (SUs) to use idle licensed bands in an opportunistic manner [1, 2]. Hence, CR empowers the communication of SUs by accessing licensed channels without any disturbance to primary users (PUs), which are the licensed users.

SUs coexist with PUs in wireless networks, which are named CR-enabled wireless networks in general. They can be divided into four domains across two dimensions, as seen in Fig. 1. First, such a network may utilize either a single licensed channel or multiple licensed channels. Second, this network may have either a centralized or a distributed network architecture. Centralized CR-enabled wireless networks, that is, cognitive radio networks (CRNs), have base stations that regulate wireless communications. On the other hand, in distributed ones, there is a flat architecture without any central entity regulating the secondary communication. These distributed CR-enabled wireless networks can be referred to as *cognitive radio ad hoc and sensor networks*. Cognitive radio ad hoc networks (CRAHNs) are flat architectures backed by CR technology to make the most use of scarce licensed spectrum [1]. Different from CRAHNs, cognitive radio sensor networks (CRSNs) are employed for sensing applications and consist of nodes with much less computational capabilities and limited battery power [2]. This article focuses on the domain of multi-channel CRAHNs and CRSNs, as seen in Fig. 1.

Each SU has DSA functionalities, which are spectrum sensing to determine idle licensed channels, spectrum decision to determine operating channel, and spectrum handoff to vacate the operating channel if PUs arrive. Hence, SUs use these functionalities to exploit spectrum opportunities, that is, vacant licensed spectrum bands.

SUs coexist with PUs, and both of them are randomly deployed in the networks. Hence, activities of PUs cause temporal variations in spectrum opportunity for nearby SUs. On the other hand, shadowing, fading, and network topology are main drivers, resulting in spatial variations of idle spectrum bands. Shadowing and fading affect spectrum sensing, and cause false alarms and misdetection of PUs. Network topology differs according to relative transmission range of PUs with respect to that of SUs. There are two network topologies for CRAHNs and CRSNs, which are Topology I and Topology II [3]. In Topology I, there are PUs in the network operating in different licensed channels. However, the transmission range of PUs is larger than that of CRs[1] such that a PU network covers a secondary network ($R \gg r$), as seen in Fig. 2a. According to licensed channel usage activities of PUs, there would be temporal variations in spectrum opportunity. Also, there would be spatial variation in vacant licensed bands due to the effects of shadowing and fading. Hence, there would be spatio-temporal variations in the available licensed spectrum bands of CRs. The vacant channel lists of CRs may differ, although two PUs using channels 1 and 2 in Fig. 2a cover all the CRs.

In Topology II, the transmission range of PUs is comparable with that of CRs ($R > r$), as seen in Fig. 2b. Hence, even if all the PUs use their licensed spectrum, there would be spectrum opportunities for the CR nodes located outside of the transmission ranges of PUs. Furthermore, time variations in the channel use of the PUs result in temporal changes in the spectrum availability of CRs located inside their transmission range. This model causes a very dynamic radio environment.

Proposed networking solutions must consider coordination among SUs for the communication in multi-channel CRAHNs and CRSNs. Clustering is a fundamental solution that can be used to manage and regulate communications in distributed wireless networks [4]. It groups neighboring nodes

[1] SU and CR are used interchangeably throughout this article.

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logically in such networks. Each of these groups is called a cluster. In a cluster structure, there is a cluster head that organizes the communication between its cluster members (intra-cluster communication) and with other clusters (inter-cluster communication). Hence, distributed networks benefit from clustering by imposing cluster heads to enhance communication performance in the network by achieving stability and supporting cooperation [4]. CRAHNs and CRSNs also benefit from clustering to coordinate spectrum-aware communication in this highly dynamic radio environment due to PU activities for Topology I and Topology II. Hence, clustering needs consideration of common idle licensed channels between cluster member CRAHNs and CRSNs in addition to physical proximity of cluster head and cluster members. Hence, this type of clustering is called spectrum-aware clustering. Due to this feature, clustering is used as a functional tool for cognitive cycle functions, medium access control, routing, and managing multi-channel communications. Despite its advantages, some key challenges such as heterogeneous licensed channels and dynamic change in vacant channels in the networks must be carefully considered to propose clustering solutions.

This article is organized as follows. Functionalities of clustering are explained in detail in the following section. After that we motivate the clustering and explain challenges thereof. Existing clustering schemes are then presented and compared based on their implementability and offered features. Following that we present design considerations and potential clustering solutions for CRAHNs and CRSNs. The final section concludes our article.

