Cooperative Incumbent System Protection MAC Protocol for Multi-channel Ad-hoc Cognitive Radio Networks

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Abstract

Cognitive radio (CR) MAC protocol provides access control of unused spectrum resources without causing interference to primary users. To achieve this goal, in this paper a TDMA based cooperative multi-channel cognitive radio MAC (MCR-MAC) protocol is proposed for wireless ad hoc networks to provide reliable protection for primary users by achieving cooperative detection of incumbent system signals around the communication pair. Each CR node maintains transmission opportunity schedules and a list of available channels that is employed in the neighbor discovery period. To avoid possible signal collision between incumbent systems and cognitive radio ad hoc users, we propose a simple but efficient emergency notification message exchanging mechanism between neighbor CR nodes with little overhead. Our simulation results show that the proposed MCR-MAC can greatly reduce interference with primary users and remarkably improve the network throughput.

Keywords: Cognitive radio, ad-hoc network, multi-channels, incumbent systems

1. Introduction

$\mathbf{A}$ recent study by the Federal Communications Commission (FCC) [1] indicates that most of the frequency bands allocated by the regulatory agency to primary users are not fully utilized all the time at all places. Although the fixed spectrum assignment policy generally worked well in the past, there has been a dramatic increase in demands for access to the limited spectrum by mobile services in recent years. Cognitive radio (CR) technology [2] has emerged as a solution to the problem of spectrum scarcity for wireless communications. By making it possible for an unlicensed user to access a spectrum hole using CR technology [3], spectrum utilization can be enhanced significantly. In general, CR users should be able to identify and use the portion of the unused spectrum efficiently and should also evacuate the current spectrum in use immediately when incumbent systems restart their operations (IEEE 802.22 [4]).

Recently, quick setup and operation without the need of any wired infrastructure (e.g., base stations, routers, etc.) make mobile ad-hoc networks (MANET) a promising candidate for military, disaster relief, and law enforcement applications. Growing interest in these applications has created the need for effective protocols and algorithms, where all nodes cooperatively maintain network connectivity. It is obvious that using multiple channels can significantly enhance the total throughput, in which transmissions can be processed on different channels simultaneously while avoiding collisions and interference between nodes in wireless ad hoc networks. In this paper, to increase the throughput, multi-channel CR ad hoc networks are considered by dynamically utilizing spectrum holes. We use both primary system/user and incumbent system/user to represent the licensed users in this paper. And there exists a total N sub channels on the licensed band. To coexist with the licensed primary users in an ad hoc based multi-channel CR environment and to achieve a higher throughput, the key issue is how to utilize multi- channel resource on the licensed band efficiently while causing minimum interference to primary users. Most conventional multi-channel ad hoc MAC protocols have focused on the methods of how to avoid possible data collisions between neighbor nodes. However, a more important concern for CR ad hoc networks should be possible interference with neighboring incumbent systems during the data transmission. The CR nodes in transmission may not sense or recognize the signal from neighboring incumbent systems because they are in different transmission ranges. Once data communications begin, this situation has a direct negative impact on the performance of the incumbent systems operating on the same data channels. This outcome contradicts the original principle of CR: the implementation of CR must not impinge upon the performance of primary users (PUs). Therefore, the immediate notification of the incumbent systems by the neighbor CR nodes that detected the primary signal is required.

In this paper, we propose a coorperative multi-channel cognitive radio MAC (MCR-MAC) protocol to address the hidden incumbent node problem in cognitive ad hoc networks. MCR-MAC does not require a centralized coordinator. Link (including sub-channel and time slots) negotiations between distributed CR nodes are performed by using a carrier sense multiple access/collision avoidance (CSMA/CA) based algorithm. Reactive reports by the CR neighbor nodes can also be transmitted on a link that was negotiated previously to immediately propagate the incumbent system appearance events. In order to protect incumbent systems, it is necessary to obtain reliable sensing results to set up or change the transmission link. Information of the hidden incumbent system in the proposed MCR-MAC can be obtained via

cooperative notification messages exchanged among neighbor CR nodes that sensed the incumbent signal. The concept of the time slot employed in this paper provides data packets transmission and the notification reporting process. To reduce sensing overhead and increase the accuracy of detecting incumbent systems, an efficient overhearing and channel-status table maintenance method with a real-time notification message exchanging mechanism are utilized in this paper. The proposed MCR-MAC can provide reliable sub-channel selection and reduce possible harmful interference to existing primary users.

The rest of this paper is organized as follows. Section 2 discusses works related to multi-channel management and ad hoc CR protocol design. Section 3 presents the proposed cooperative multi-channel cognitive radio MAC protocol features and overall architecture. Section 4 illustrates the proposed MCR-MAC protocol in detail. The simulation results are presented in Section 5, and Section 6 concludes this paper.

2. Related Works

Two kinds of hidden node problems exist for single transceiver users in conventional wireless ad hoc networks. One is the hidden node problem in a single channel, while the other is the multi-channel hidden node problem [5]. To solve the single channel hidden node problem, which is caused by the lack of overheard signals of other CR nodes, the distributed coordination function (DCF) of the standard IEEE 802.11 ad hoc networks is proposed. To successfully address this issue, a ready-to-send/clear-to-send (RTS/CTS) exchange mechanism is employed.

Compared with single channel environment, multi-channel MAC protocols can achieve higher throughput. However, as mentioned in [5], with a pure CSMA/CA scheme, it is hard to solve the multichannel hidden node problem. To deal with the multichannel hidden node problem, a multi-channel MAC (MMAC) protocol [5] was proposed, in which synchronizing each node is required. At the beginning of the beacon period, to avoid data collision with neighbor nodes during channel negotiation, every node should be tuned to a common channel in ad hoc traffic indication message (ATIM) windows as in the IEEE802.11 power saving mode [6]. After the ATIM window, the nodes will switch to their agreed channels and exchange messages during the remainder of the beacon interval. DCR-MAC [7] discovers a new hidden incumbent node problem and proposes an efficient neighbor reporting solution. In [7], the incumbent signal sensing scheme is not only performed by the communicatin pair, but also with the cooperation of their neighbors and the revolutionary pulse based sensing reporting scheme, it is able to provide reliable protection to the incumbent system working around. Since DCR-MAC relies on the separated common control channel and only cares about the single hop issues, [8] proposed a synchronization MAC where separared common control channels can be avoided, and [9] extends [7] and proposes a distributed multichannel MAC protocol for multi-hop cognitive radio networks with energy efficient concept in consideration, respectively. In [10], a cognitive MAC protocol is proposed for multichannel wireless networks (C-MAC), which operates over multiple channels and thus able to effectively deal with the dynamics of resource availability due to PUs and mitigate the effects of distributed quiet periods utilized for PU signal detection.

