Transmission Range-Aware Clustering for Green Cognitive Radio Ad Hoc Networks

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***Abstract*—The absence of network infrastructure and opportunistic spectrum access in cognitive radio ad hoc networks (CRAHNs) results in connectivity and stability problems. Clustering is known as an effective technique to overcome this problem. Clustering improves network performance by implementing a logical network backbone. Therefore, how to efficiently construct this backbone among CRAHNs is of interest. In this paper, we propose a new clustering algorithm for CRAHNs. Moreover, we model a novel cluster head selection function based on the channel heterogeneity in term of transmission ranges. To the best of our knowledge, this is the first attempt to model the channel heterogeneity into the clustering formation in cognitive radio networks. Simulation results show that the performance of clustering is significantly improved by the channel heterogeneity considerations.**

***Index Terms*—Channel heterogeneity, cognitive radio ad hoc network (CRAHNs), clustering.**

1. Introduction

The last decade has witnessed a fast growth in wireless networks, which leads to a dramatically increasing in demand for spectrum, resulting in severe spectrum shortage. To address the spectrum shortage, the Federal Communications Commission (FCC) has endorsed the unlicensed devices to work in licensed frequency bands[1]. Consequently, cognitive radio (CR) technology is introduced. Beside, to solve the problem of spectrum scarcity, one of the main goals of intelligent CRs is to decrease the overall energy consumption in the network[2]. CR is distinguished as an adaptive and autonomous device empowered by advanced intelligent functionality, which interacts with its surrounding environment and learns from its experiences to reason, plan, and decide future actions to fit with various needs. Considering these capabilities, CR technology will provide a significant improvement in radio resource (spectrum) efficiency, networking efficiency, and energy efficiency[3]. Therefore, we could refer to the cognitive radio technology as green technology regarding to the definition of the purpose of green communication in [4] which is as follows:

"The purpose of green communication is to reduce energy consumption, lower the electromagnetic radiation, improve resource utilization, and make resource consumption and environmental impact to a minimum".

However, the feature brought by CR technology introduces spectrum management and network coordination challenges. Precisely in cognitive radio ad hoc networks (CRAHNs), the distributed multi-hop architecture, the rapid change in the network topology, and the time and space varying spectrum availability are some of the key distinguishing factors. Therefore, the clustered structure is proposed as a good solution to handle these challenges.

Clustering is a powerful technique known to efficiently manage the topology of the wireless ad hoc network by implementing a virtual network backbone. Clustering partitions network nodes into logical groups named clusters in order to improve the basic network performances such as routing delay, bandwidth consumption, and throughput[5]. Moreover, clustering may provide a simple and feasible power control mechanism[6].

A typical clustering structure is shown in Fig. 1, where geographically adjacent nodes are allocated into logical groups based on their node's behavior or node's resources with some specified rules[7]. Under the clustered structure, nodes have different functions, such as cluster head (CH), cluster gateway, or cluster member. A CH acts as a coordinator or a temporary base station within its cluster. A cluster gateway is a node with inter-cluster links, so it can act as a relay between neighboring clusters. A cluster member is a normal node without any privileges.

Many clustering techniques have been proposed in the literature for ad-hoc network[6],[8],[9] and sensor networks[10]. In ad-hoc networks, the major focus of clustering is to preserve connectivity (under static channel conditions) or to improve routing. In the context of sensor networks, the emphasis of clustering has been on longevity and coverage.

Manuscript received March 16, 2016; revised April 27, 2016.

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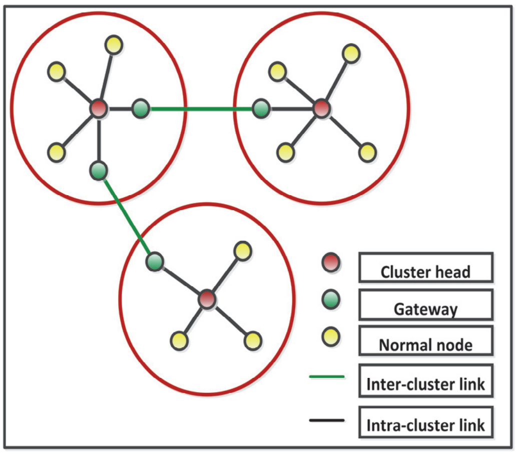

Fig. 1. Typical clustering structure.

