Control Information Exchange in Cognitive Radio Ad Hoc Networks with Heterogeneous Spectrum

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***Abstract*—To overcome the constraint of spectrum heterogeneity, i.e., different spatial locations may have different available spectrum resources, a cognitive radio ad hoc network (CRAHN) should exchange necessary control information among nodes. To improve the performance of this exchange, the present paper proposes to establish a cluster-based Hamiltonian cycle within the CRAHN to provide an ordered flow of control information among clusters and reduce the collision and delay for control information exchange. Moreover, to offer a better clustering result for this establishment, we also design a novel distributed mechanism for randomly selecting a unique node to collect network information and develop an efficient layered clustering algorithm based on the collected information. Numerical simulation shows that, compared with the existing methods, the proposed collection mechanism is more efficient and incurs less packet collisions in collecting network information, while the proposed clustering algorithm yields a smaller average number of clusters under the condition that each cluster has at least one control channel and helps reducing the overhead of control information exchange.**

I. Introduction

As a branch of cognitive radio networks, Cognitive Radio Ad Hoc Networks (CRAHN) [1] inherit the characteristics of traditional ad hoc networks, i.e., multi-hop, self-organizing, distributed control, lack of infrastructure, changing topology, etc, and are enhanced by cognitive radio techniques, i.e., spectrum sensing/decision and multi-channel access/handoff. Thus CRAHNs are suitable for such applications as battlefield communication, emergency rescue and vehicle networking.

As illustrated by Figure 1, a CRAHN may face an environment of heterogeneous spectrum, i.e., nodes at different spatial locations may have different available spectrum resources. This makes it more difficult for the CRAHN to perform spectrum management. For example, in the environment of homogeneous spectrum, each node CR_i can find the activity of a neighbor CR_j by sequentially sensing its available channels. This, however, is not applicable to the environment of heterogeneous spectrum given that CR_j resides at a spectrum unavailable for CR_i. To remedy this, nodes in a CRAHN should exchange necessary control information, such as available spectrum, time clock, channel reservation, and network topology, for negotiating communication opportunities available for both transmitters and receivers. Thus the present paper concentrates on the design of control information exchange in a CRAHN with heterogeneous spectrum.

To facilitate this exchange, the existing literatures normally divide all nodes in a CRAHN into multiple clusters, each consisting of neighbor nodes with similar available spectrum. How to establish these clusters efficiently [2] then becomes an important challenge. For example, in [3], a node forms a cluster on a particular spectrum channel and invites adjacent nodes sharing the same channel to join its cluster. In [4], each cluster head first collects the topological and spectrum information of its multi-hop neighbors and then chooses a local control channel based on the collected information. Two distributed clustering algorithms are proposed in [5] based on the bipartite graph theory, which may require each node to exchange information with its neighbors for multiple times and can achieve a tradeoff between the average number of control channels in each cluster and the average cluster size. As these methods only utilize partial information of the whole CRAHN for clustering, they normally yield a relatively large number of clusters and hence may increase the overhead for inter-cluster exchange of control information.

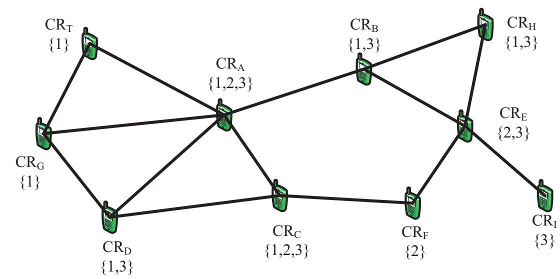

Fig. 1. A cognitive radio ad hoc network with heterogeneous spectrum, where the number below each node represents the label of an available channel .

Meanwhile, once a CRAHN with heterogeneous spectrum is clustered, how to exchange control information among clusters is also very crucial for the efficient and reliable operation of the network. However, [4] and [5] do not consider this problem. In [3], although a dedicated timeslot is allocated in each frame for exchanging inter-cluster information, no specific mechanism is designed for this exchange. In [6], the inter-cluster exchange of control information relies on an interference-free global control channel, which may not be possible in the environment of heterogeneous spectrum. To our best knowledge, the existing literatures have not formulated any specific mechanism for inter-cluster exchange of control information for CRAHNs with heterogeneous spectrum.