There are several related studies that proposed to manage the multi-channel spectrum resource sharing and protect the incumbent systems in cognitive radio networks. In [11], a novel cross-layer based opportunistic multi-channel MAC protocol is proposed, in which time is divided into small time slots in the control channel and each slot consists of reporting phase and negotiating phase. According to the number of sensing nodes, either simple sensing

scheme or the neighbor coodinated sensing scheme will be used to guareete accuracy of the incumbent signal sensing. Decentralized cognitive MAC (DC-MAC) for dynamic spectrum access is presented in [12]; it is a cross layer distributed scheme for spectrum allocation and sensing. It provides an optimization framework based on partially observable Markov decision processes. In DCA (Dynamic Channel Assignment) protocol [13], it is assumed that each node is equipped with two transceivers: one constantly monitors the common channel to avoid the multi-channel hidden node problem, while the other tunes onto the data channel for data transmissions. Any node that has a packet to transmit must ensure that the channel it wants to use is unoccupied. If there is no available channel, the node must wait until an idle channel comes up by monitoring the common control channel and then select a random back-off time to access that available channel.

Distributed CR MAC (COMAC) protocol is presented in [14] that enables unlicensed users to dynamically utilize the spectrum while limiting interference to PUs. COMAC does not assume a predefined SU-toPU power mask and requires active coordination with PUs. The CR enabled multichannel MAC (CREAM-MAC) protocol is proposed in [15] integrates the spectrum sensing at physical layer and packet scheduling at MAC layer. CREAM-MAC enables the SUs to efficiently utilize the unused frequency spectrum while avoiding the collisions among SUs and between SUs and PUs. Even though SMACS (Self-organization Medium Access Control for Sensor-networks) [16] is originally designed as an infrastructure-building protocol for sensor networks, its combined link setup and neighbor discovery concepts are adapted into CR networks. In [16], a link will be assigned to a pair of neighbors immediately after the link's existence is discovered, in which the contention period can be avoided completely, resulting in a reduction in access delay. By the time that all CR nodes hear all their neighbors, they will have formed a connected network. In a connected network, at least one multi-hop path exists between any two distinct CR nodes. To reduce the likelihood of collisions, each link is required to operate on a different frequency. This frequency band is chosen at random from a large pool of possible choices when the links are formed. Therefore, collision can be avoided to enhance the overall network throughput. A resource sharing approach to improve licensed spectrum utilization (AS-MAC) is presented in [17]. It is a spectrum sharing protocol for cognitive radio networks that coexists with a GSM network. CR users select channels based on control information exchange and GSM broadcast information. Coordination from incumbent users is required. SCA-MAC (Statistical Channel Allocation MAC) [18] exploits the statistics of spectrum usage in terms of decisions regarding channel access. A polling based primary user locating scheme is proposed in [19]. [20] and [21] propose good serveies of current cognitive radio MAC protocols.

Previous CR ad-hoc multi-channel MAC protocols generally have two features: 1) frame structure and common control channel and data channel operations; and 2) the multi channel spectrum resource sharing and protecting the incumbent systems. However, few of them consider the hidden incumbent node and the method of how to avoid interference to those hidden incumbent nodes. The proposed MCR_MAC not only eliminates unacceptable interference to primary users, but also enhances the secondary throughput with efficient time slot based resource scheduling. Also most of the existing CR MAC protocols assume at least two transceivers, in which one is for common control channel monitoring and the other is for data transmission. The proposed protocol uses only single transceiver and, a CR device learns the multi-channel time schedule by periodically overhearing the common channel. One of unique contributions of MCR_MAC is rapid propagation of the primary detection notification event to the neighbors using other available data channels that do not cause any harmful interference.

3. Proposed Multi-channel CR Ad-hoc MAC Architecture

3.1 Hidden Incumbent Node Problem in CR Ad-hoc Networks

In ad hoc based multi-channel CR environment, when a certain primary user tunes into the current channel occupied by the secondary nodes, the lack of notification to its neighbor nodes may cause severe interference to the primary users, even if one of the ad-hoc nodes detects the incumbent signal. In this paper we refer to this problem as the hidden incumbent node problem.

Fig. 1 explains the situation of the hidden incumbent nodes. Suppose CR node A has six available channels (SC1 ~ SC6) based on its local channel status table. The available channel indicates that no incumbent signal was sensed and no other neighbor nodes use the channel. As exhibited in Fig. 1, some incumbent devices are operating on SC1, SC2, SC3, and on SC4 inside the transmission ranges of CR nodes A, B, and C. As the radio waves from incumbent systems cannot reach some CR nodes, not all nodes can sense the incumbent signal. It is possible that after channel negotiation between A and B, they may choose SC1 as an optimum data channel, which will directly cause interference to the incumbent system working on SC1 inside the A's transmission range. On the other hand, within the transmission range of node C, there are also three sub-data channels (SC2, SC3, SC4) taken by incumbent devices. The incumbent signal on SC4 can be sensed by C; therefore, the available channel list of C will not include SC4. If node C selects a channel from one of the incumbent channels (SC1, SC2 or SC3) for data exchange with nodes A and B, then some neighbor incumbent devices will receive harmful interference from them during data transmissions. In this scenario, C selects SC3 and SC2 to communicate with A and B, respectively, so that some incumbent devices around A and B will receive interference from them. Therefore, it is necessary to exchange the incumbent system information with the one-hop neighbors of the CR nodes.
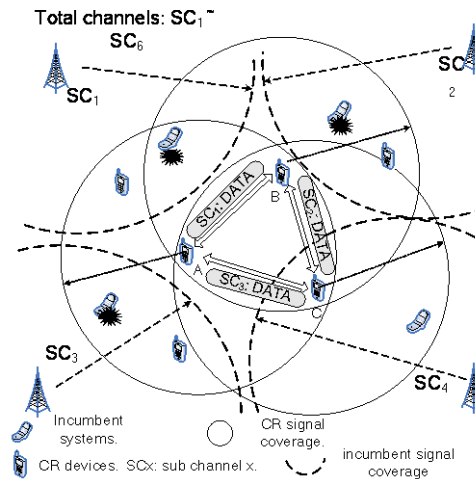

Fig. 1. Hidden incumbent node problem in CR ad-hoc networks.

3.2 MCR-MAC Features

In this paper, the design goal of MCR-MAC is to protect primary users from possible interference from CR ad-hoc nodes and, at the same time, to utilize the benefits of multi-channel operation (such as higher aggregate throughput and better robustness). The key requirements for multi-channel ad-hoc CR MAC protocol include negligible performance degradation due to the shared operation with incumbent devices, resolution of multi-channel

hidden incumbent node problem, efficient radio resource usage, and ad-hoc mobility support. To meet the CR ad hoc MAC requirements, the following approaches are used in this paper:

- **Control and data channel separation:** A common control channel and multiple data channels are utilized in this paper. Since the common control channel should be stationary and dedicated only for exchanging control messages, we assume that a separate control channel (e.g., an empty channel of ISM band) exists. The data channels occupy the spectrum holes that are shared by secondary users for high-speed data transmission.

- **Single transceiver model:** Every node is equipped with one half-duplex transceiver capable of dynamically switching channels, and it can only transmit or receive on a definite channel at any given time.