However, common issues when using clustering in CRAHNs are opportunistic and unpredictable nature of channel availability, which complicates the clustering process and introduces additional challenges. These challenges are lack of a common global control channel due to opportunistic spectrum access feature and rapid topology variations, not only due to CR user's mobility, but also due spectrum mobility. Therefore, clustering in CRNs has been investigated in the context of facilitating fundamental CR network functions such as cooperative spectrum sensing[11], control channel assignment[12]-[15], a MAC protocol implementation[12],[14], spectrum management[16], and routing improvement[17]. Furthermore, clustering in cognitive radio sensor networks (CRSNs) has been addressed in the context of energy saving[18],[19].

In [12], Zhao *et al*. proposed a distributed coordination protocol for CRNs. In this protocol, CRs self-organize into groups based on the similarity between their lists of available channels. CRs are grouped in the same cluster as long as they have at least one common available channel. Besides establishing of local control channel, this protocol aims to minimize the number of clusters in the entire network, in order to reduce the communication overhead. Given that the minimum number of common available channels permitted per cluster is one, clusters having only one channel are common. Such clusters usually suffer from frequent re-clustering in the presence of high PR activity.

In [14], Chen *et al*. proposed the CogMesh architecture for addressing the problem of control channel assignment in CRNs. In cog-mesh, CR nodes are allocated into the clusters based on the local channel availability. Initially, each CR chooses the channel with the largest number of neighbors as a local common control channel (LCCC) and constructs a cluster. Then merging process based on a minimal dominating set (MDS) in graph theory is conducted to reduce the cluster number. This algorithm optimizes the cluster size while guarantees one LCCC in each cluster. However, the robustness of the cluster is not guaranteed and re-clustering is easily caused by the variation in spectrum availability due to the primary user (PU) activity.

In [15], Baddour *et al*. proposed a clustering algorithm for CRNs based on affinity propagation. In this protocol, several CRs are declared to be the CHs, with nearby nodes joining clusters based on the similarity of their available channel lists with those of the CH. As in the case of [7] and [9], frequent re-clustering occurs.

To cope the frequent re-clustering due to PU activity, the idea of backup control channels has been proposed. In [20], Bahl *et al*. proposed a control channel protocol for CR networks in which one main channel and one backup channel are assigned as control channels. The main and backup channels are then interchanged based on the channel availability. In [21], Liu *et al*. enhanced the idea of backup control channel in CRAHNs by introducing a cluster-based control channel allocation scheme, called spectrum opportunity-based clustering (SOC). Instead of forming the cluster with the largest number of nodes as introduced in [12] and [14] or with just one backup channel as proposed in [20], they proposed that each cluster is built in a way that the product of the number of common channels per cluster and the cluster size is maximized. Therefore, clusters are built in a way that provides a balance between the cluster size and the number of common channels per cluster.

All above mentioned clustering techniques aim to ease the network topology management and solve the problem of control channel assignment under the assumption of homogenous channel characteristics. Moreover, all considered a common fixed transmission range for CR nodes. Hence, none of these works takes into account the heterogeneity of channel in term of transmission range.

Considering a common fixed transmission range is not acceptable for two reasons. First, a common transmission range of all channels will override the unique feature of CR: interacting and adjusting with the surrounding environments. Second, the value of the radio transmission range effects in the network connectivity and energy consumption significantly. Using a common large transmission range increases the connectivity of the network by increasing the number of direct links. But this comes at the expense of high energy consumption. Moreover, CR nodes cannot use any arbitrarily high level of transmission power in all channels because the transmission power for each spectrum band is restricted identified by FCC regulations to prevent interference to other users. In contrast, using a short transmission range considerably can reduce the power consumption as well as the interference, but at the expense of network connectivity. Consequently, a new approach that exploits the capability of CR to adapt its transmission parameters based on operating environment must be considered in clustering formation. This approach is expected to enhance the network performance by making a desirable balance between network connectivity and power consumption.