In view of this, the present paper first proposes a distributed

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mechanism in Section III for selecting a unique node randomly to collect the topological and spectrum information of the CRAHN with heterogeneous spectrum, then designs an efficient layered clustering algorithm in Section IV for the selected node to perform clustering based on the collected information, and finally develops a cluster-based Hamiltonian cycle in Section V for the inter-cluster exchange of control information. More specifically, the proposed distributed mechanism for information collection adopts a CSMA-based multichannel unicast scheme to exchange the topological and spectrum information among nodes. Compared to the distributed collection mechanism in [4], the proposed mechanism incurs less collection time, transmitted packets and packet collisions in distributed collection and is more robust in the sense of the random selection of a unique node for ensuing clustering. Meanwhile, compared with the two distributed clustering algorithms in [5], the proposed layered clustering algorithm incurs less computational complexity and yields a smaller average number of clusters given that each cluster is equipped with at least one local control channel. Next, the proposed inter-cluster control mechanism can effectively reduce the collision and delay for exchanging control information by establishing a cluster-based Hamiltonian cycle for coordinating the control flow among clusters and hence is preferable to the uncoordinated information exchange among clusters. All above characteristics of the proposed mechanisms are further verified in Section VI via numerical simulation and the main contribution of this paper is finally concluded in Section VII.

II. System model

The CRAHN considered in this paper can be abstracted as a graph $(\mathbf{V}, \mathbf{E})$, where $\mathbf{V}$ is the set of vertices in the graph. CRAHN) and $\mathbf{E}$ the set of communication links between the vertices in $\mathbf{V}$. Hereafter throughout this paper, we will use the terms CRAHN and graph interchangeably.

Assume that each node in $\mathbf{V}$ can only access the set $\Phi = \{CH_1, CH_2, \ldots, CH_M\}$ of M spectrum channels and always keep a fixed transmission range by adjusting its transmission power over different available channels. Because primary users may occupy any channel in Φ at any time, adjacent cognitive nodes can utilize a channel $CH_j \in \Phi$ for control or data communication only when this utilization does not affect primary communications. For the simplicity of further description, denote by $C_i \subseteq \Phi$ the set of available channels of $CR_i \in \mathbf{V}$. The constraint of spectrum heterogeneity implies that any two sets C_i and C_k may be different.

During the initialization of network communication, each node CR_i should first perform spectrum sensing on all channels in Φ to identify the set C_i of local available channels. Then, CR_i can execute various algorithms of distributed neighbor discovery, e.g., [5] for synchronized nodes and [7] for non-synchronized nodes, to detect its neighbors and obtain their available channels under the environment of heterogeneous spectrum. Thus, after the period of neighbor discovery, CR_i obtains the set NB_i of all neighbor nodes as well as the set C_k of available channels for each neighbor $CR_k \in NB_i$.

III. Random node selection and distributed collection of network information

This section is devoted to the random selection of a unique cognitive node for collecting the topological and spectrum information of the whole CRAHN in a distributed way. The selected node will then perform the node clustering in Section IV and form a cluster-based Hamiltonian cycle in Section V.

A. Topological and spectrum information table

After executing distributed neighbor discovery ([5], [7]), each node $CR_i \in \mathbf{V}$ can initialize a local *Topology & Spectrum Information Table* (*TSIT*), which records its neighbor nodes and their available spectrums. To help finding a unique node with the complete information of CRAHN, CR_i should exchange its latest TSIT with its neighbors. On the other hand, when CR_i receives a TSIT destined to it, it will merge the received TSIT and the local TSIT into a new TSIT. Because CR_i may receive multiple TSITs from its neighbors, its local TSIT may change for multiple times. For the convenience of further discussion, denote by $TSIT_i^{(0)}$ the TSIT initialized by CR_i right after distributed neighbor discovery and by $TSIT_i^{(t)}$, $t \geq 1$, the TSIT generated by CR_i right after CR_i receives the t^{th} TSIT that is destined to it.

Each $TSIT_i^{(t)}$, $t \geq 0$, at least includes four types of information: the set $SN_i^{(t)}$ of source nodes that contributes to the content of $TSIT_i^{(t)}$, the set of available channels for each $CR_j \in SN_i^{(t)}$, the set NSN_j of neighbor nodes for each CR_j, and the set of available channels for each $CR_k \in NSN_j$. Thus a $TSIT_i^{(t)}$ consists of $|SN_i^{(t)}|$ rows, each corresponding to a different $CR_j \in SN_i^{(t)}$. In particular, because $TSIT_i^{(0)}$ is only initialized by CR_i, $SN_i^{(0)} = \{CR_i\}$. For example, Figure 2(a, b) depict $TSIT_D^{(0)}$ and $TSIT_C^{(0)}$, respectively, which are initialized by the nodes CR_D and CR_C in Figure 1, i.e., $SN_D^{(0)} = \{CR_D\}$, $NSN_D = \{CR_G, CR_C, CR_A\}$, $SN_C^{(0)} = \{CR_C\}$, and $NSN_C = \{CR_A, CR_D, CR_F\}$.