Functionalities of Clustering in CRAHNs and CRSNs

This section elaborates how clustering can be employed for various functionalities and their correspondence with network operations. Such functionalities broadly relate to three operation areas, which are sensing, network layers, and DSA operations, as seen in Fig. 3. Detailed explanations of each operation area are given in the following subsections.

Sensing Operation

Sensor networks utilize clustering to aggregate gathered information at the cluster heads by exploiting correlation. Hence, clustering can exploit spatial and temporal correlation of sensor nodes' observations on spectrum sensing. Since observations are correlated in time and spatial domains, both topologies can benefit from clustering for sensing operations. Another benefit of clustering is fewer packet transmissions due to aggregation and hence less energy consumption. Sensing correlation affects routing, medium access, and wireless transmission functionalities due to aggregation.

Network Layer Operations

Clustering provides functionality to routing in wireless ad hoc networks. However, CR brings additional challenges due to dynamic variations in available spectrum bands. A common channel between communicating SUs is an additional constraint to forward a packet. Since clusters are formed to have common channels among their members by exploiting spatial and temporal correlation, it pro-

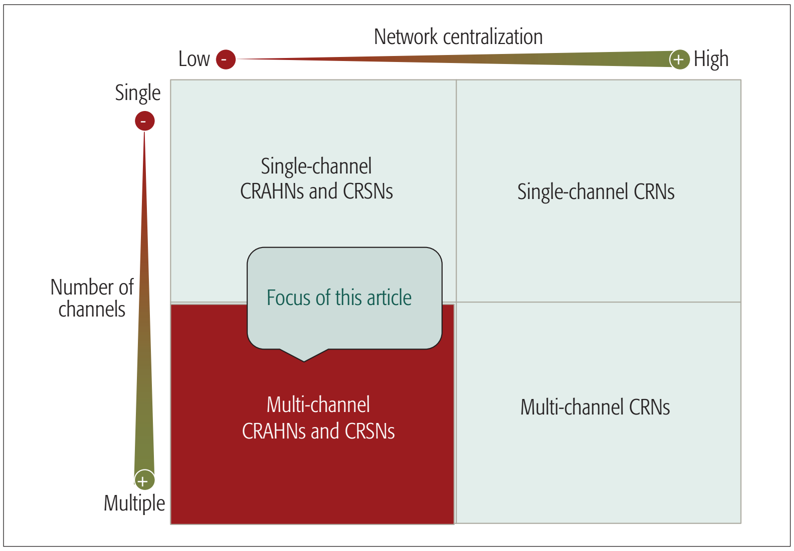

Figure 1. CR-enabled wireless networks segmented into four domains across two dimensions.

vides functionality to routing to reduce overheads while conveying packets from source to destination. Hence, both network topologies can utilize routing functionality of clustering. References [5, 6] are two examples how clustering is utilized for routing in a dynamic radio environment. Directed routing from event to sink is proposed by clustering in [5]. Clustering is also utilized to route multimedia packets in CRSNs according to DSA and quality of service (QoS) requirements [6].

Medium access functionality is also provided with clustering. In a dynamic radio environment, one of the most important factors is the PU presence and contention for the idle licensed channel. A medium access scheme can be designed such that every node in a cluster can access the idle channel without contention [7]. The cluster-based medium access provides higher throughput and smaller delays with less energy consumption. Cluster heads can behave as coordinators for accessing spectrum after sensing vacant channels collaboratively. Medium access can be performed with clustering in both topologies to assist spectrum-aware communications depending on spatial and temporal variations of licensed bands.

DSA Operations

Spectrum sharing and decision operations are CR-specific. Contention toward vacant licensed bands and PU arrivals are two important factors to share spectrum and decide on an operating band. Since clusters are formed according to common vacant channels, the cluster head decides on the operating communication channels for intra-cluster communication, which contributes to the spectrum decision. For instance, clustering can be utilized to decrease the interference among SUs by power and sub-channel allocations [8]. The clustering is beneficial for both of the topologies while sharing and deciding on the operating spectrum band.

Spectrum sensing is one of the DSA operations. The nodes in a cluster send their observation about the spectrum to the cluster head for making a local decision about the vacancy in licensed channels. The cluster head behaves as a fusion center to determine the PU presence, Clustering forms logical groups to better utilize the resources in ad hoc networks. It becomes more beneficial for ad hoc networks with DSA since spectrum-aware communication can be performed efficiently by grouping neighbor nodes according to their idle channels.