In this paper, we propose a new clustering technique for CRAHNs that takes into account the channel heterogeneity in term of transmission ranges and variable transmission ranges for CR users, where CR users form a cluster, by focusing on the requirement that there needs to be more than one common channel available for all CR users in the same cluster. This constraint makes the cluster structure more immunity against the primary user activities. A new metric for cluster head selection, named selection factor, is introduced. This metric is determined by considering the number of available channels and the number of common channels that a CR user has, with each of its neighbors, channel reward (coverage) for the available channels and the number of neighbors.

The remainder of this paper is organized as follows. The concept of the channel heterogeneity in CR networks is identified in Section 2. Section 3 states the assumption and network model. The main idea of the clustering algorithm is explained in Section 4. The simulation parameters and settings are explained in Section 5. Section 6 presents the simulation results, and finally the paper is concluded in Section 7.

2. Channel Heterogeneity

In this section we introduce the concept of the channel heterogeneity, which is a unique feature in CR networks.

A. Heterogeneous Set of Available Channels

In traditional multi-channel networks, the set of usable channels at each node is similar. But in CR networks, each CR node individually detects its available channels, so each CR node has a different set of available channels that can be used for communication.

B. Heterogeneous Transmission Ranges

In multi-channel networks, the channels are homogeneous, i.e., different channels have a common transmission range. However, practically in CR networks the homogeneity assumptions are overridden since different channels may be located on vastly separated frequencies with different bandwidths and different propagation characteristics. Moreover, FCC regulations may define different transmission range for different channels. As a result, different channels correspond to different transmission ranges[22]. Also, A CR user can adjust its transmission parameters to fit with the environment[23]; therefore, the transmission range of the CR user is varied for different channels.

C. Heterogeneous Set of Neighbors

Since each CR node has a different set of available channel and every channel has different transmission range, whether or not a node can reach a neighboring node depends on the channel that is used for the communication. Therefore, a CR node may have different sets of neighbors on different channels.

3. Assumptions and System Model

For clarity purposes, we first present the notation that will be used in the rest of this paper.

Symbol	Description
A	Set of authorized users
S	Set of cognitive users
C	Set of channels licensed to AUs
M	Number of authorized users
N	Number of Cognitive users
L	Number of types of channel
r_l	Transmission range of type l channel
$r_{\max}$	Maximum transmission range
C_i	Set of available channel for cognitive user S_i
C_l	Set of channel of type l
m_i	Number of available channel for cognitive user S_i
i, j	ID for cognitive user S_i and S_j
$D_{i,y}$	The distance between cognitive user S_i and authorized users p_y
$d_{i,j}$	The distance between cognitive user S_i and S_j
$C_{i,j}$	Set of common channel between cognitive user S_i and S_j
N_i	Set of 1-hop neighbour for cognitive user S_i
n_i	Number of 1-hop neighbour for cognitive user S_i
$N_{i,c}$	Set of 1-hop neighbour for cognitive user S_i in channel c
SF_i	Selection factor for cognitive user S_i
Y_i	The cumulative channel reward value of node S_i
$Y^{i,j}$	The relative channel reward matrix for node S_i with neighbour node S_j.
$V^{i,j}$	The common channel availability matrix between node S_i and node S_j.
I	Transpose matrix of unit matrix.
V_i	Availability matrix for node S_i
CH_i	Cluster head i
K_i	Set of cluster member for CH_i
$\mathrm{Ch}_{\mathrm{sh}}$	Minimum channel threshold per cluster

We consider the co-existence of M authorized users (AUs) denoted by set $A=\{a_1, a_2, a_3, \cdots, a_M\}$ and N cognitive user denoted by set $S=\{s_1, s_2, s_3, \cdots, s_M\}$ in the same geographical area. We also assume the existence of M heterogeneous non-overlapping orthogonal channels, denoted by a set $C=\{c_1, c_2, c_3, \cdots, c_M\}$. These channels are divided into L types of channels based on their transmission ranges. Thus, $C = \bigcup_{l=1}^{L} C_l$, where C_l is the set of type l channels. The transmission range of each type (denoted by l, $1 \le l \le L$) of channels is r_l.