On the other hand, because $TSIT_i^{(t)}$, $t \geq 1$, is generated by merging $TSIT_i^{(t-1)}$ and some $TSIT_j^{(\tau)}$, $\tau \geq 0$, the set $SN_i^{(t)}$ should include CR_i and CR_j and the table $TSIT_i^{(t)}$ must have at least two rows. Figure 2(c) depicts the table $TSIT_C^{(1)}$, which is generated by merging $TSIT_C^{(0)}$ with $TSIT_D^{(0)}$ and includes the sets $SN_C^{(1)} = \{CR_C, CR_D\}$, NSN_D and NSN_C.

B. A CSMA-based multi-channel unicast scheme

During distributed collection of network information, the exchange of TSITs among nodes should overcome the constraint of spectrum heterogeneity. To facilitate this exchange, we design a simple CSMA-based multi-channel unicast scheme. In this scheme, each node CR_i independently sets the length T_i of a local timeslot as $T_i = |C_i| \triangle t$, where $|C_i|$ is the number of available channels of CR_i and $\triangle t$ the length of a minislot. Normally, $\triangle t$ should be long enough for CR_i to first transmit a TSIT and then receive an ACK replied by the receiver. For all nodes, the length $\triangle t$ is a common knowledge.

Source Node (SN)	Available Channels of SN	Neighbor of SN (NSN)	Available Channels of NSN
CR_D	1,3	CR_A	1,2,3
		CR_C	1,2,3
		CR_G	1

(a)

Source Node (SN)	Available Channels of SN	Neighbor of SN (NSN)	Available Channels of NSN
CR_C	1,2,3	CR_A	1,2,3
		CR_D	1,3
		CR_F	2

(b)

Source Node (SN)	Available Channels of SN	Neighbor of SN (NSN)	Available Channels of NSN
CR_C	1,2,3	CR_A	1,2,3
		CR_D	1,3
		CR_F	2
CR_D	1,3	CR_A	1,2,3
		CR_C	1,2,3
		CR_G	1

(c)

Fig. 2. In the CRAHN of Figure 1, upon receiving (a) $TSIT_D^{(0)}$ transmitted by CR_D, CR_C will merge it with (b) $TSIT_C^{(0)}$ into a table (c) $TSIT_C^{(1)}$.

After distributed neighbor discovery ends, each node CR_i should first select a backoff counter d_i randomly and then begin to hop over all $|C_i|$ local available channels according to a fixed hopping sequence. At the beginning of each minislot, CR_i should handoff from one available channel to another and, in each timeslot, CR_i must visit all $|C_i|$ available channels. During a timeslot, if CR_i detects all channels of C_i being idle, then it will reduce d_i by 1; else, it will keep d_i unchanged. When $d_i = 0$, CR_i will choose a neighbor CR_k and randomly select a channel $CH_j \in C_i \bigcap C_k$ to transmit its TSIT. In each minislot of this transmission, CR_i should first transmit its TSIT and then listen at the channel CH_j. If CR_i does not receive an ACK replied by CR_k, it will transmit its TSIT again in the next minislot. This retransmission will last until it receives the desired ACK or the retransmission times reaches a maximum value. If CR_i still cannot receive ACK after the maximum times of TSIT retransmission, it will restart the CSMA-based unicast again.

In general, the selection of the maximum times of TSIT retransmission relies on whether CR_i knows the channel hopping sequence of CR_k and whether the time clocks of CR_i and CR_k are synchronized. If CR_i knows the channel hopping sequence of CR_j from neighbor discovery and the time clocks of CR_i and CR_j are fully synchronized, then CR_i can know the exact minislot, when CR_j will appear at CH_j, and hence transmit TSIT only in this minislot; else, CR_i has to increase the maximum times of TSIT retransmission so as to make sure that CR_j can finally hop to the channel CH_j for receiving TSIT. However, a large maximum times of repeated transmission will increase the overhead for TSIT transmission. In view of this, an reasonable tradeoff between the reliability and delay for TSIT transmission is set the maximum retransmission times as $|C_j|$.

C. Rules for TSIT transmission

To randomly select a unique node for collection network information, if a node CR_i receives a TSIT destined to it, it will perform the merging operation specified in Section III-A to update its TSIT. On the other hand, CR_i should decide whether to transmit its TSIT according to the following rules:

(1) When CR_i decides to transmit its TSIT, if it has not yet exchanged TSIT with all neighbors, it will first randomly select one from those neighbors that it has not yet exchanged TSIT with as the receiver; else, it will randomly select a neighbor as the receiver.

(2) After the distributed collection period begins, CR_i needs to successfully transmit the latest version of its TSIT to a neighbor selected by the rule (1) for at least one time.

(3) Once CR_i successfully transmits its TSIT to a neighbor, it will continue to listen on its available channels via channel hopping until it receives a TSIT destined to it.