- **In-band and out-band sensing scheduling:** Each CR node periodically performs in-band sensing on the current active license channels (current using channels). For in-band sensing, all CR nodes should cease their data transmission during the quiet period (QP) on the licensed channels. To avoid interference from any neighboring CR transmission during the in-band sensing, the QP scheduling is notified to neighbor CR users. Therefore, if any neighbor CR nodes use the same licensed bands, then they can cease data transmission using the same QP. Neighboring CR users should exchange their timeslot schedule and sensing result to guarantee the correctness of primary signal detection. When CR nodes do not have any data transmission, they will be scheduled by the cluster head to perform the out-band sensing to capture the availability of licensed channels.
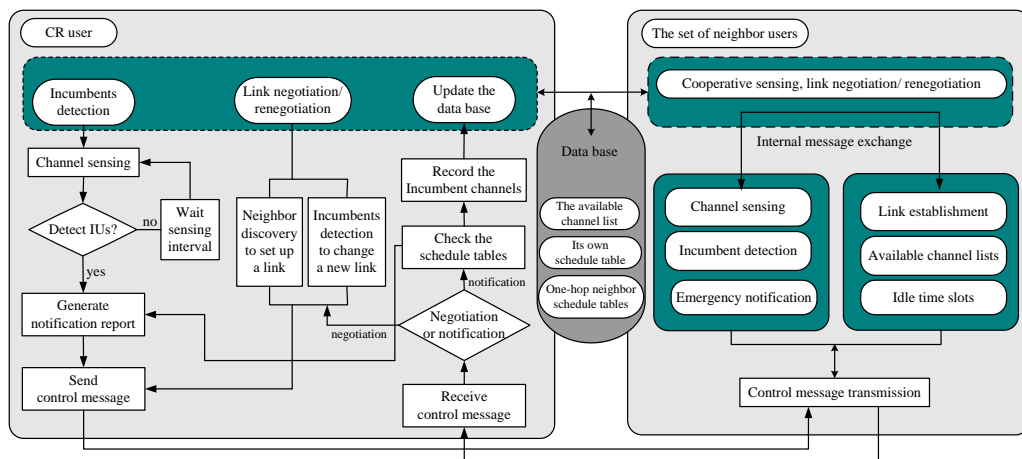

Fig. 2. The proposed MCR-MAC architecture.

- **Reactive and collision free neighbor reporting:** Proactive neighbor information exchanges require a great deal of packet overhead and frequent control message transmissions to report the spectrum usage of incumbent systems. Additionally, a simple broadcast of each node's sensing result is very unreliable due to the lack of ACK mechanism to broadcast packets and for possible collisions. Consequently, a new collision-free notification method is proposed to report status of the incumbent channel status.

- **Neighbor node synchronization:** In order to control the exchange of messages and data packets in non-overlapping timeslots, all neighbor CR nodes in the network should

synchronize with each other.

Fig. 2 illustrates the architecture of the proposed MCR-MAC system. The proposed system consists of three main functionalities. Each node periodically senses the licensed spectrum and searches for spectrum holes. This incumbent system channel information should be delivered to neighbor ad hoc nodes in an appropriate and reliable manner. In the network initialization phase, the neighbor discovery scheme is employed by each node to find its direct neighbor nodes; and this scheme will be described in detail in Section 4. Once they find each other, they will cross-check their available channels and idle schedules, where each node's idle schedule includes the time slots that are not currently reserved for its communication and are not used by any one-hop neighbor node for receiving data. After the link is connected, the pair of nodes can transmit and receive according to the reserved schedule on a selected channel. If any node detects the incumbent signal due to the fact that a certain primary user has suddenly appeared on the current selected channel, then it will generate a control message about this event to alert all communication peer nodes to make them leave the channel immediately and will renegotiate a new link. To further protect the incumbent devices, it is very important that this information should be delivered to all neighbor nodes that use the channel in accordance with their schedules because such nodes cannot sense the incumbent signal due to their location out of the transmission range of the incumbent device.

According to the proposed scheme, each node has a database that stores its available channel list, its schedule table, and the schedule tables of its one-hop neighbor nodes, as is shown in **Fig. 2**. Using the database, when a node negotiates or renegotiates a link with its neighbors, they can select a common available data channel and idle time slots and successfully protect the primary users by avoiding the multi-channel hidden incumbent node problem. Besides, it will be also a collision-free link with its neighbor nodes. Additionally, some new terminologies are defined in this paper; a glossary of names and definitions is provided in **Table 1**.

Table 1. Glossary of new terminologies

Variable	Definition
C_i^{IC}	Set of sub-channels occupied by incumbent systems and sensed by node i, $\forall i \in M$, M is a set of nodes.
$C_i^{nbr\_IC}$	Set of sub-channels occupied by incumbent systems and sensed by neighbor node i, $\forall i, j \in M$
SC_j	j-th sub-channel, $\forall j \in M$
S_i	i-th time slot, $\forall i \in M$
C_{all}	Set of all sub-channels, $C_{all} = \{SC_1, SC_2, \dots, SC_N\}$
C_i^{avc}	Set of available sub-channels of node i, $\forall i \in M$
C_{j-k}^{avc}	Set of available sub-channels of the pair of nodes j and k, $\forall k, j \in M$
C_{j-k}^{*}	The selected sub-channel between nodes j and k, $\forall k, j \in M$
$T_j^{idle(c)}$	Set of idle time slots that are not used by node j or one hop neighbors of node j on channel c, $\forall j \in M$
$T_{i-j}^{idle(c)}$	Set of common idle time slots between nodes i and j on channel c, $\forall i, j \in M$
$T_{i \to j}^{(c)}$	Time slot used for transmitting from node i to node j using channel c, $\forall i, j \in M$

3.3 MCR-MAC Architecture

The proposed MCR-MAC uses a TDMA frame structure, as is shown in **Fig. 3**.
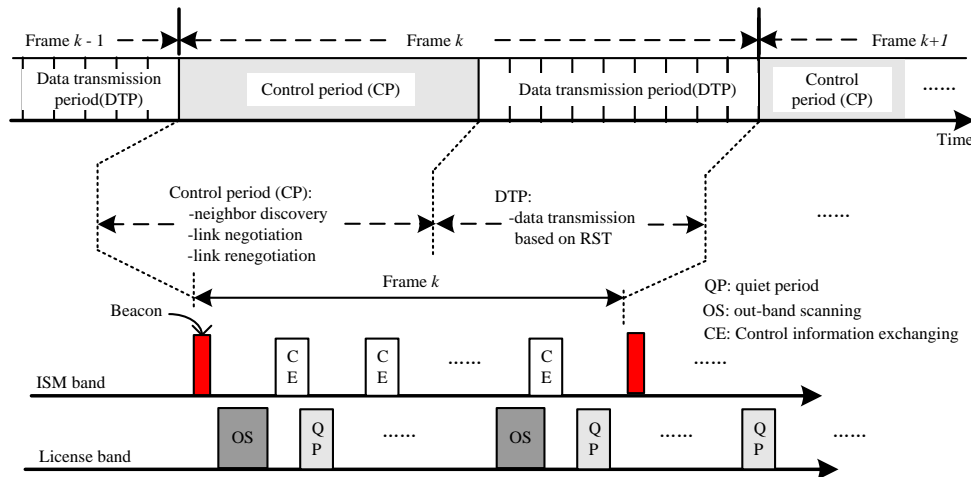

Fig. 3. The TDMA frame structure.