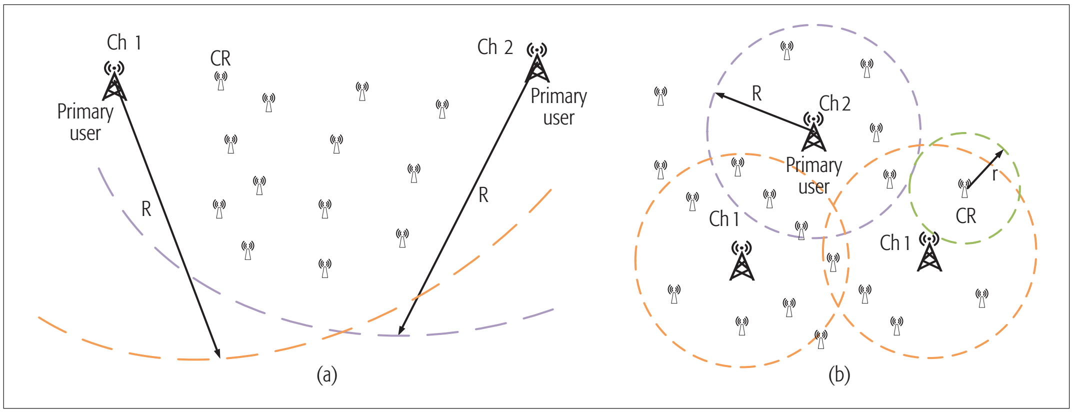

Figure 2. Network topologies: a) Topology I; b) Topology II.

which affects the physical layer of the network. The nodes in the cluster cooperate to reach a consensus for more reliable spectrum sensing. Although clustering can be utilized for spectrum sensing in both topologies, it is mainly used in Topology I due to fewer spatial variations. Due to shadowing, fading, and imperfections of spectrum sensing, CRs within clusters cooperate to determine vacancy of the spectrum bands in Topology I.

Availability of a common control channel throughout the network is another problem in CRAHNs and CRSNs. Clustering functionality provides local control channels among cluster members. Control messages among cluster members are transmitted through these control channels [9]. Since Topology II causes highly dynamic spatial and temporal variations, control channel assignment is more suitable for Topology II.

Motivations and Challenges of Clustering in CRAHNs and CRSNs

Clustering is an efficient method to organize the networks and to impose local coordinators so that spectrum-aware communications can be performed in a structured way. Hence, we describe key motivations and challenges of clustering in CRAHNs and CRSNs in detail.

Motivations of Clustering

Clustering forms logical groups to better utilize the resources in ad hoc networks. It becomes more beneficial for ad hoc networks with DSA since spectrum-aware communication can be performed efficiently by grouping neighbor nodes according to their idle channels. Accordingly, we itemize the motivations of clustering as follows.

Coordination between Nodes: In each cluster, there is a cluster head that controls the communication within its group. Furthermore, the neighboring cluster heads may communicate directly via their common channels or via multiple hops through their members. The cluster heads can be considered as virtual backbones regulating the spectrum-aware communication between SUs, which provides coordination among the SUs.

Scalability: Ad hoc and sensor networks have high network density, so protocols and the solutions in these networks may not be scalable. Furthermore, the dynamic change in the spectrum availabilities of the nodes deteriorates scalability in proposed solutions due to spectrum-aware communications of a large number of nodes in the network. On top of a homogeneous network, clustering imposes virtual nodes (i.e., cluster heads) to improve scalability of the network [4].

Improvement in Network Performance: Neighboring nodes are grouped according to their idle licensed channels in the multi-channel dynamic radio environment. If one common channel in the cluster becomes occupied by a PU, the communication in the cluster continues through another common channel. Hence, CRAHNs and CRSNs become immune to PU arrivals on their operating channels due to spectrum-aware clustering, which increases the network performance.

Cooperation between Nodes: Cognitive cycle functions, which are spectrum sensing, spectrum decision, and spectrum handoff, can be managed in a highly structured way with clustering. These complex tasks are performed in a cooperative manner between cluster members. Since there are common channels among cluster members, a cluster head can assist cooperation easily. Furthermore, cooperation between cluster heads results in better communication performance of the nodes.

Imposing Local Control Channels: The most important problem in spectrum-aware communication is to assume a common control channel in the whole network. However, this assumption is not realizable due to dynamic behavior of the idle licensed channels throughout the networks (i.e., PU activities). Since clusters are formed within a neighborhood, local common control channels exist in the clusters for regulating the communication between the cluster members.