(4) After CR_i merges a received $TSIT_j^{(\tau)}$ with the local table $TSIT_i^{(t)}$ into a new table $TSIT_i^{(t+1)}$, if the smallest MAC address of the nodes in $SN_j^{(\tau)}$ is larger than that of the nodes in $SN_i^{(t)}$, then CR_i will neither transmit $TSIT_i^{(t+1)}$ nor execute the computation of node clustering; else, if $SN_i^{(t+1)} = \bigcup_{CR_q \in SN_i^{(t+1)}} NSN_q$, then CR_i will stop transmitting $TSIT_i^{(t+1)}$ and begin the computation of node clustering; else, CR_i will transmit $TSIT_i^{(t+1)}$ to a neighbor selected by the rule (1).

Theorem 1. If every node in a CRAHN follows the rules (1)~(4) to transmit TSIT, then there exists a unique node that can collect the topology and spectrum information of the CRAHN and execute the computation for node clustering.

IV. A LAYERED CLUSTERING ALGORITHM UNDER HETEROGENEOUS SPECTRUM

Once a unique node, say CR_e, is randomly selected with the topological and spectrum information of the CRAHN, it will begin the computation for node clustering. Each cluster resulted by this computation should have at least one local control channel, which is available for all nodes in this cluster, for supporting the efficient exchange of intra-cluster control information. Moreover, to reduce the overhead for exchanging inter-cluster control information, the number of resulting clusters should be as small as possible. This, however, may incur high computational complexity. Thus the proposed clustering algorithm should also achieve a tradeoff between the number of resulting clusters and the computational complexity.

Based on the graph $(\mathbf{V}, \mathbf{E})$ of a CRAHN and the set C_j for each $CR_j \in \mathbf{V}$, CR_e can generate a graph $(\mathbf{V}_j, \mathbf{E}_j)$ for each channel $CH_j \in \Phi$, where $\mathbf{V}_j$ is the set of nodes with CH_j being available and $\mathbf{E}_j$ the set of possible communication links between any two nodes $CR_k \in \mathbf{V}_j$ and $CR_q \in \mathbf{V}_j$. Obviously, $\mathbf{E}_j \subseteq \mathbf{E}$. For example, Figure 3 depicts the 3 graphes of CH_1, CH_2 and CH_3 in the CRAHN of Figure 1.

With these $|\Phi|$ graphs, CR_e can transform the original problem of node clustering under the environment of heterogeneous spectrum into $|\Phi|$ independent problems of node clustering under the environment of homogeneous spectrum over $|\Phi|$ channels. A classic solution for each of these $|\Phi|$ problems is by discovering a *dominating set* $\mathbf{D}_j \in \mathbf{V}_j$ of nodes, $j \in [1, |\Phi|]$, such that each node $CR_v \in \mathbf{V}_j$ either belongs to $\mathbf{D}_j$ or is adjacent to a node in $\mathbf{D}_j$. By setting each node in $\mathbf{D}_j$ as the head node of a different cluster and letting each node

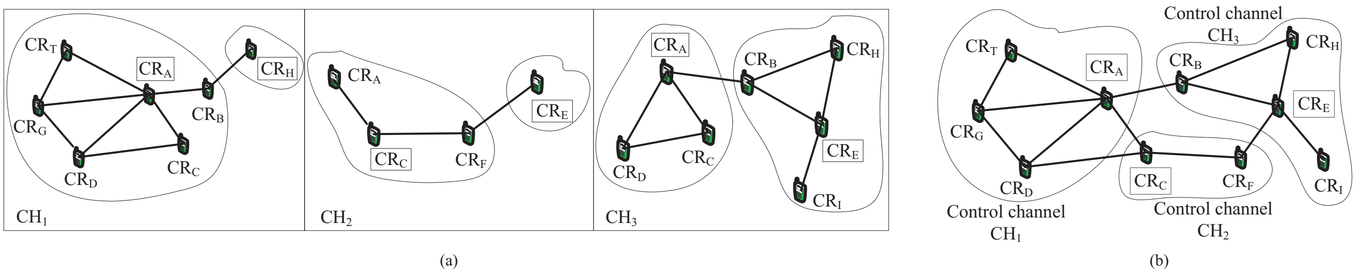

Fig. 3. The layered clustering results of the CRAHN in Figure 1 at each of the 3 spectrum channels CH_1, CH_2 and CH_3 are depicted in (a) and merged into a final clustering result in (b) via first eliminating redundant clusters and then merging effective clusters, where each cluster is surrounded by a circle and each node in a square denotes a cluster head.

in $\mathbf{V}_j \setminus \mathbf{D}_j$ be the member of an appropriate cluster, the graph $(\mathbf{V}_j, \mathbf{E}_j)$ then can be divided into $|\mathbf{D}_j|$ clusters.