The frame length is fixed for all CR nodes, and is a parameter of the MAC design. Every frame consists of two parts: a control period (CP) and a data transmission period (DTP). During the control period (CP), all CR nodes must tune into the common control channel so that the control information can be exchanged. Nodes can access the control channel for initial neighbor discovery, negotiation, and renegotiation procedures. Specially, a renegotiation request is sent due to the primary appearance so that the renegotiation is more important than others. In this paper, the spectrum access of CR nodes on the common control channel follows the CSMA/CA scheme with different back-off priorities as defined in IEEE 802.11e WLAN to reduce collision possibility. We give higher priority to the renegotiation event with shorter back-off time.

The proposed CR protocol requires timing synchronization and a neighbor discovery procedure between nodes. Each communication pair reserves the dedicated time slots so that guaranteed service and efficient emergence notification about the primary user appearance without collision are possible. The notification and renegotiation procedures using the dedicated time slots are effective to protect primary users. Many time synchronization algorithms have been proposed for sensor networks such as RBS [22], TPSN [23], and LTS [24]. However, it should be noted that as the number of neighbor nodes increases, the protocol complexity of synchronization and neighbor discovery also increases. To handle this scalability issue, we can use clustering technology, which is out of the scope of this paper. At each packet's header, the frame size, CP and data slot size are included. At the beginning of each frame, all nodes should tune onto the common control channel. CP is used for neighbor node discovery and link (re)negotiation with communication peers. DTP consists of N time slots where each node can use a time slot to transmit or receive data. During CP, CR nodes exchange control messages that carry the reserved schedule table (RST) of each node. RST includes a list of available sub-channels and information about currently reserved time slots.

The neighbor discovery procedure is performed to handle the appearance of new nodes or the movement of nodes. When a new node wants to join the ad-hoc network or a node moves to a different position so that the neighbor relationship has changed, the node can initiate a

neighbor discovery procedure during the CP of any frame. Once a node discovers its neighbors, this procedure may not be necessary at every frame. Therefore, in MCR-MAC, the neighbor discovery operation of the existing node is executed in every M frame (MAC design parameter). Due to the uncertainty of the appearance of the primary user, the spectrum holes of the licensed bands vary unpredictably. The CR nodes must leave the channel on which the primary users have been detected and must renegotiate a new link with the communication pair. The information of the incumbent signal detection should be delivered to the neighbor nodes immediately, regardless of whether the detection time is in CP or DTP. During CP, the detection node simply broadcasts a control message to its neighbors with the detected sub-channel list. In this paper, we propose an efficient primary detection information delivery method in DTP (in DTP, each time slot is dedicated only to the communication pair) only to the neighbor nodes that may cause harmful interference to the primary users.

3.4 Reserved Schedule Table (RST)

MCR-MAC is a TDMA (Time Division Multiple Access)-based protocol, where packet collisions are avoided using time slot reservations for actual data transmissions. In the proposed architecture, the reserved schedule table (RST) at each node indicates whether or not each time slot of all available channels is reserved. If the time slot is reserved, then the table also records which sub-channel is used, which node will use the slot, and whether it is for packet transmitting or receiving. When a node discovers a neighbor node, it exchanges its RSTs and available channel lists to set up a link. Therefore, each node can know which sub-channels and time slots are used by its neighbors for transmitting or receiving packets. Since the spectrum holes of the licensed bands are time varying, the reserved schedules should be dynamically updated by each node when incumbent systems are detected. In addition, mobility management of ad-hoc nodes also requires consideration for RST updating. RST of the neighbor node is obtained via the neighbor discovery procedure by exchanging or overhearing the table described in Section 4.

Table 2. Reserved schedule table of node i

Time ID	Timeslot 1	Timeslot 2	Timeslot 3	Timeslot 4	…
Node i	Transmitter to j on SC1	Receiver from j on SC1	Transmitter to k on SC2	Receiver from k on SC2	…
Node j	Receiver from i on SC1	Transmitter To i on SC1			…
Node k	Receiver from l on SC3	Transmitter To l on SC3	Receiver from i on SC2	Transmitter to i on SC2	…

Take RST of node i (**Table 2**) as an example. In this example, node i has two direct neighbor nodes: node j and node k. Node i reserved time slots 1 and 2 to transmit and receive with node j, respectively. Node i also has a link with neighbor node k at time slots 3 and 4. Suppose node k detected a signal of a primary user on the sub-channel SC3 that is currently being used by node k to communicate with its neighbor node l. In our MCR-MAC, node k will notify node l to immediately leave that channel. When they renegotiate to set up a new link, they will first exchange RST to find available common channels and time slots between them. At the renegotiation time, the available channels of node k are $C_k^{avc} = \{SC1, SC2, SC4\}$ and those of node l are $C_l^{avc} = \{SC1, SC5, SC6\}$. It is observed that the only common available channel for nodes k and l is SC1. To reselect a link, they also need to find their common idle time slots.

Suppose $T_k^{idle(SC_1)}$ = {S5, S6} and $T_l^{idle(SC_1)}$ = {S1, S2, S3, S4} so that there is no intersection of common idle time slots between nodes k and l on sub-channel SC1.

However, when node k checks RST that it has maintained, it can find useful relationships among nodes i, j, k, and l. Since node k knows that even if node i has reserved time slots S1 and S2 on sub-channel SC1 with node j, node j is not the neighbor of node k (i.e., the nodes j and k are outside of the each other's transmission range) so that node k can assign the time slot S1 to transmit packets to node l without interfering with node j by receiving from node i. Furthermore, node l is not the neighbor of node i so that k can receive from l in time slot S2, as is shown in **Fig. 4**. In this way, there will be no packet collision with nodes i and j when nodes k and l also use the same sub-channel and the same time slots for communication. By adopting this mechanism, not only the throughput but also the efficiency of channel utilization can be significantly improved. When each node uses a time slot for transmitting a packet, it can piggyback an ACK to indicate the successful reception of previous packets from the peer node.
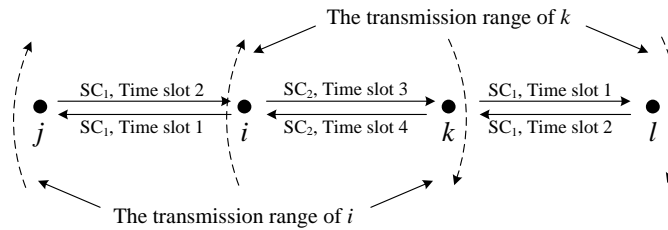

Fig. 4. The renegotiated link between nodes k and l.