Multi-Channel Communication Support: Each cluster has multiple common channels among its members. Hence, cluster heads can allocate spectrum resources among cluster members by supporting usage of multiple channels simultaneously.

Challenges of Clustering

Despite the various motivations of clustering in CRAHNs and CRSNs, there are challenges, which are outlined as follows.

Multi-Channel Environment: CR capability offers the utilization of channels owned by PUs. In this type of environment, the clustering is performed according to not only physical proximity but also common channels among the nodes forming clusters. Hence, nodes should be aware of idle licensed channels while clustering and tune to the same frequency band for the communication.

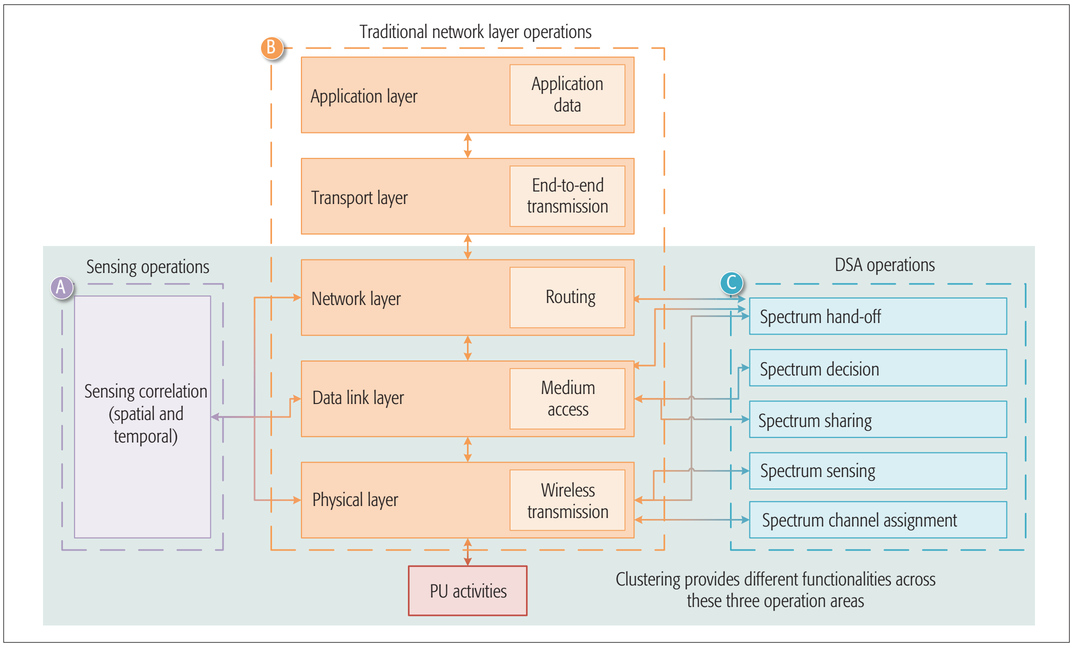

Figure 3. Functionalities of clustering and their relations with traditional network layers and dynamic spectrum access functions.

Having common idle licensed channels among cluster members is a joint requirement for spectrum-aware clustering protocols in literature. However, they have different approaches apart from common spectrum availabilities in neighborhood while forming clusters.

Dynamic Change in Availability of Licensed Bands: One of the most important factors that threaten the stability of clusters is dynamic change in vacant spectrum bands of the clusters. If there is no common channel among the cluster members, these nodes should be re-clustered. Hence, the formed clusters must be robust to the changes in the available spectrum bands. Furthermore, frequent re-clustering causes energy consumption due to control messages for the formation of new clusters.

Heterogeneity in Licensed Channels: Characteristics of licensed channels such as bandwidth and carrier frequency may differ in a realistic scenario in multi-channel CRSNs and CRAHNs. This difference may result in different bit rate, transmission range, and so on.

Spectrum-Aware Clustering Schemes

Having common idle licensed channels among cluster members is a joint requirement for spectrum-aware clustering protocols in the literature. However, they have different approaches apart from common spectrum availabilities in a neighborhood while forming clusters. We overview recent existing approaches for clustering in dynamic radio environment.

