An Efficient MAC Protocol for Distributed Cognitive Radio Networks

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Abstract
Rendezvous is the essential operation in distributed cognitive radio networks (CRNs). Rendezvous means that secondary users (SUs) access the same channel at the same time to establish a communication link between each other. Channel hopping (CH) schemes have been proposed to establish pairwise rendezvous. But how to carry out the CH scheme with the MAC protocol is a challenging problem. To solve this problem, we propose a MAC protocol for distributed CR networks (CRNs), with the aim of using the idle spectrum more efficiently. Under this framework, a CH scheme based on quorum theory was proposed. Our CH scheme can guarantee rendezvous between any two SUs if they have at least a common available channel. Simulation results show that the proposed MAC protocol with CH scheme can get a better comprehensive performance in terms of throughput and packet delay.

Key words: Cognitive Radio, Channel Hopping Scheme, Rendezvous, Quorum System, MAC

1. INTRODUCTION
In cognitive radio networks (CRNs), secondary users (SUs) can use the idle spectrum unused by the primary users (PUs) in an opportunistic manner (Akyildiz and Lee, 2006; Akyildiz and Lee, 2009). The main technology of cognitive radio including spectrum sensing, spectrum sharing and spectrum management. Spectrum sensing is the premise and key technology for detecting spectrum holes in CRNs. After spectrum holes are detected, SUs can allocate the idle spectrum resources fast and efficiently by using the spectrum sharing technology. So, how to design the Medium Access Control (MAC) protocol is the main issue in spectrum sharing for CRNs.

According to the network architecture, CRNs can be classified as centralized networks and distributed networks. In centralized CRNs, a number of SUs form cluster, and the cluster head is the controller of a cluster. It is responsible for the spectrum allocating and exchanging control information between other clusters. (Lazos and Liu, 2009) formulates the clustering as a maximum edge biclique graph problem, and (Chen and Zhang, 2009) provides mechanisms for neighbor discovery, cluster formation and network topology management. A MAC protocol for cluster-based CRNs is proposed by (Li and Hu, 2013) The protocol is integrated with the proposed cluster structure. The clustered-based MAC protocol can make SUs access channel with less contend, but how these clusters are formed in a distributed manner before establishing cluster is a primary concern.

In distributed networks, due to the lack of the centralized support, SUs need to exchange control information before they can access idle spectrum for data transmission (Kaushik and Akyildiz, 2011). Rendezvous is the essential operation to exchange control information. Rendezvous means that SUs access the same channel at the same time to establish a communication link between each other. In order to achieve rendezvous, SUs tune themselves to the available channels following predetermined channel hopping (CH) sequences. CH scheme has been proposed to generate CH sequences. There are several CH schemes so far. Two algorithms, the modular clock algorithm (MC) and the generated orthogonal sequence-based algorithm (GOS), have been proposed in (Theis and Thomas, 2011). The MC algorithm uses prime number modular arithmetic to generate CH sequences. But this algorithm does not guarantee a bounded time-to-rendezvous (TTR). The TTR is defined as the number of time slots for any pair of SUs to rendezvous. The GOS algorithm repeats a selected sequence based on the permutation of the available channels. Based on the quorum theory, three schemes, namely M-QCH, L-QCH and A-QCH have been proposed in (Bian and Park, 2009). The M-QCH and L-QCH schemes have
been proposed for synchronous system. The A-QCH has been proposed for asynchronous system, but it is applicable to the systems with only two channels.

All of the MAC protocols in distributed networks only focus on the CH scheme, but how to carry out the scheme with the MAC protocol is not clear. In order to solve this problem, we propose a MAC protocol for distributed CRNs. The protocol is integrated with the proposed CH scheme. The goal of this protocol is to make the SU more robust to PU activities so as to use the free spectrum more efficiently (Li, 2015). Under this framework, we proposed a CH scheme based on quorum theory. Our scheme can guarantee rendezvous between any two SUs if they have at least a common available channel. Beside, our scheme can generate a short CH sequence, and make SUs independently generate their CH sequences.

The rest of this paper is organized as follows. In Section 2, the signal model is briefly discussed. In Section 3, the structure of superframe and the flow of MAC protocol are introduced. In Section 4, a CH scheme based on quorum theory for rendezvous is proposed. Simulation results and analysis are given in Section 5. Finally, conclusions are drawn in Section 6.

2. SYSTEM MODEL

We assume that there are totally \( N = \{0, \ldots, N-1\} \) channels in a CRN (Khan, 2014). For simplicity, we use the terms node and SU interchangeably. Each node is equipped with a single half-duplex transceiver. Nodes within the transmission range of each other can communicate if they tune to the same channel at the same time.