As explained in Section 3.3, every node returns to the common control channel at the start of a frame. Therefore, a node can also overhear a neighbor node's negotiated (or renegotiated) schedule so that it is able to update its local RST. As a result, if it needs to negotiate (or renegotiate) the schedule with any of the neighbor nodes, then it can select a collision free link (sub-channel and time slot) based on the newest RST information.

4. Multi-channel CR Ad-hoc MAC Protocol

In this section, we present the proposed MCR-MAC protocol in detail. The protocol includes the multiple neighbor discovery procedure and emergency notification message exchange mechanism.

4.1 Multiple Neighbor Discovery Procedure

As explained in Section 3, a new node or moving node can initiate the neighbor discovery procedure during the control period at any frame, but the nodes that have already discovered neighbors may execute the procedure at every M-th frame. During CP, all nodes move onto the common control channel. The nodes that perform the neighbor discovery mechanism exchange control messages with neighbors to negotiate time slots and sub-channels to transmit and receive data packets. The negotiated link between two nodes will be saved in their respective RSTs, and the selected time slots of the chosen channel can be used periodically during the DTP of each frame until the incumbent systems appear on the selected channel. The following control messages are defined for the neighbor discovery procedure in this paper.

- **Invitation Message (IM):** a short invitation message simply containing the node ID of the inviter itself.

- **Joining Message (JM):** a response to an IM. The node that sends it will be the invitee. There may be more than one invitee for each inviter. This message includes the RST of the invitee and the incumbent channels (occupied by incumbent systems) sensed by itself or its one-hop neighbors. By receiving or overhearing JM, neighbor nodes can update their RSTs.
- **Link Notification (LN):** After an inviter selects the links (time slots and sub-channels to be used) with all the invitees, it will broadcast a response to all JM messages that it has received. LN consists of the inviter's newest RST so that every invitee can be aware of the reserved schedule between the inviter and itself and also can keep the whole schedule of the inviter in its table.
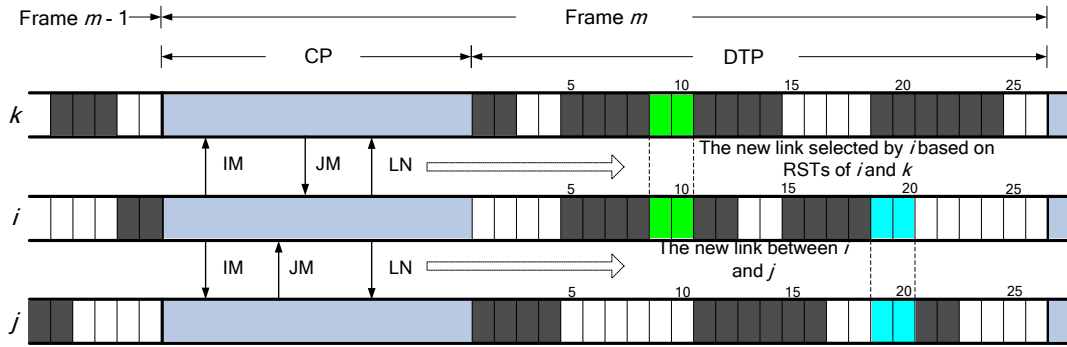

Fig. 5. The multiple neighbor discovery procedure.

Fig. 5 shows an example scenario of the neighbor discovery procedure. Suppose nodes j and k are new neighbors of node i. If node i senses that the common control channel is idle, then it will broadcast an invitation message (IM) to invite its neighbors to connect. Once its direct neighbor nodes j and k receive this message, each of them will reply with a joining message (JM) to node i as a response to IM after a random back-off time. It is assumed that if JMs do not collide, then node i can hear from j and k in order. When node i receives a JM from j first, it can obtain the information about the idle time slots and incumbent channels of node j.

Actually when they find each other on the common control channel, in order to set up a link between them, they should get the set of common available sub-channels C_{j-k}^{avc} and then must select a common data channel c and idle time slots $T_{j-k}^{idle(c)}$. The information included in the JM is used to calculate these two sets. The incumbent channels of node j are sub-classified into C_j^{IC} sensed by node j itself and C_j^{nbr-IC} sensed by node j's one-hop neighbors. Note that if node i receives this information from JM, then C_j^{IC} will be included in C_i^{nbr-IC}. The set of available channels for inviter node i and invitee node j is derived as:

$$C_i^{avc} = C_{all} - (C_i^{IC} \bigcup C_i^{nbr-IC}), \quad C_j^{avc} = C_{all} - (C_j^{IC} \bigcup C_j^{nbr-IC}) \tag{1}$$

where C_{all} is the entire sub-channel set. Therefore, the available channels between inviter node i and invitee node j can be denoted as follows:

$$C_{i-j}^{avc} = C_i^{avc} \bigcap C_j^{avc} \tag{2}$$

From (1) and (2), the common available channels between nodes i and j can be rewritten as

$$C_{i-j}^{avc} = C_{all} - (C_i^{IC} \bigcup C_i^{nbr-IC} \bigcup C_j^{IC} \bigcup C_j^{nbr-IC}) \tag{3}$$

if $C_{i-j}^{avc} \neq \phi$, then there exist sub-channels that can be used by both nodes i and j. When node i selects a channel to communicate with j, it should check whether or not the channel has

enough common idle time slots. The common idle slots are derived as follows:

$$T_{i-j}^{idle(c)} = T_i^{idle(c)} \bigcap T_j^{idle(c)} \qquad c \in C_{i-j}^{avc} \tag{4}$$

If enough idle slots exist on channel c (if each node needs one time slot to transmit data to the peer node, then there should be two idle slots), then channel c is selected as the data channel ($C_{i-j}^{*} = c$) between nodes i and j and the required number of time slots from the set $T_{i-j}^{idle(c)}$ are reserved. The selected channel and reserved time slots are broadcasted in a LN message. When there is no available channel that has enough idle time slots for nodes i and j, then node i will check for possible synchronous transmission slots with neighbor nodes, as described in Section 3.4. The idle time slot of each direction is derived as in (5) and (6) if the already reserved time slot ($T_{k \to l}^{(c)}$ or $T_{l \to k}^{(c)}$) satisfies the following conditions. As long as l is not the neighbor of i and k is not the neighbor of j, the timeslot used for transmission from k to l on channel c can be used for transmission from i to j.

$$T_{i \to j}^{idle(c)} = \sum_{c \in C_{i-j}^{avc}} T_{k \to l}^{(c)}, \quad l \notin \left\{ \text{Neighbors of } i \right\} \text{ and } k \notin \left\{ \text{Neighbors of } j \right\} \tag{5}$$

$$T_{j \to i}^{idle(c)} = \sum_{c \in C_{i-j}^{avc}} T_{l \to k}^{(c)}, \quad i \notin \left\{ \text{Neighbors of } l \right\} \text{ and } j \notin \left\{ \text{Neighbors of } k \right\} \tag{6}$$

When node i finishes choosing the valid links between itself and each of the neighbors it has heard, it will broadcast the selected links in a LN message. The links can be used for communicating with each other after achieving a successful reception of the LN message by the neighbor nodes. After the three handshakes, a link is established. As a result, these nodes can know when to turn on their transceivers ahead of time to communicate with another node. Their transceivers will turn off when no communication is scheduled. This scheduled mode of communication also enables power saving for all nodes.