Robust Spectrum Sharing (ROSS) [10]: This clustering scheme aims at robustness of clusters, which means ultimate sustainability of them in case of increased PU activity. The authors in [10] propose a distributed clustering algorithm, which enables the cluster formation by interactions among neighbors of CR nodes. It consists of two cascaded phases, which are cluster formation and membership clarification. First, cluster heads are selected according to connectivity vector, which consists of individual connectivity degree and neighborhood connectivity degree. In this phase, common channels between cluster members are guaranteed, and the cluster size is controlled. The second phase is for the clarification of cluster membership. The process of membership clarification is realized as a congestion game. The debatable nodes, which are overlapping nodes with different clusters, choose the cluster with highest common channels after joining them.

Affinity Propagation (AP) [11]: This algorithm applies affinity propagation so that CR nodes are data points and the cluster heads are exemplars. The main aim is to minimize the number of clusters in the whole network. The similarity measure is the common channels shared by CRs. The objective of the clustering is to have as high a number of available channels as possible with other nodes in the cluster. The cluster heads are chosen with a probability that is determined by the node degree of the CRs.

Spectrum Opportunity Clustering (SOC) [9]: SOC is a cluster first algorithm. There are three steps for the formation of clusters. In the first step, the nodes know their neighbors and their vacant channels, and they form bicliques, which are a maximum edge bicliqus and a maximum one-sided edge biclique. The formed bicliques are broadcast to the neighbors, and the best biclique is selected according to largest cluster size or edges in the biclique as the second step. In the last step, the nodes with more than one cluster affiliation are removed. The cluster head is the node with one-hop communication distance with the cluster members.

Combo [12]: In this clustering scheme, nodes know their *k*-hop neighbors and their corresponding vacant channels. All CRs calculate a minimum number of common channels with their *k*-hop neighbors. According to this information, a weight is assigned to each CR for the cluster head selection process. The node with the highest weight in its neighborhood becomes a cluster head. These nodes send membership requests for their clusters. If a node receives more than one request, it selects the one with the highest weight.

Protocol	Approach	Network Type	Network Topology	Offered features: En. eff.[1]	Maintenance	Imperfect sensing[2]	Multi-channel[3]	Mobility
ROSS [10]	Game theory	CRAHN	II	x	x	x	x	x
AP [11]	Affinity propagation	CRAHN	II	x	x	x	x	✓[4]
SOC [9]	Bipartite graphs	CRAHN	I, II	x	✓	✓	x	x
Combo [12]	Adaptive clustering	CRAHN	II	x	x	x	x	x
CogLEACH [13]	No. of idle channels	CRSN	I, II	✓	x	x	✓	x
DSAC [14]	Groupwise constraint	CRSN	II	✓	x	x	x	x

[1] Energy efficiency; [2] Resilience to faults in spectrum sensing; [3] Support for heterogeneous multi-channel; [4] Supports only low mobility

Table 1. Overall comparison of existing clustering schemes in CRAHN and CRSN.

CogLEACH [13]: In this clustering method, the expected number of cluster heads is fixed, and the nodes with higher numbers of channels more likely to become cluster heads. According to these conditions, every node is assigned a probability to become a cluster head. Non-cluster-head nodes send join requests to the cluster head with minimum communication cost based on the received signal strength.

Distributed Spectrum-Aware Clustering (DSAC) [14]: The DSAC scheme tries to minimize total energy consumption, which is the sum of energy consumed for intra-cluster and inter-cluster communications. The optimal number of clusters is determined according to the average consumed energy. For the distributed algorithm, locally closest pairs are merged for clustering with a group-wise available channel constraint.

Table 1 summarizes the above discussions and gives overall comparison of existing clustering schemes according to the networks and offered features by clustering.

Distributed Clustering in CRAHNs and CRSNs

Despite the assumption of clustering scheme existence for spectrum management, medium access control, and routing solutions in the literature, there are not enough clustering studies to satisfy inherent requirements of CRAHNs and CRSNs. To that end, we determine network requirements and clustering design considerations. Afterward, we briefly overview potential solutions for a distributed clustering approach in CRAHNs and an event-driven approach in CRSNs.

Network Requirements

CRAHNs have unique requirements, one of which is managing high fluctuation in spectrum availability due to mobility of CRs and/or PUs. Furthermore, different QoS demands must be satisfied. For instance, multimedia applications require limited delay and lower jitter. Another requirement is limited interference to PUs. If the operating channel change is due to PU activities, there may be interference to the PU, which is undesirable.