In general, there exist multiple dominating sets in a graph $(\mathbf{V}_j, \mathbf{E}_j)$. To reduce the number of resulting clusters, the dominating set with the minimum number of nodes, namely *minimum dominating set* or *MDS* in short, is more preferable than a non-minimum dominating set. However, the existing algorithms for finding an MDS of the graph $(\mathbf{V}_j, \mathbf{E}_j)$ normally incur an exponential computational complexity, e.g., $O(2^{0.955N})$ in [8] and $O(2^{0.598N})$ in [9], where $N = |\mathbf{V}_j|$. To achieve a tradeoff between the number of resulting clusters and the computational complexity, we can adopt the following simple clustering algorithm, which searches for a dominating set only and has the computational complexity of $O(N^2)$ only.

Step 1. For a $CH_i \in \Phi$, initialize the set $\mathbf{H}_i$ of cluster heads and the set $\mathbf{M}_i$ of cluster members as $\emptyset$.

Step 2. Randomly choose a CR_{j*}, of which the number of neighbors is the largest among all nodes in $\mathbf{V}_i$, as a cluster head, add CR_{j*} into the set $\mathbf{H}_j$, and update $\mathbf{V}_i$ as $\mathbf{V}_i \backslash \{CR_{j*}\}$.

Step 3. Add all neighbor nodes of CR_{j*} in $\mathbf{V}_i$ into the set $\mathbf{M}_i$, form a cluster from these nodes and CR_{j*}, and eliminate the neighbor nodes of CR_{j*} from the set $\mathbf{V}_i$.

Step 4. If $\mathbf{V}_i \neq \emptyset$, then go back to Step 2; else, the node clustering process ends.

For example, Figure 3(a) depicts the clusters resulted from this clustering algorithm over CH_1, CH_2 or CH_3 in the CRAHN of Figure 1. As the clustering result at one channel may be different from that at another, CR_e should further merge the clustering results on all Φ channels into a single clustering result for the CRAHN with heterogeneous spectrum.

Denote by $Cluster_n^{(i)} = \{\mathbf{V}_n^{(i)}, \mathbf{E}_n^{(i)}\}$ a cluster on the channel CH_i with CR_n being the head node, where $\mathbf{V}_n^{(i)}$ and $\mathbf{E}_n^{(i)}$ are the set of nodes and communication links, respectively, in this cluster. For any two clusters $Cluster_n^{(i)}$ and $Cluster_m^{(j)}$, $j \neq i$, if $\mathbf{V}_n^{(i)} \subset \mathbf{V}_m^{(j)}$ and $\mathbf{E}_n^{(i)} \subset \mathbf{E}_m^{(j)}$, then $Cluster_n^{(i)}$ qualifies as a redundant cluster because any exchange of control information within $Cluster_n^{(i)}$ over CH_i can always be implemented by that within $Cluster_m^{(j)}$ over CH_j; else, if $\mathbf{V}_n^{(i)} = \mathbf{V}_m^{(j)}$ and $\mathbf{E}_n^{(i)} = \mathbf{E}_m^{(j)}$, then either $Cluster_n^{(i)}$ or $Cluster_m^{(j)}$ should be chosen as a redundant cluster. To reduce the number of node clusters after cluster merging, CR_e should eliminate the redundant subsets on all channels and only include the remaining clusters, to be called *effective clusters*, for further merging of clusters.

Denote by $SCH_n^{(i)}$ a final cluster resulted from the merging of effective clusters, of which the head node is CR_n and the control channel CH_i. Below are the two rules designed for the merging of the effective clusters on all Φ channels:

(5) For each effective cluster $Cluster_n^{(i)}$, $\forall n, i$, its head node CR_n will become that of $SCH_n^{(i)}$ and its member nodes, which do not belong to any other effective cluster, will become those of $SCH_n^{(i)}$.

(6) If a node CR_q is a member node in at least one effective cluster $Cluster_n^{(i)}$ and a head node in the remaining effective clusters it belongs to, then it will not join $SCH_n^{(i)}$; else, if CR_q is always a member node of multiple effective clusters, then it will randomly choose one effective cluster $Cluster_{n*}^{(i*)}$ from these clusters and become a member node of $SCH_{n*}^{(i*)}$.

From (5), if there exists M effective clusters before cluster merging, then the final clustering result should also have M clusters and the head node of each effective cluster will remain as a cluster head after cluster merging. In particular, if a node CR_q is the head node for $k \in [1, |\Phi|]$ effective clusters, then it will remain as the head node of k merged clusters with different control channels. This enables CR_q to offer an effective coverage for those neighbor nodes with different sets of available channels and also helps reducing the overhead for exchanging control information among those clusters with CR_q being head nodes. Moreover, (5) and (6) together can avoid the overlapping among clusters. For example, Figure 3(b) depicts the final clustering result obtained by first eliminating redundant clusters in Figure 3(a) and then merging the remaining effective clusters by (5) and (6).

V. Control information exchange over cluster-based Hamiltonian cycle

After node clustering, the execution node of clustering, say CR_e, can further design a specific mechanism for inter-cluster exchange of control information, e.g. spectrum sensing, time clock, channel reservation, and network topology. To effectively control the exchanging overhead and improve the reliability of inter-cluster exchange, this section proposes to exchange control information based on Hamiltonian cycle.