4.2 The Emergency Notification Message Exchanging Mechanism

Given that CR nodes cannot detect all neighboring incumbent systems, to avoid the hidden incumbent node problem exhibited in **Fig. 1**, sensing reports from the one-hop ad hoc neighbor nodes are required. Achieving a cooperative reporting mechanism is very significant in cognitive radio ad hoc networks. One possible approach is a proactive periodic reporting message exchange method between ad hoc neighbors. This requires frequent message exchanges and results in a high level of control message overhead. Therefore, in the proposed mechanism, a reactive reporting method is used where detection messages are exchanged when incumbent systems appear on the channel reserved by neighbor nodes. The remaining problems are how to immediately notify this emergency condition to neighbors without packet collision with neighbors' normal data transmission and how to determine which neighbor nodes should be informed about this condition. During neighbor discovery, CR nodes can avoid using the incumbent channels. However, as time goes by, the incumbent system can appear on these channels at any time, hence all CR devices that can impact the primary users should immediately change their links. To fully handle the hidden incumbent node problem, four cases are considered in this paper.

Case 1) **When the node that detects the appearance of incumbent systems is a transmitter of the first reserved slot with its communication pair:** As shown in **Fig. 6**, node i uses slots 3 and 4 on SC_1 to send and receive data to/from node j and uses slots 5 and 6 on SC_2 to communicate with node k. If the primary users suddenly appear on channels SC_1 and SC_4, only node i can sense the signal due to the limited signal coverage of the incumbent system. To avoid persistent interference with the primary users, node i should check the RST

that it has maintained. As shown in this figure, node i will inspect whether or not there is a pair of time slots reserved for transmission with node j on channel SC_1. Node j cannot be aware of the appearance of the incumbents, so a sensing report to node j is requested to protect the primary users. Suppose in the reserved slots between nodes i and j that node i is the first transmitter (time slot S_3 in **Fig. 6**). In this case, instead of data packet transmission, node i sends a short emergency notification message (E_NOTI) to tell node j to leave the channel SC_1. In this situation, the E_NOTI message includes the list of channels on which the incumbent systems are detected and its current RST. When node j successfully receives the E_NOTI message, based on the information in E_NOTI and its own RST, node j can select another pair of time slots and a channel as a new link to be used from the next frame. In time slot S_4, node j will reply with an E_ACK message to node i that includes the new selected channel and timeslots. The new link will be valid from the next frame when the E_ACK message is received by node i successfully. With this scheme, the possible interference time to the primary user can be limited to a two-slot time. If the incumbent signal strength is too strong to correctly receive the E_ACK at node i, then node i cannot learn the new link selected by node j. In this situation, renegotiation is executed in the following CP of the next frame.
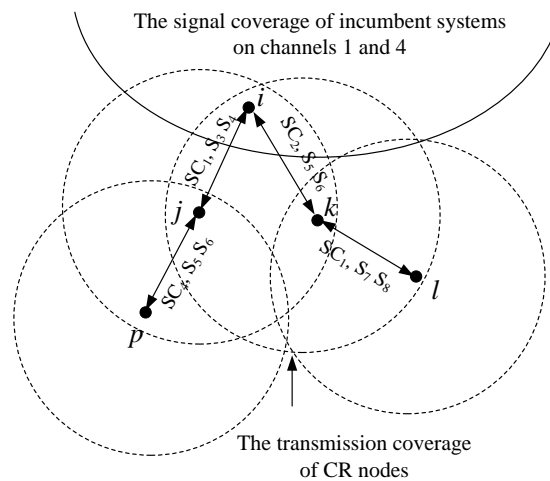

Fig. 6. The case when a sender detects incumbents.

Case2) **When the node that detects the appearance of incumbent systems is a receiver of the first reserved slot with its communication pair:** Node that detects the appearance of incumbent systems is a receiver of the first slot reserved for communication with other another node; the incumbent system appeared on the channel that both nodes currently use. As in the example shown in **Fig. 6**, node i is supposed to first receive a data packet from j in time slot S_3. If node i successfully receives the data packet from node j in S_3, node i will know that node j did not detect the incumbent systems. In this case, since only node i can be aware of the appearance of the incumbent systems, node i is responsible for notifying other nodes that they should stop using the current channel and need to renegotiate the link. In time slot S_4, node i sends an E_NOTI message to inform node j to leave the current channel. The E_NOTI message is only composed of the channels on which the primary users are detected. By receiving the E_NOTI message, node j will become aware of the appearance of the incumbent system. The renegotiation of nodes i and j is performed in the next CP on the common control channel.

Case3) **When both communicating pair nodes detect the incumbent system:** When both

nodes i and j are within the transmission range of the incumbent signal, they exchange E_NOTI and E_ACK. If they can renegotiate successfully in the current pair of time slots, then a new link will be put into use in the next frame. Otherwise, they need to wait for re-negotiating the common control channel in the following CP.

Case4) **Considering possible interference from the neighbor nodes:** In CR ad-hoc networks, it is possible that transmission from neighbor nodes outside the incumbent system coverage may harmfully interfere with the incumbent users. As shown in **Fig. 6**, when nodes k and l and nodes j and p are transmitting on channels SC_1 and SC_4, they cannot sense the signal from the primary users due to being out of the influence range of the incumbent signal. Therefore, packet transmission from nodes j and k can impact any incumbent users inside their transmission range. To solve this hidden incumbent node problem, nodes can detect this possibility in advance by investigating the RST entries. **Fig. 6** shows the following two different scenarios.

4.1) If node i detects the incumbent signal, then it sends an E_NOTI message to the neighbor node j because they use the incumbent detected channel. Once node j knows of the appearance of incumbents, it searches for any communicating nodes using the channels listed in E_NOTI message from node i. In this example, node j uses SC_4 slots to communicate with node p so that it will also generate an E_NOTI message to node p in the reserved transmission schedule and renegotiate a new link for communication without continuously interfering with the primary users.

4.2) When node i detects the incumbent signal, it also checks whether or not there exist other one-hop neighbors that use the incumbent detected channels with node i's two-hop neighbors even though node i and the one-hop neighbor do not use the incumbent detected channels. As shown in **Fig. 6**, nodes i and k do not use an incumbent detected channel. However, node i can know that node k reserved time slots on the channel SC_1 (incumbent detected channel) to communicate with node l since node i received node k's RST information during the neighbor discovery or renegotiation procedure. Data transmission from node k to node l will generate harmful interference to primary users. Therefore, According to the proposed method, if any one hop neighbor node has a possible interference link with two hop neighbors when node i sends a data packet to this node, then an E_NOTI message will be piggybacked on this data packet to the neighbors on the safe link. In this case, the message of E_NOTI consists of the channels on which incumbents are detected. After receiving the piggybacked packet, node k will subsequently renegotiate a new link with node l via exchanging the emergency notification message.