There are additional requirements for clustering in CRSNs. First of all, sensor nodes have limited battery power. Hence, the clustering solutions must be energy-efficient. Since clustering requires control signaling for cluster formation and maintenance, proposed clustering solutions should avoid excessive overheads, which decrease energy levels of the CRs. In terms of cognitive operations, the proposed clustering should avoid frequent change in operating channel since cognitive cycle functions such as spectrum handoff and spectrum sensing consume great amounts of power. Furthermore, the sensor nodes have limited computational energy. Hence, the proposed clustering approaches should be simple. Energy efficiency and low computational overhead are two additional requirements for clustering solutions in CRSNs.

Clustering Design Considerations

CR operations and distributed network architecture are the main considerations when designing clustering solutions. Design considerations of clustering in CRSNs and CRAHNs differ due to their unique requirements. Hence, we explain common and different design considerations according to the network types as follows.

Common Design Considerations: The first common consideration is that there needs to be at least one mutual vacant channel among the formed clusters. The cluster nodes must communicate with each other via common channels.

Imperfections in spectrum sensing are also important since the clustering is performed according to the vacant spectrum bands. The clusters can be formed according to erroneous vacant channel lists of CRs due to poor channel sensing performance. The common method for spectrum sensing is energy detection due to its simplicity [1]. However, this method has imperfections in the sensing process. Hence, the probabilities of misdetection and false alarm are important for the stability of clusters.

Mobility of the nodes highly affects the heterogeneity in spectrum availability, which directly alters the cluster formation. A cluster head may lose connection with its members due to mobility of SUs. Hence, the cluster structure changes, and association and disassociation mechanisms should be designed for the incoming and outgoing nodes in the clusters. Furthermore, the mobility of PUs causes more dynamic spatio-temporal changes in spectrum availability of the SUs.

Maintenance of the clusters is another consideration. Highly changing licensed users' activities increase the cost to preserve the clusters. Due to these dynamic effects, some nodes may leave their current clusters or join another one, which results in packet overhead and energy consumption.

Design Considerations Specific to CRAHNs: The flows in an ad hoc network have different QoS levels. This consideration becomes difficult due to activities of PUs. Clustering must take them into account to support different QoS levels.

In order to support better communication quality, another consideration for clustering is heterogeneous licensed channels, which cause different characteristics such as transmission range and bit rate. The channels with less PU arrivals must be utilized in cluster formation to decrease the probability of spectrum handoff, which increases energy consumption.

Design Considerations Specific to CRSNs: CRSNs have event-driven communication. The nodes report their observations after detection of an event. If the frequency is low enough, there is no need to maintain clusters after the event since they will not be utilized until the next event. Clustering solutions should consider this unique property of CRSNs.

Energy efficiency is another consideration for CRSNs since the nodes have limited power. Despite the fact that clustering provides energy savings, PU activities may degrade the energy efficiency provided by clustering due to re-clustering and control overhead.

Distributed Clustering Approach for CRAHNs

The absence of a centralized entity in CRAHNs necessitates cooperation between CRs. Clustering provides hierarchical structure on top of ad hoc networks architecture to improve local cooperation in the network. To this end, we explain possible problems and solutions in a distributed clustering approach for CRAHNs.

There is a general assumption about the existence of a common control channel in the whole network. However, this is quite unrealistic due to PU activities. To make it more realistic, this channel is assumed to be a very narrowband channel, which may get congested easily. Hence, the proposed protocols must not rely on the existence of such a channel. Channel hopping or rendezvous approaches could be adopted to communicate via the same channel to cooperate for the formation of the cluster in the neighborhood. However, this approach has high overhead due to channel switching. A blind rendezvous algorithm is proposed for distributed cognitive radio networks such that communicating nodes do not need a common control channel and available channel information [15]. The proposed algorithm guarantees rendezvous without any need for time synchronization and consumes a short time to rendezvous.

Existing clustering schemes form robust clusters against dynamic available channel variations. Hence, a clustering scheme that maximizes the number of common channels or number of member nodes in clusters should be devised by heuristic algorithms. A balance between the sizes of common channels and cluster members may be established to form robust clusters as in [9]. Apart from the formation of clusters, their maintenance is another issue to be considered in a realistic scenario. Cluster maintenance solutions should adapt to the variations of common channels in the cluster. A cluster head may re-form the cluster with less nodes to achieve common channels. Associated nodes should not deteriorate the cluster stability by decreasing the number of common channels.