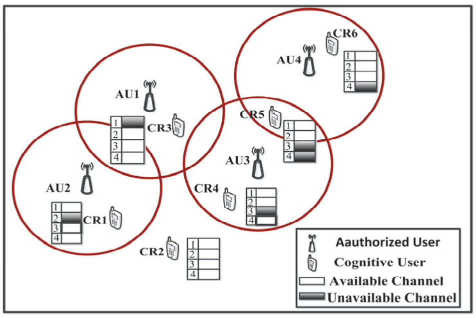

Fig. 2. Co-existence of authorized users and cognitive users.

Each AU is assigned a specific channel. CRs can access licensed bands after validating that the channel is not occupied by any AUs. Hence the channel availability depends on CR node's proximity to the primary users of that band such that the channel is available to the CR user if it is located outside the interference area for AU of that channel, as shown in Fig. 2. For simplicity, we assume the channel transmission range is equal to interference range. Thus, channel c_y of type l, which is assigned to the primary user a_y is available to any secondary user s_i if and only if $D_{i,y}>r_l$, where $D_{i,y}$ is the distance between the secondary user s_i and the primary user a_y. So, $C_i^l=\{c_y:D_{i,y}>r_l,\ y\in A\}$ where C_i^l is the set of available channel of s_i with a transmission range equal r_l. Let C_i denote the set of available channels observed by s_i and m_i denote the number of available channels. Thus, $C_i=\bigcup_{l=1}^{L} C_i^l$, $C_i\subseteq C$ and the cardinality $|C_i|=m_i\leq M$.

Since each CR node has a different set of available channels and these channels have different transmission ranges, subsequently, each CR node has different neighbors in each channel. Two secondary users s_i and s_j are neighbors in any channel c of type l only if that channel is available for both of them, and the distance $d_{i,j}$ between them is less than or equal to the transmission range of that channel r_l. Let N_i denotes the set of 1-hop neighbors of s_i and $N_{i,c}$ the set of neighbors of s_i in channel c, thus $N_{i,c}=\{j:d_{i,j}\leq r_l,\ c\in C_{i,j}^l\}$, where $C_{i,j}^l=C_i^l\cap C_j^l$, so $N_i=\bigcup_{c=1}^{m_i} N_{i,c}$ and the number of neighbors of node i is the cardinality $|N_i|=n_i\leq N$.

We also assume that each CR node accurately sensed the primary user activity and interference to AUs from CRs is strictly controlled. Therefore, CRs should immediately release the channel once detecting AU activity. CRs are equipped with half-duplex transceivers that can either receive or transmit on a single channel at a time. Each CR node can switch between channels. Each CR user can adjust its transmission range based on the transmission range of used channel by tuning its transmission power. Additionally, we assume the AUs are static and CR user's mobility is slow and the channel availability changes at a low rate such that the topology does not change during the clustering process. The well-designed neighbor discovery and MAC protocol that allows the CR users to exchange and gathers the information of other nodes in its neighborhood perfectly also is assumed.

4. Clustering with Channel Heterogeneity Consideration

4.1 Modeling of Cluster Head Selection Factor Function

The main idea is to find a cluster head selection function with the following considerations:

- Preference to select the candidates with the highest number of neighbors N_i.
- Preference to select the candidate with the highest number of common channels with its neighbors.
- Preference to select the candidate with the highest available channel coverage.
- Preference to select the candidate with the highest available channel with respect to its neighbors.

The selection factor (SF) that fulfills these properties can be modeled by the following equation:

$$\mathrm{SF}_i=Y_i\frac{m_i}{\max m_k},\quad k\in N_i. \tag{1}$$

Given

$$Y_i=\sum_{j\in N_i}Y^{i,j},$$

$$Y^{i,j}=\mathbf{V}^{i,j}\mathbf{I},$$

$$\mathbf{I}=\left[1_1,\ 1_2,\ 1_3,\ \cdots,\ 1_M\right]^T,$$

$$\mathbf{V}^{i,j}=\left(\mathbf{V}_i\cdot\mathbf{V}_j\right)\cdot\mathbf{R},\ \forall j\in N_i,$$

herein the product of two matrices is element-wise product.

$$\mathbf{R}=\left[R_1,\ R_2,\ R_3,\ \cdots,\ R_M\right]\ \text{ and }\ R_c=\frac{r_c^2}{r_{\max}^2},$$

$$\mathbf{V}_i=\left[v_{i1},\ v_{i2},\ v_{i3},\ \cdots,\ v_{i,M}\right],$$

$v_{i,c}=1$ if channel c available for cognitive user s_i,

$v_{i,c}=0$ otherwise.