We also assume that the time is divided into equal-length slots and each slot is long enough to exchange multiple packets. Nodes in the network are synchronized, and the set of available channels observed by node \( i \) is denoted by \( S_i \). A CH sequence \( w = \{u_0, u_1, \ldots\} \) with the size of \( T \) slots, in which \( u_i \) denotes the channel to be visited in the \( j^{th} \) slot, determines the order with which a node visits its available channels. The sequence would then repeat itself after it is generated.

According to a CH sequence, a node hops between different channels. When nodes visit a channel, they will follow the 802.11 RTS/CTS protocol to transmit and receive packets. If two SUs successfully establish a link, the transmitter will change its CH sequence in accordance with the receiver. After the data is successfully transmitted, the transmitter rejoins its original CH sequence.

3. Distributed MAC Protocol

3.1. The Structure of Superframe

In order to make the SU’s work more efficiently and more robust to PU activities, we propose a new MAC protocol for rendezvous operation. In our protocol, channel access time is divided into a sequence of superframes. The structure of the superframe is shown in Figure 1.

\( 1 \) Spectrum sensing period

At the beginning of each superframe, SUs carry out the spectrum sensing first. At this period, all nodes keep quiet and detect idle spectrum. The synchronization of spectrum sensing period helps to reduce the false
As the spectrum sensing is the premise and key technology for detecting spectrum holes in CRNs, we proposed a coarse-and-fine spectrum sensing method to detect the spectrum holes efficiently with low signal-to-noise ratio.

The coarse sensing technique adopted the energy detection to provide fast sensing over a wide frequency range. Energy detection has been used firstly because it involves simple algorithms and does not require transcendental knowledge of the PUs’ signals. After the coarse sensing, the probable spectrum holes can be discovered. Then the fine sensing technique can be used for second sensing on those probable spectrum holes to detect whether specific type of signals existed in the received signals. For more efficient and reliable performance, cyclostationary feature detection or matched filter detections employed as a fine sensing technique (Li and Sun, 2015).

(2) Data transmission period
Data transmission period is the significant constituent part of the superframe. After spectrum sensing period, the spectrum holes can be defined. According to the spectrum holes, CH scheme generates CH sequences, and each node following this predetermined channel hopping sequences to access the spectrum holes.

As the characteristic of the CH sequences, data transmission period divided into equal-length slots and each slot is long enough to exchange multiple packets. After SU accesses any channel successfully, it broadcast control information first for neighbor discovery. Through neighbor discovery, node can discover its neighboring nodes, exchange control information and negotiate transmission schedule with them. After neighbor discovery, the communicating nodes switch to the assigned channel to transmit packets. Before transmission, the transmitter generates a random backoff time. If the assigned channel remains idle when the time expires, the transmission begins. If a collision is detected, node pair will stay quite and does not switch to any other channels. Parallel transmissions are allowed in this period if the transmission sessions use different channels.

If a node does not have any packets to send, it will follow its channel hopping sequence to tune to different channels for neighbor discovery. It will not tune to the specific channels which have been assigned to the communicating nodes. This mechanism makes an additional period for neighbor discovery unnecessary.

(3) Reward period
After each transmissions behaviour, SU generates a reward to evaluate this transmission. The reward is used to support the actions of the node throughout its lifetime, such as helping it find neighbors quickly, forming CH sequences and selecting channels for data transmission. The reward including the total duration to access one channel for data transmission, the total bits delivered on one channel and the time when this channel is used by PUs.

![Figure 2. MAC protocol flow chart](image-url)
3.2. The Flow of the MAC Protocol

Summarize the structure of superframe aboved, the flow chart of our proposed MAC protocol can be described as Figure 2.

At the beginning of each superframe, all nodes keep quiet and detect idle spectrum with dual-stage sensing technique which are coarse sensing and fine sensing. When PU appears on the coarse sensing period, all SUs keep quiet and waits for the next superframe. If PUs do not return during the coarse sensing period and some probable spectrum holes are detected, SUs implement fine sensing scheme. After the fine sensing, spectrum holes can be detected. If no spectrum hole existing, SUs should keep quiet and wait for the next superframe too. During the spectrum sending period, the time when channels are used by PUs is considered as the reward to store.

If there existing spectrum holes, SUs use the reward value stored to generate the CH sequences. At each slot to access different channel, SUs implement neighbor discovery to exchange control information and negotiate transmission schedule with other nodes. After neighbor discovery, the communicating nodes switch to the assigned channel to transmit packets. During neighbor discovery and data transmission, SUs can get reward such as total duration to access one channel for data transmission and the total bits delivered on one channel to store.

4. QUORUM-BASED CHANNEL HOPPING SCHEME

4.1. The Quorum Theory

In this section we give a brief overview about the quorum system where the details can be found in (Jiang and Tseng, 2005).