In addition to the dynamic radio environment, mobility of network nodes makes the cooperation among them more challenging due to connection losses. The proposed clustering algorithms should be mobility-aware. If a cluster head loses connection with its members, this results in re-clustering, which an energy-efficient clustering approach should avoid. To overcome this problem, a node with higher mobility in its neighborhood should not be a cluster head. The nodes may have weight to measure the mobility of the nodes to select the cluster heads in local neighborhoods. By doing this, it is less likely to re-cluster the nodes since the cluster head will not be disconnected from its members. Furthermore, the cluster must manage incoming and outgoing CRs to update cluster memberships for the management of network topology. Radio resource allocation in a cluster is degraded by association and disassociation of nodes due to mobility.

Intra-cluster communication management should also be taken into account due to spectrum mobility. The operating frequency band of the cluster may become occupied; hence, the cluster members should organize intra-cluster communication accordingly to a new vacant channel with limited delay. Due to spectrum handoff, CR nodes consume energy. Hence, the cluster channel with the least PU arrival statistics should be chosen as the operating channel to avoid spectrum handoff. Weighing channels according to PU arrival statistics helps choosing more idle channel for intra-cluster communication.

Existing clustering schemes assume homogeneous licensed channels such that their channel characteristics are the same. However, in a realistic multi-channel CRAHN scenario, their bandwidth and center frequencies may be different. Hence, characteristics of these channels vary. For instance, spectrum sensing results for the licensed channels differ in such a case. Furthermore, the bit rate of the licensed channels become different. The characteristics of PUs on different channels may vary significantly, which results in very vigorous channel availability. If the network requires more coverage, a possible solution to form a cluster is to group neighboring nodes with channels having lower center frequencies.

We outline some of the problems in clustering and their respective solutions and research directions carefully to fulfill the objectives of clustering in a multi-channel dynamic radio environment. However, a holistic clustering solution should be proposed to overcome the problems of CRAHNs.

An Event-Driven Approach for CRSNs

CRSNs have event-driven traffic such that the resources are utilized when events occur. Hence, an event-driven clustering approach is shown to be energy-efficient for CRSNs in [5]. Furthermore, this approach solicits clustering in the area between the event and the sink since the nodes located in this region will take part in forwarding event packets to the sink. We explain possible solutions and research directions in a distributed clustering approach for CRSNs as follows.

CRSNs have event-driven-type communication. The nodes report their observations after detection of an event. If the frequency is low enough, there is no need to maintain clusters after the event since they will not be utilized until the next event. Clustering solutions should consider this unique property of CRSNs.

Possible clustering solutions should also consider connectivity of clusters. The solutions should arrange cluster-heads so that neighboring cluster-heads can communicate via common channels via single hop. If there is not a common channel between cluster-heads of neighboring clusters, they may communicate via multiple hops in dynamic radio environment.

•The event readings by cluster members are aggregated at corresponding cluster heads by exploiting spatial and temporal correlation between them. Furthermore, the mobility-aware Event-to-sink Spectrum Aware Clustering Protocol (mESAC) [5] considers the mobility of the CR nodes to maintain the clusters. However, a definitive re-clustering procedure is not studied. Maintenance of the clusters during the event should be considered carefully by contemplating the energy constraint of CRSN nodes. The cluster heads may decrease the number of their members to increase the number of common channels to avoid a complete re-clustering. Instead, possible re-clustering solutions should consider partitioning of the nodes locally. Hence, nodes which needs re-clustering may be associated with a neighboring cluster which should located in the direction of those nodes. Association processes should be performed with minimal overhead and should not degrade the number of common idle channels of the associated cluster.

•Fast convergence of clustering structures is one of the most important goals to decrease communication overhead of clustering to transport event readings to the sink. Preference on cluster head or cluster first for designing the clustering algorithm may affect the convergence. Cluster head first algorithms converge faster due to the fact that cluster heads associate with their neighbors to form clusters according to vacant licensed channels by fewer iterations. After determining the cluster heads, they directly form clusters by sending the clustering request to the neighboring nodes.

•Heterogeneous multi-channel is not addressed in the CRSN domain. The heterogeneity causes different channel throughput, communication ranges, and error probabilities. Hence, it affects the clustering performance and energy consumption. Channel switching may occur frequently to use channels becoming idle with better characteristics. Hence, possible clustering solutions must include the channels with fewer PU arrivals and more idle probability, which decreases the possibility of re-clustering.