In graph theory, a Hamiltonian cycle is a closed path in an graph that visits each vertex exactly once. In a CRAHN, a Hamiltonian cycle can provide a path for exchanging control information among all nodes and reduce the overhead by unordered exchange of control information. However, the larger the network size, the longer the delay for exchanging control information among nodes. To remedy this, we shall construct a cluster-based Hamiltonian cycle for providing an ordered inter-cluster exchange of control information.

A. Construction of a cluster-based Hamiltonian cycle

Based on the clustering result, CR_e can generate a cluster-based graph $(V^{(C)}, E^{(C)})$, where $V^{(C)}$ is the set of clusters and $E^{(C)}$ the set of communication links between clusters. For any two clusters $SCH_A^{(i)} \in V^{(C)}$ and $SCH_B^{(j)} \in V^{(C)}$, if there exist two neighbor nodes $CR_a \in SCH_A^{(i)}$ and $CR_b \in SCH_B^{(j)}$ that have at least one common channel, then there exists a communication link $e_{A,B}^{(C)} \in E^{(C)}$ between $SCH_A^{(i)}$ and $SCH_B^{(j)}$ based on the node pair CR_a and CR_b.

As a branch of Traveling Salesman Problem (TSP), finding a Hamiltonian cycle in the graph $(V^{(C)}, E^{(C)})$ is an NP-hard problem. To reduce the finding cost, we adopt an algorithm [10] that can yield an approximated Hamiltonian cycle, of which the length is always less than 1.5 times the optimal one, and has the time complexity of $O(n^2\sqrt{n})$. For the purpose of robustness, if two adjacent clusters in the Hamiltonian cycle have multiple communication links based on different node pairs, CR_e should choose the node pair with maximum number of common channels as the gateway nodes between these two clusters. Once the cluster-based Hamiltonian cycle is established, CR_e can broadcast the detail information of this cycle and the beginning time for Hamiltonian-cycle-based control information exchange to all nodes. Because all nodes can be synchronized by this broadcast, they can begin to execute the control information exchange simultaneously.

B. Hamiltonian-cycle-based control information exchange

At the beginning of information exchange, the cluster head of CR_e will initialize a Hamilton Control Packet (HCP) and transmit it to the next cluster in the Hamiltonian cycle via the inter-cluster link between them. In general, a HCP includes the latest information on available spectrum, time clock, channel reservation, and topology change of each cluster it has trespassed. After receiving HCP from the previous cluster, a cluster will first renew these information and then transmit the new HCP to the next cluster. To facilitate this renewal without affecting data transmission, each node should be equipped with two pairs of transceivers, one for exchanging HCP and intra-cluster control information over the local control channel and the other for hoping on local non-control channels to exchange data or inter-cluster control information.

The control channel of each cluster is divided in the time domain into multiple frames. Each frame consists of a control period for channels reservation and a HCP period for HCP reception, renewal and transmission. More specifically, before the transmission from CR_i to CR_j during a control period, if they are in the same cluster, they will directly exchange RTS/CTS/RES over their control channel [11] to reserve an appropriate common channel for data transmission; else, if CR_i can access the control channel of CR_i, then CR_i will wait for the control period of CR_j, handoff its transceiver on a local non-control channel to the control channel of CR_j, and exchange RTS/CTS/RES with CR_j; else, CR_i will select a common channel that is available for both CR_i and CR_j and repeatedly transmitting RTS to CR_j until it receives the CTS replied by CR_j or the retransmission times reaches $|C_j|$. If CR_i cannot reach CR_j in a control period, then it can further report the channel reservation request to its cluster head in the ensuing HCP period, which will include this request into HCP such that CR_j can finally receive this request from HCP.

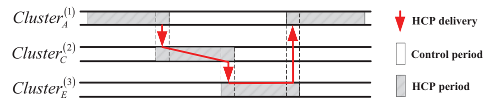

Fig. 4. The timetable for the flowing of HCP along a Hamiltonian cycle over the 3 clusters in Figure 3(b).