**Definition 1.** Given a universal set \( U = \{0,...,n-1\} \), a quorum system \( Q \) under \( U \) is a collection of non-empty subsets of \( U \), each called a quorum, which satisfies the intersection property:

\[
\forall p,q \in Q, \quad p \cap q \neq \emptyset
\]  

**Definition 2.** Given a non-negative integer \( i \) and a quorum \( p \) in a quorum system \( Q \) under \( U = \{0,...,n-1\} \), we define

\[
\text{rotate} (p,i) = \{(k + i) \mod n | k \in p, i \in [1, n-1]\}
\]

**Definition 3.** A quorum system \( Q \) under \( U = \{0,...,n-1\} \) is said to have the rotation closure property if

\[
\forall p,q \in Q, \quad i \in [1, n-1], \text{rotate}(p,i) \cap q \neq \emptyset
\]

For example, \( Q = \{\{0,1,2\}, \{1,2,3\}, \{0,2,3\}\} \) is a quorum system under \( U = \{0,1,2,3\} \) and it has three quorums. Two quorums, \( \{0,1,2\} \) and \( \{1,2,3\} \), have intersections which are \( \{1,2\} \).

4.2. The Quorum-based Rendezvous Scheme

By utilizing the quorum theory, we consider the total channel set \( \{0,...,N-1\} \) in the CRN as a universal set \( U \), and the available channel set of a node as a quorum. If nodes have common available channels, we can say that those nodes belong to the same quorum system. Through the CH scheme, we can make nodes belong to the same quorum system rendezvous. Next, we provide two definitions related to our scheme.

**Definition 2.** Given a total channel set \( N = \{0,...,N-1\} \) \((N \geq 3)\), there exist three positive integers \( P, r \) and \( c \). Here \( P \) is the minimum non-prime number greater than or equal to \( N \), and the three integers satisfy the following property:

\[
P = r \times c, \quad r \leq \frac{N}{2}, \quad c \leq N \text{ and } c \text{ (mod } 2) \neq 0
\]

In our scheme, we set a CH sequence that is composed of \( c \) subsequences and each subsequence has \( N \) slots numbered 0 through \( N-1 \). So the length of a CH sequence is \( T = N \times c \).

**Definition 3.** A rendezvous matrix \( R \) is an \( n \times c \) array in a row-major manner. The \( N \) channels are arranged into the matrix \( R \), which means that each channel \( n \in [0, N-1] \) is placed into a position \((d, g)\) of \( R \), where

\[
d = \left\lfloor \frac{n}{c} \right\rfloor + 1, \quad g = n \text{ (mod } c) + 1, \quad d = 1,...,r, \quad g = 1,...,c
\]
**Definition 4.** Given a rendezvous matrix \( R \) and an available channel set, channels not belonging to the available channel set are removed from the matrix \( R \). The following two rules are used to adjust the positions of the available channels:

1. In a column, if a channel is missed in one row, the channel placed in the next row will be moved to this row.
2. If there is no channel in a column, variable \( h \) will be assigned to this column. We use \( h \) to denote a randomly selected channel from the available channel set.

Then, the remaining channels in \( R \) form a new matrix, named the sub rendezvous matrix \( SR \).

For example, given \( R=\begin{bmatrix} 0 & 1 & 2 \\ 3 \end{bmatrix} \) and a node’s available channel set \( S=\{1,3\} \), the sub rendezvous matrix of this node is \( SR=[3 \ 1 \ h] \).

So, a node’s CH sequence generated by your scheme is outlined in the following steps.

1. For the total number of channels \( N \), the rendezvous matrix \( R \) and the length of a CH sequence \( T \) are determined. Combined with the node’s available channel set \( S \), the matrix \( SR \) is constructed.

2. Consider \( S \) as a quorum, and find the slots in each subsequence whose indexes are equal to the elements in \( S \). Those slots are called the quorum slots. The remaining slots in each subsequence are called the ordinary slots.

3. Assign the channel in the \( i^{th} \) column of \( SR \) to the quorum slots in the \( h^{th} \) subsequence, \( i \in [1,c] \). During this process, if more than one channel exists in the same column of \( SR \), the following additional rules can be used for arrangement:
   1. Arrange a channel into the quorum slot when they have the same index.
   2. Then, arrange the channel with odd index into the quorum slots with odd index, and vice versa.