Fig. 7 shows the proposed emergency notification procedures. By employing the MCR-MAC reactive reporting mechanism between neighbor nodes, the channel status information that has been kept by each node can be updated in real-time so that persistent interference can be avoided to protect the primary users.

If two communication nodes were not able to successfully finish the renegotiation process using E_NOTI and E_ACK messages to set up a new link, then both nodes should switch to the common control channel at the start of the CP of the next frame. Using the CSMA/CA algorithm with backoff, the node that sent E_NOTI message in the previous frame sends a renegotiation request message R_REQ, which includes its own ID, its pair node ID, the incumbent channels list, and its own RST. When the peer node receives R_REQ, it will select a new link based on the information from the R_REQ message and its available channels and RST. Thereafter, a renegotiation reply message R_REP is addressed back to the requesting

node. The acknowledgement (ACK) received successfully by the pair node will validate the new link.
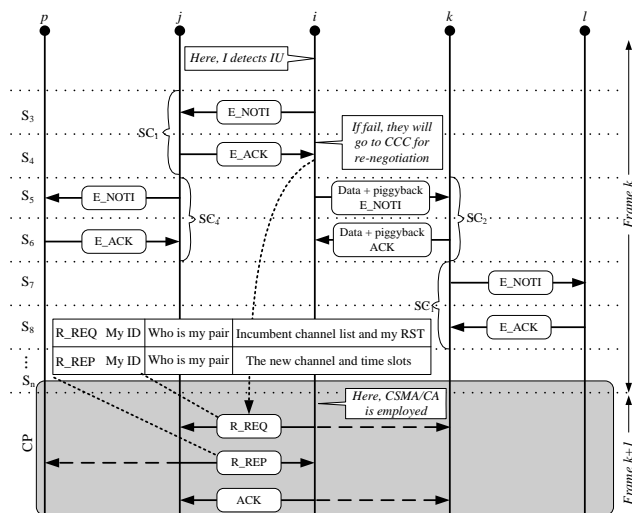

Fig. 7. Emergency notification procedures.

Emergency notification on the data channel can cause harmful interference to primary users around the transmitting CR device. Because, we assume a single transceiver CR device, this short time interference is not avoidable for immediate notification of the primary detection. The main issue is how to guarantee that the possible interference is less than the predefined allowed maximum time. The interference time from a single CR node is for transmitting E_NOTI and E_ACK messages (two slot times). However, when the detection node can communicate with neighbor nodes to notify the emergency notification only through the primary detected channel, the total interference time from multiple CR nodes can be increased more than two slot times. Therefore, the exact total interference should be tightly controlled by the sensing interval. Since each sensing node can detect the primary signal within the sensing interval, the sensing interval should not be larger than the allowed interference time (e.g., channel move time <=2sec in TV band defined in the IEEE 802.22 standard). As a result, the timing condition related to the sensing interval and time slot size is as in (7).

$$\text{Ts} \leq T_{IX} \text{ and } 2 \times TI_s \leq T_{IX} \tag{7}$$

where T_s is the sensing interval; TI_s is the slot duration; and T_{IX} is the maximum allowed interference time.

5. Simulation Results

In this section, we performed a simulation to confirm the effectiveness of the proposed MCR-MAC protocol. Within the cognitive radio environment, the protection of incumbent systems is the most important MAC protocol design requirement. Moreover, the successful packet transmission ratio and throughput show successful data transmission opportunities without collisions with the primary systems, which demonstrate the feasibility of our proposed scheme. The performance of our protocol was analyzed in terms of the following: 1) the average interference time for neighboring incumbent systems during a data transmission, 2) successful packet transmission ratio, and 3) throughput. The SMACS-based cognitive radio MAC protocol was implemented ([16] and [19]) for performance comparison. Since this is a

typical multi-channel MAC protocol, it reserves the schedule and selects the channel for a link between the sender and receiver based on local incumbent systems sensing information without neighbor node notifications.
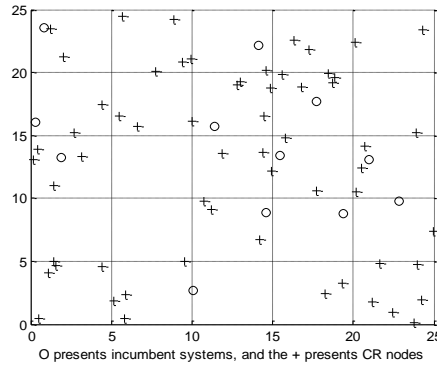

O presents incumbent systems, and the + presents CR nodes

Fig. 8. Network topology of simulation.

Table 3. Simulation paremeters

Parameter	Value	Parameter	Value
E_{ON}: the average busy time of an incumbent system	1 ~ 8 s	N: the number of channels	14
P_{ON}	0.1~0.9	N_T: the number of total incumbents	12
m : periodic neighbor discovery interval in frame	11	The number of grids	25
The number of time slots in a frame	20	The number of CR nodes	20~90
The length of a time slot	4 ms	Transmission rate of a data channel	1 Mbps
The signal propagation radius of incumbent system	10 unit	Data size	500 bytes
The signal propagation radius of CR ad-hoc nodes	5 unit	Simulation time	4000 s

Fig. 8 shows a sample network topology used in this simulation study. There are 25 grid areas, and it was assumed that there were 12 incumbent systems (ISs) and 14 data channels. Each incumbent system uses 1 of 14 data channels and is randomly distributed in 1 of 25 grids. Besides, each grid contains one incumbent system at most. CR nodes can be located in any position of the whole area. The use of a sub-channel by an incumbent system is modeled using an On/Off model. During the ON (busy) time, the channel is occupied by the incumbent system. The On time (T_{ON}) and Off time (T_{OFF}) follow exponential distributions with λ and μ, as in (8). The incumbent system appearance probability P_{ON} is derived as (9). **Table 3** shows the simulation parameters used in this section.

$$F_{ON}(t) = \Pr(T_{ON} \le t) = 1 - e^{-\lambda t},$$
$$F_{OFF}(t) = \Pr(T_{OFF} \le t) = 1 - e^{-\mu t} \tag{8}$$

$$P_{ON} = \frac{E_{ON}}{E_{ON} + E_{OFF}} = \frac{1/\lambda}{1/\lambda + 1/\mu} = \frac{\lambda\mu}{\lambda(\lambda+\mu)} \tag{9}$$

Fig. 9 shows the number of incumbent systems that can be detected as the number of CR nodes increases. It is demonstrated that the detection ratio increases with the number of total CR nodes. Thus, a large number of CR nodes is required to reliably sense neighbor incumbent systems. With the help of neighbor nodes' incumbent notifications, the proposed MCR-MAC can detect 35% more incumbent systems compared to those detected by the conventional method.
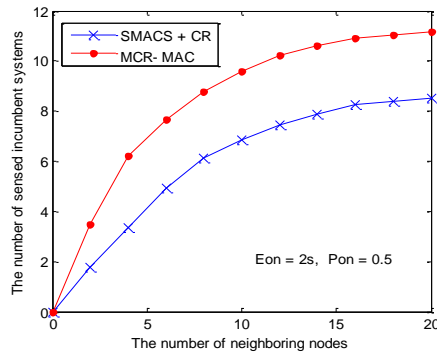

Fig. 9. The number of detected incumbent systems.