On the other hand, a HCP period of each cluster $SCH_A^{(k)}$ consists of 5 phases, i.e., HCP reception, HCP broadcast, spectrum sensing, member reporting and HCP transmission. In the phase of HCP reception, the gateway node of $SCH_A^{(k)}$ receives the HCP from the previous cluster in the Hamiltonian cycle and relays it to the head node CR_A, which then broadcasts the HCP to all members of $SCH_A^{(k)}$ in the phase of HCP broadcast. In the phase of spectrum sensing, each node in $SCH_A^{(k)}$ will temporarily stop data transmission and perform fast energy detection to obtain a list of local available channels. While energy detection can not differentiate the signals of licensed and cognitive users, each node can easily exclude those unavailable channels occupied by other clusters based on the channel reservation information in the latest HCP and regard the remaining unavailable channels as being occupied by licensed users. In the phase of member reporting, all members of $SCH_A^{(k)}$ will report their information of channel sensing, channel reservation, and topological changes to CR_A for updating HCP. In the phase of HCP transmission, which overlaps with HCP reception of the next cluster, CR_A will broadcasts the new HCP to all members and the gateway nodes will further relay this HCP to the relay of the next cluster in the Hamiltonian cycle. Based on this HCP, if a cluster member realizes its former reservation of data transmission becomes impossible because of topology change or spectrum agility, then it will immediately stop data transmission to avoid more collisions. Figure 4 illustrates the flowing of HCP along a Hamiltonian cycle over the clustering result in figure 3(b).

VI. Numerical Simulation

This section simulates those mechanisms proposed in Sections III∼V. In this simulation, we consider a CRAHN, in

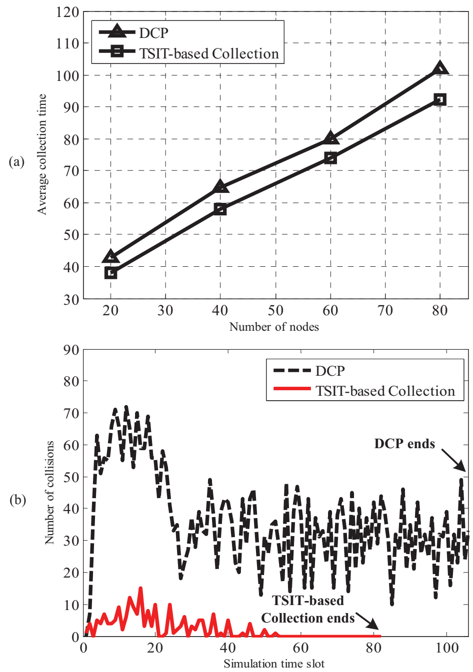

Fig. 5. (a)The average time for distributed collection of network information; (b)the number of collisions in distributed collision.

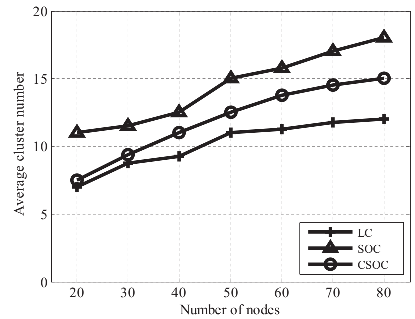

Fig. 6. The average number of clusters vs the number of nodes.

which all nodes locate within an square area of $100m \times 100m$ and the transmission distance of each node is $40m$. To create an environment of heterogeneous spectrum, the probability of a channel in $|\Phi|$ to be available for a node is 0.5.

A. Distributed collection of network information

To evaluate the performance of the distributed collection mechanism for network information proposed in Section III, we compare it with the distributed coordination protocol (DCP) in [4]. In DCP, to collect the topological and spectrum information of a CRAHN under the environment of heterogeneous spectrum, a node CR_i can broadcast a collection request to its neighbors, which then rebroadcast the received request to their neighbors again. This process will continue until all nodes in the CRAHN receives the collection request or this process lasts for a maximum time length. At the end of this process, each node will report its topological and spectrum information back to CR_i along a former path of the collection request. Through this reporting, CR_i can finally collect the information of the whole network.

Figure 5(a) compares the average time for the proposed mechanism and DCP to collect network information and Figure 5(b) the number of collisions incurred in distributed collection in terms of simulation timeslots, where $|\Phi| = 5$ and the initial backoff counter for transmitting a TSIT is randomly selected from [0, 15]. It shows that the proposed mechanism incurs less collection time and packet collisions than DCP.

B. Clustering under heterogeneous spectrum

To evaluate the performance of the layered clustering (LC) algorithm proposed in Section IV, we compare it with the two distributed clustering algorithms in [5], namely Spectrum-Opportunity Clustering (SOC) and constrained-SOC (C-SOC), both of which find a maximum edge bipartite clique from the bipartite graph $G(\mathbf{V} \bigcup \Phi, \varepsilon)$, where every edge in ε means the availability of a channel in Φ for a node in $\mathbf{V}$, and incur a worst-case computational complexity of $O(|\mathbf{V}|^2|\Phi|)$. As LC guarantees each cluster with at least one control channel, we also set the minimum number of control channels in each cluster resulted by C-SOC as 1 for fair comparison.

Figure 6 compares the average number of clusters resulted from LC, SOC and C-SOC in terms of the number of nodes. It shows that LC always outperforms both SoC and C-SOC by generating a smaller average number of clusters, which can help reducing the overhead for exchanging inter-cluster control information. The reason is that LC is based on the complete topological and spectrum information of the whole network, while both SOC and C-SOC distribute clustering computation to neighbor nodes with only partial network information.