4. The ordinary slots in each subsequence are assigned with channels randomly selected from the available channel set.

We now illustrate the above scheme. For \( N=\{0,1,2,3,4\} \), \( R=\begin{bmatrix} 0 & 1 & 2 \\ 3 & 4 \end{bmatrix} \), and \( c=3 \), the length of a CH sequence is \( T=N\times c=15 \). Given the available channel sets of three nodes \( S_A=\{0,1,2,4\} \), \( S_B=\{2,3,4\} \), \( S_C=\{1,2,3,4\} \). We can find that the three quorums belong to the same quorum system. From definition 4, we can get \( SR_A=\begin{bmatrix} 0 & 1 & 2 \\ 4 \end{bmatrix} \), \( SR_B=[3 \ 4 \ 2] \), and \( SR_C=\begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} \). For node A, the slots with indexes \( \{0,1,2,4\} \) in each subsequence are quorum slots, as shown in Figure 3.

![Figure 3. Quorum slot and ordinary slot](image-url)

According to \( SR_A \), in the first and third subsequences, the quorum slots are assigned with channel 0 and 2 respectively. When referring to the second subsequence of \( SR_A \), two elements exist here, so the additional rules are used. According to the additional rule a), we assign channel 1 to the quorum slot whose index is 1 and channel 4 to the slot whose index is 4. Then, according to the additional rule b), we assign channel 4 to the
slot whose indexes are 0 and 2. After this, we randomly select channels from \( S_3 \) to the ordinary slot of the sequence. The same process can be done for the other two nodes. The results are illustrated in Figure 2. From Figure 4, we can find that any two nodes can rendezvous on their common channels in a sequence period (for any two nodes, we just use a slot to show the rendezvous situation).

<table>
<thead>
<tr>
<th>Subsequence</th>
<th>1st subsequence</th>
<th>2nd subsequence</th>
<th>3rd subsequence</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot number</td>
<td>0 1 2 3 4</td>
<td>0 1 2 3 4</td>
<td>0 1 2 3 4</td>
<td>...</td>
</tr>
<tr>
<td>Node A</td>
<td>0 0 0 h 0 4 1 4</td>
<td>h 4 2 2 2 0 0 h</td>
<td>h 0 ...</td>
<td></td>
</tr>
<tr>
<td>Node B</td>
<td>h h 3 3 3 h h 4</td>
<td>h 4 4 h 2 2 h 3</td>
<td>h 3 3 ...</td>
<td></td>
</tr>
<tr>
<td>Node C</td>
<td>h 3 3 3 h 1 4 4</td>
<td>h 4 4 h 2 2 h 3</td>
<td>h 3 3 3 ...</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4. An illustration of the CH scheme

5. SIMULATION AND ANALYSIS

For performance comparison purpose, we simulate the proposed distributed MAC protocol called quorum-scheme (QS) in matlab with two other existing approaches: the QCH algorithm (Bian and Park, 2009) which using the CH scheme to get rendezvous and a cluster-based approach from (Chen and Zhang, 2009), which is called Cogmesh. We use two major metrics for performance evaluations: network throughput, packet delay.

Our simulation setup uses 100×100 m area, with 10 PUs, 10 channels and 30 SUs. The PU accesses each channel independently and at least one channel to be used by PUs at a time. The length of a slot is 10ms. The transmission range of a PU is 40m, and the SU is 20m. The data rate is 1Mbps and the packet size is 512 bytes. We perform the simulations for 100 runs and average the results, and each simulation sustains a network time of 900 seconds.

![Aggregate MAC throughput](image)

Figure 5. The aggregate throughput

Figure 5 depicts the maximum MAC throughput achievable in the three protocols under different network traffic. With a low traffic volume, nodes in the CH schemes which are QS and QCH can easily find a channel to transmit, and thus has better performance than the cogmesh protocol. As traffic (flow rate) is increasing, the throughput of QChand QS degrades. This is because more collisions are raised and the channel utilization is low. The throughput of our protocol QS is higher than that of QCH. This is because the designed MAC protocol is integrated with the proposed CH scheme which can maximize the throughput. The Cogmesh protocol is cluster-based structure, and the cluster heads responsible for managing communications between nodes in their clusters. Thus all available channels can be fully used under high traffic.

Figure 6 shows the average packet delay of the protocols as the network load increases. When network traffic is low, the Cogmesh protocol shows higher delay because nodes have to wait until the transmission schedule is determined by the clusterhead. While in QCH and QS, node pair starts transmission once they contend for a channel. When the traffic load increases, QCH suffers from high contention and SUs must wait for a long time for transmission. It is clear that a higher traffic amount results in a longer process time on channel negotiation. Due to more stable cluster structure, our protocol has lower delay than Cogmesh and QCH.
6. CONCLUSIONS

In this paper, a new MAC protocol based on the distributed architecture for CRNs is proposed. The goal of this protocol is to make SUs more robust to PUs and use spectrum efficiently. Besides, a CH scheme based on quorum theory was proposed. The proposed CH scheme can make SUs independently generate their CH sequences and guarantee rendezvous between any two SUs if they have at least a common available channel. Simulation results show that the proposed distributed MAC can achieve higher throughput and lower delay than other protocols.

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