The average interference time (AIT) indicates the average interference time to the incumbent systems during a data packet transmission time. **Fig. 10** presents the AIT of the SMACS-based approach and proposed MCR-MAC when the number of neighbor nodes =40, and P_{ON} = 0.5. As Eon increases, the average busy time (channel occupancy time) of incumbent systems on a certain channel extends and primary system activity changes slowly for the given simulation time. As shown in **Fig. 10**, longer busy time slightly reduces AIT because less frequent incumbent appearances may decrease the possibility of interference. We can see that the proposed MCR-MAC greatly reduces AIT compared to the SMACS+CR method (on average, 75% reduced AIT was achieved).
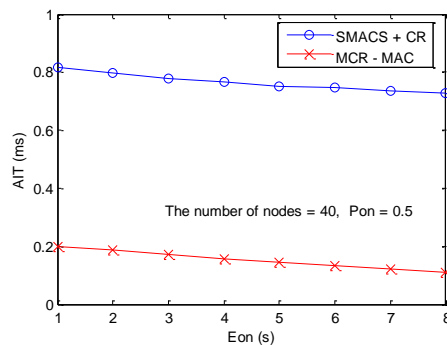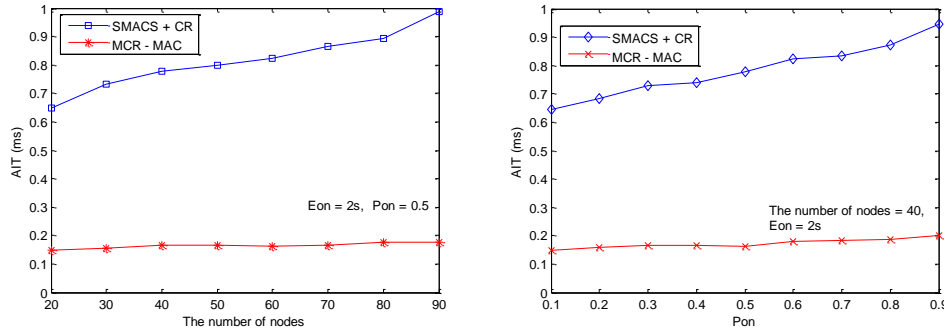

Fig. 10. Average interference time with E_{ON}.

In **Fig. 11**, we evaluated the average interference time in accordance with a different number of CR nodes and different incumbent appearance probability. by incresing the number of CR ad-hoc nodes in the given area, the incumbent system detection ratio also increases, as is shown in **Fig. 9**, and MCR-MAC contributes to reducing interference to primary users. However, since more nodes interfere with the primary users, it results in a larger total AIT, as is shown in **Fig. 11-(a)**. The AIT increasing rate in accordance with the increment of the number of nodes is less sensitive than that of SMACS+CR. For the fixed E_{ON} = 2 (sec) and

number of nodes = 40, the increment of P_{ON} results in longer AIT, as is shown in **Fig. 11-(b)**.

(a) AIT with the number of CR nodes   **(b)** AIT with P_{ON}

Fig. 11. Average interference time with the number of nodes and P_{ON}.

To analyze the effective protection of an incumbent system, successful packet transmission ratio (SPTR) is defined to represent successful data transmission opportunities without collisions with any primary users. As shown in **Fig. 12-(a)**, the proposed MCR-MAC protocol can achieve a high successful packet transmission ratio with increasing E_{ON}, and almost 15% higher SPTR values are obtained compared to the SMACS-based scheme. In **Fig. 12-(b)** and **Fig. 12-(c)**, as the number of CR nodes and incumbent appearance probability increase, the SPTRs of the compared method SMACS+CR show relatively large decrements. On the other hand, the SPTR of the proposed MCR-MAC is almost constant (very little decrement).
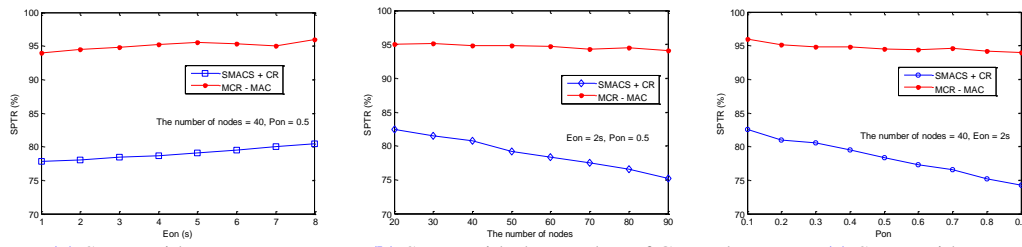
(a) SPTR with E_{ON} **(b)** SPTR with the number of CR nodes   **(c)** SPTR with P_{ON}

Fig. 12. Successful packet transmission ratio.

Fig. 13 illustrates the trend of the total aggregated throughput from all ad-hoc nodes along all available channels as the number of neighbors increases. As the number of CR nodes increases, the number of concurrent transmission also increases. Therefore, even if the successful packet transmission ratio slightly decreases as shown in **Fig. 12-(b)**, the accumulated throughput increases. As we can see, the throughput of the proposed MCR-MAC protocol outperforms that of the SMACS+CR method.
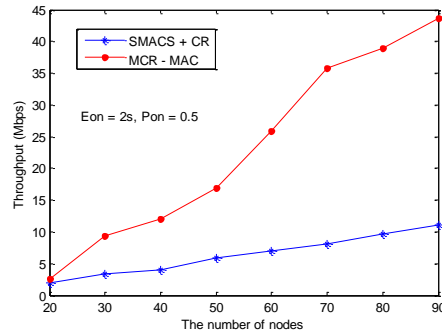
Fig. 13. The total throughput.

6. Conclusions

In this paper, a new CR MAC protocol with TDMA-based architecture in a multi-channel ad-hoc environment is proposed. The hidden incumbent node problem is solved through employing cooperative notification by the neighboring CR nodes. To effectively avoid possible interference with incumbent systems and to efficiently utilize spectrum holes, a neighbor discovery scheme based on the reserved schedule table (RST) and available sub-channel list maintenance mechanism are proposed. Within an ad hoc CR network, each CR node will perform primary signal scanning, and if the signal of the primary users is detected, then the cooperative reporting messages are exchanged between CR neighbor nodes, providing reliable protection for the incumbent systems. When a greater number of CR nodes exist, a more accurate cooperative sensing is possible. Our simulation results in terms of the average interference time, successful packet transmission ratio, and total aggregated throughput in various network conditions have been evaluated. The performance of the MCR-MAC protocol outperforms that of the conventional multi-channel protocol. We can conclude that the proposed method cannot only reduce the harmful interference to the primary users, but it also increases the overall CR network throughput.

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