4.2 Description of Clustering Algorithm

In this section we describe our distributed clustering algorithm for CRAHNs. Our algorithm consists of two phases: cluster-head selection and cluster construction.

The main purpose of the cluster head selection phase is to solve (2) in a distributed manner:

$$\mathrm{CH}=\arg\max\left(\mathrm{SF}\right) \tag{2}$$

The algorithm is executed at each node in a distributed way that a CR user s_i decides its own role (cluster-head or ordinary member) depending only on the decision of its neighbors with bigger selection factors. Thus, initially, only those CR users with the biggest selection factors in their neighborhood will broadcast a message to their neighbors stating that they will be cluster-heads. On receiving one or more of these "cluster-head" messages, a CR user s_i will decide to join the cluster of the neighboring cluster-head with the biggest selection factor. If no CR user with the bigger selection factor has sent such a message, then a CR user s_i will send a cluster-head message. The algorithm is terminated when all CR users being either the cluster-head or cluster member.

The steps of the proposed distributed clustering are as follows:

Step 1: Every s_i broadcasts its set of idle channels C_i.

Step 2: Every s_i computes its selection factor SF_i using (1).

Step 3: Every s_i broadcasts its selection factor SF_i.

Step 4: If $\mathrm{SF}_i > \mathrm{SF}_j$, $\forall j \in N_i$, s_i declares itself as CH_i and constructs a cluster K_i where $K_i=\{i\}$ and $C_i=C_j$. If two or more neighbouring CRs have the equal selection factor, the priority is given to the CR which has the lowest ID.

Step 5: For each CH_i, if $|C_i| \geq \mathrm{Ch}_{\mathrm{sh}}$, do (Step 6 to Step 8).

Step 6: Find $s_j \in N_i$ such that $s_j = \arg\max_{j\in N_i} \left|C_i \cap C_j\right|$ and send an invitation message.

Step 7: If there is more than one $s_j \in N_i$ which satisfies the condition in step 6, choose the one with minimum distance such that $s_j = \arg\min_{j\in N_i} \left|d(\mathrm{CH}_{i,s_j})\right|$.

Step 8: If CH_i receives the accept message from s_j then a new cluster is built so $K_i=\{i,j\}$ and $C_i=|C_i \cap C_j|$.

Step 9: If s_j receives more than one invitation message, it chooses to accept the message from CH with the highest selection factor and also it considers as potential gateway.

Step 10: If s_j does not receive any invitation message, it waits until all neighbours with the highest selection factor, being CH, or joins the cluster as a member and then declare itself as the CH.

5. Simulation Environment

The performance of our algorithm is evaluated using MATLAB. In order to perform our evaluation, we randomly deployed the primary users and CR users in a 5 km×5 km square area according to a uniform distribution. There are 10 primary users; each of them has one license channel. Thus, the total number of channels is 10. Simulation results are averaged over 100 different randomly deployed topologies to ensure statistical validity.

To evaluate our algorithm, two different scenarios are considered. First, we consider all channels are homogenous (L=1). Thus, they have equal channel transmission ranges (R_1=1000 m) and fix the transmission range for both primary users and secondary users as 1000 m and 500 m respectively. Second, we consider the heterogeneity of channels (L=2) with different transmission ranges such as (R_1=500 m) and (R_2=1000 m), the transmission range of each primary user is equal to the transmission range of its assigned channel, and the CR user's transmission ranges are varied according to its available channels.

6. Simulation Results

Fig. 3 shows the connectivity of the network with respect to the network density obtained by the two scenarios. Herein we use the neighborhood factor as an indicator for the network connectivity. Obviously the connectivity is high for the heterogeneous transmission range scenario.