•Possible clustering solutions should also consider connectivity of clusters. The solutions should arrange cluster heads so that neighboring cluster heads can communicate via common channels via single hops. If there is not a common channel between cluster heads of neighboring clusters, they may communicate via multiple hops in a dynamic radio environment. If the cluster heads directly communicate with each other, it may lead to collisions and interference to the other SUs and PUs due to higher-range communication, and this needs packet overheads to rendezvous on the same channel between two neighboring cluster heads. Multihop communication between cluster heads over member nodes is more efficient in terms of interference to PUs and energy consumption.

Conclusion

This article investigates clustering in multi-channel cognitive radio ad hoc and sensor networks. To this end, we describe how clustering can provide functionalities for different operation regions and explain its benefits. Motivations and challenges of clustering CRAHNs and CRSNs are outlined. Existing solutions for clustering are studied and compared. Furthermore, we present possible clustering solutions to overcome problems in CRAHNs and CRSNs.

References

[1] I. F. Akyildiz, W.-Y. Lee, and K. R. Chowdhury, "CRAHNs: Cognitive Radio Ad Hoc Networks," *Ad Hoc Networks*, Elsevier, vol. 7, 2009, pp. 810–36.

[2] O. B. Akan, O. B. Karli, O. Ergul, "Cognitive Radio Sensor Networks," *IEEE Network*, vol. 23, no. 4, July/Aug. 2009, pp. 34–40.

[3] M. Ozger and O. B. Akan, "On the Utilization of Spectrum Opportunity in Cognitive Radio Networks," *IEEE Commun. Letters*, vol. 20, no. 1, Jan. 2016, pp. 157–60.

[4] K.-L. A. Yau *et al.*, "Clustering Algorithms for Cognitive Radio Networks: A Survey," *J. Network and Computer Applications*, Elsevier, vol. 45, 2014, pp. 79–95.

[5] M. Ozger, E. A. Fadel, and O. B. Akan, "Event-to-Sink Spectrum-Aware Clustering in Mobile Cognitive Radio Sensor Networks," *IEEE Trans. Mobile Computing*, vol. 15, no. 9, pp. 2221–33.

[6] G. A. Shah *et al.*, "A Spectrum-Aware Clustering for Efficient Multimedia Routing in Cognitive Radio Sensor Networks," *IEEE Trans. Vehic. Tech.*, vol. 63, no. 7, Sept. 2014, pp. 3369–80.

[7] Y. Xu *et al.*, "A Cluster-Based Energy Efficient MAC Protocol for Multi-hop Cognitive Radio Sensor Networks," *Proc. GLOBECOM 2012*, pp. 537–42.

[8] J. Dai and S. Wang, "Clustering-Based Spectrum Sharing for Cognitive Radio Networks," *IEEE JSAC*, vol. 35, no. 1, Jan. 2017, pp. 228–37.

[9] S. Liu, L. Lazos, and M. Krunz, "Cluster-Based Control Channel Allocation in Opportunistic Cognitive Radio Networks," *IEEE Trans. Mobile Computing*, vol. 11, no. 10, Oct. 2012, pp. 1436–49.

[10] D. Li, E. Fang, and J. Gross, "Versatile Robust Clustering of Ad Hoc Cognitive Radio Network," arXiv: 1704.04828v1 [cs.GT], Apr. 2017.

[11] K. E. Baddour, O. Ureten, and T. J. Willink, "A Distributed Message-Passing Approach for Clustering Cognitive Radio Networks," *Springer Wireless Personal Commun.*, vol. 57, 2011, pp. 119–33.

[12] A. Asterjadhi, N. Baldo, and M. Zorzi, "A Cluster Formation Protocol for Cognitive Radio Ad Hoc Networks," *Proc. IEEE Euro. Wireless Conf.*, 2010, pp. 955–61.

[13] R. M. Eletreby, H. M. Elsayed, and M. M. Khairy, "CogLEACH: A Spectrum Aware Clustering Protocol for Cognitive Radio Sensor Networks," *Proc. Int'l. Conf. Cognitive Radio Oriented Wireless Networks*, 2014, pp. 179–84.

[14] H. Zhang *et al.*, "Distributed Spectrum-Aware Clustering in Cognitive Radio Sensor Networks," *Proc. IEEE GLOBECOM*, 2011, pp. 1–6.

[15] J. Li *et al.*, "Sender-Jump Receiver- Wait: A Simple Blind Rendezvous Algorithm for Distributed Cognitive Radio Networks," *IEEE Trans. Mobile Computing*, vol. 17, no. 1, Jan. 2018, pp. 183–96.

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