Moreover, the worst-case computational complexity for clustering at all $|\Phi|$ channels, elimination of redundant clusters and merging of effective clusters in LC is same as that for SOC and C-SOC. However, in LC only the node that has collected the full information of the CRAHN needs to perform computation once, while in SOC and C-SOC every node in the network may have to perform clustering computation and exchange information with its neighbors for multiple times. Thus LC enjoys much less overhead than SOC and C-SOC.

C. Inter-cluster exchange of control information

To evaluate the performance of the control information exchange over cluster-based Hamiltonian cycle proposed in Section V, we compare it with the following cluster-based control information exchange without any coordination among clusters. In this mechanism, each node is equipped with two pairs of transceivers, one being fixed on the local control channel for exchanging intra-cluster control information and the other hopping at local non-control channels for exchanging inter-cluster control information or transmitting data. That is, in the communication between any two nodes CR_i and CR_j, if they share a same cluster, they will exchange control information over the control channel of this cluster; else, CR_i will first hop to the control channel of CR_k and then exchange control information with CR_k. This exchange of inter- or intra-cluster control information is also based on [11].

Before this comparison, we adopt the clustering algorithm in Section IV to form 9 clusters over a CRAHN of 40 nodes and simulate the proposed mechanism and the uncoordinated mechanism for 30 times to avoid possible fluctuation of simulation results. In the proposed mechanism, the length of a HCP period, excluding its phase of HCP reception, is set as 12 simulation timeslots and hence that of a control period is 96 timeslots. Figure 7(a) depicts the average number of collisions in exchanging the control information in terms of the simulation time. It shows that, compared with the uncoordinated mechanism, the proposed mechanism largely reduces the average number of packet collisions. This reduction comes from the ordered flowing of inter-cluster control information along the Hamiltonian cycle. Figure 7(b) depicts the average delay for control packet exchange in terms of the simulation time. It shows that, when the simulation time increases, the average delay in the proposed mechanism is always less than $108(= 9 * 12)$ timeslots, i.e., the length of a frame in each control channel, while that in the uncoordinated mechanism keeps increasing and surpasses that in the proposed mechanism after about 250 timeslots. The reason is that the proposed mechanism supports each node to reserve channel in a control period without the help of HCP or, if unsuccessful, in the ensuing HCP period via the HCP updated by its cluster head, which can guarantee the reservation to be successful within a frame. Moreover, Figure 7(b) also shows that, with the passing of simulation time, the variation of average delay in the uncoordinated mechanism also increases, while that in the proposed mechanism remains relative stable. Thus the proposed mechanism is more suitable for providing QoS guarantee for various types of traffic.

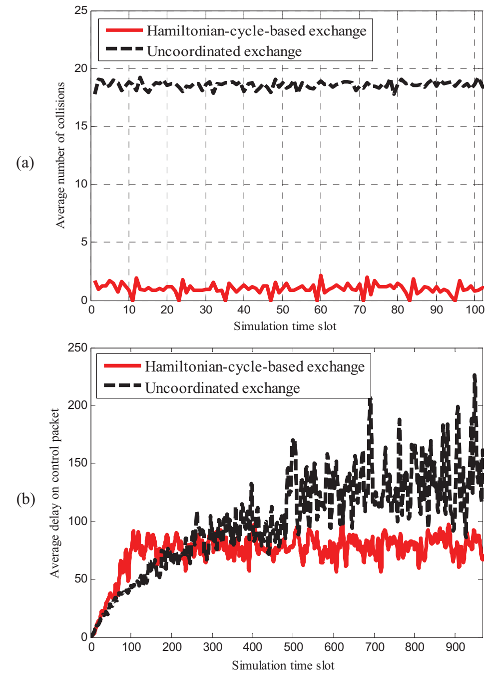

Fig. 7. Comparison between Hamiltonian-cycle-based and uncoordinated control information exchanges among clusters. (a)Average number of packet collisions; (b)Average delay of control packets

VII. Conclusion

To solve the difficulty of spectrum management for cognitive radio ad hoc networks (CRAHNs) imposed by the environment of heterogeneous spectrum, this paper introduces a novel mechanism for exchanging control information over a cluster-based Hamiltonian cycle. To further reduce the exchange overhead, we also propose a layered clustering algorithm under heterogeneous spectrum for reducing the average number of resulted clusters and the clustering overhead. Moreover, to provide necessary information for the layered clustering, we formulate a distributed mechanism for randomly selecting a unique node to collect the topological and spectrum information of the CRAHN. Numerical simulation verifies the advantages of the proposed mechanisms, e.g., less delay and collisions for control information exchange and better QoS guarantee for various types of traffic, over the existing algorithms for cluster-based control information exchange.

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