Fig. 4 shows the average number of clusters with respect the network density obtained by the two scenarios. Clearly the average number of clusters increases as the number of node increases. However, the heterogeneous transmission range scenario produces a lower number of clusters than the fixed CR transmission range scenario. This makes sense, because considering a variable transmission range of CR users increases the network connectivity, as shown in Fig. 3.

Fig. 5 shows the average number of clusters with respect to the network density considering different constraints for the minimum number of common channels per cluster. It is seen from Fig. 5 the number of clusters is increased as the constraint value increases.

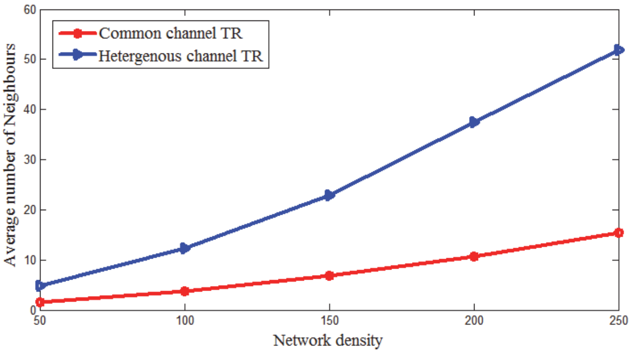

Fig. 3. Impact of heterogeneous channel transmission range on the connectivity of the network with varying network density.

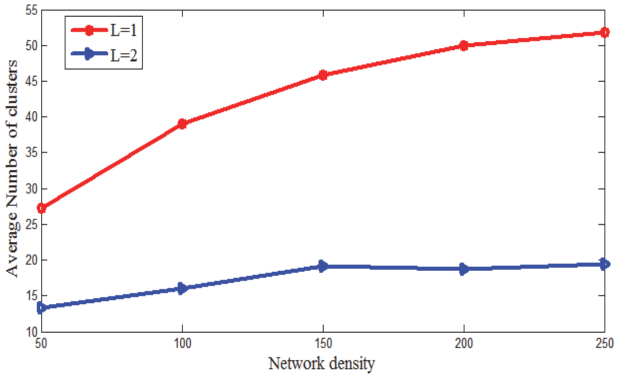

Fig. 4. Impact of channel heterogeneity on the average number of cluster with varying network density.

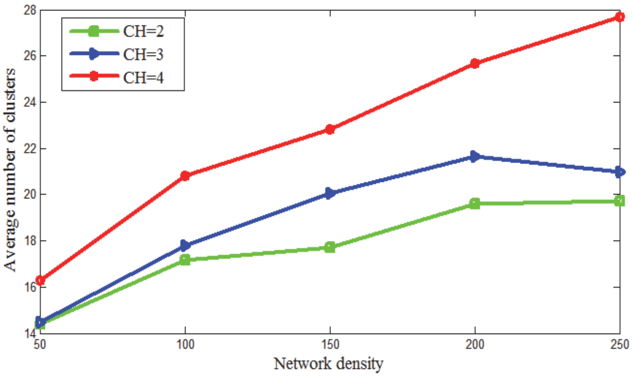

Fig. 5. Comparison of average number of clusters for different common channel constraints.

7. Conclusions

In this paper, we proposed a new clustering algorithm for distributed CRAHNs using a novel CH selection function that considers the channel heterogeneity in term of transmission ranges. Our simulation results show that, the heterogeneous channel transmission range scenario always outperforms the homogenous scenario regardless of the density of the networks in terms of minimizing the number of clusters. Decreasing the number of clusters positively affects the network scalability because it leads to decreasing the intercommunication overhead. It likewise shows that, the number of common channels per cluster increases, which is a desirable feature for enhancing the cluster stability and intra-communications, as the average number of clusters increases, which means the cluster size decreases. Apparently there is an inverse relationship between the cluster size and the number of common channels in the cluster. Therefore, a fair trade-off between the cluster size and the number of common channels in each cluster should be done. For our future work, we will consider the same heterogeneous transmission range scenario, but with load balance per cluster to enhance the energy efficiency and prolong the network lifetime.

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