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A MAC protocol by applying staggered channel model for cognitive radio networks

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Abstract Cognitive radio (CR) is a novel and promising spectrum management technique, which aims to cope with the spectrum scarcity problem occurring in unlicensed bands and alleviate the inefficient spectrum utilization of licensed bands. To ensure that the operation of licensed users will not be adversely affected and that the licensed bands can be efficiently utilized by unlicensed users, this paper proposes a cognitive radio MAC protocol called SMC-CR-MAC. When any primary user is detected, the proposed SMC-CR-MAC protocol applies Contiguous Channel Switching and Sender-Receiver Channel Swap rules to cope with the rendezvous, packet collision, and channel congestion problems. Simulation results show that the proposed SMC-CR-MAC protocol can significantly improve the network performance in terms of utilization of licensed bands, standard deviation of traffic load on each channel, and probability of successful rendezvous.

Keywords Cognitive radio network · Multichannel MAC protocol · CRNs

1 Introduction

The wireless spectrum demand has greatly increased in the last decade because the rapid deployment of new wireless devices accesses unlicensed bands and hence raises collision and congestion problems. On the other hand, a report published by the Spectrum Policy Task Force of the Federal Communications Commission (FCC) in 2002 [1] showed that the utilization of licensed band was only from 15 to 85 %. To improve the utilization of licensed band and mitigate the collision and congestion problems in unlicensed bands, *Cognitive Radio* (*CR*) technology [2–5] has been considered as a promising technique to improve utilization of spectrum resources.

In CR network, nodes that are licensed to access the certain spectrum band are called *primary users* (PUs). On the contrary, nodes that are not licensed but intend to access the licensed bands are called *secondary users* (SUs). Cognitive Radio enables the usage of a temporarily unused spectrum which is referred to as *spectrum hole*. To improve spectrum utilization without interfering with PU, four states of CR have been proposed in [6]; these are *Spectrum sensing*, *Spectrum decision*, *Spectrum mobility*, and *Spectrum sharing*. First, the SU switches to the licensed band and changes its state to *spectrum sensing*. The spectrum-sensing operation is a basic functionality in CR networks, aiming at sensing the unused licensed bands. Once available spectrums are detected, SU switches its state to *spectrum decision* and then selects the most appropriate spectrum hole for further data transmission. Since the spectrum holes of licensed band could be shared by multiple SUs, all SUs should change their state to *spectrum sharing* and coordinate their transmissions to prevent data collisions with the other SUs. Finally, when the SU detects the appearance of PUs, it switches its state to *spectrum mobility* and immediately vacates that spectrum. After that, the SU should continue its data transmission in the other spectrum holes. To achieve this, a proper CR *Medium Access Control* (MAC) protocol should be proposed to

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coordinate the transmissions of SUs to continue their unfinished data exchange on licensed band without interfering with PU. To design an appropriate CR MAC protocol, two challenges are needed to be overcome. Firstly, since CR network is a multichannel environment, the *rendezvous problem* between sender and receiver is one of the major challenges. Another big challenge is the selection of a spectrum hole to continue data transmission when PU is detected on the licensed band. To cope with the rendezvous problem, channel models of existing studies can be classified into two categories: *Control-Channel Based* (CCB) [7–14] and *Control-Period Based* (CPB) [15, 16] channel models. In the CCB-based channel model, the wireless spectrum is divided into a common control channel and many non-overlapping data channels. The common control channel is mainly used for negotiation between each pair of sender and receiver for further data exchange. In the CPB channel model, the available nodes should stay on the common control channel to execute a negotiation task with a potential sender. The sender will compete to exchange the control packets with the receiver, aiming to determine the most appropriate data channel for further data exchange. On the other hand, the CPB-based channel model divides the wireless spectrum into many non-overlapping channels. Each channel is further partitioned into several beacon intervals with equal length. In this channel model, each beacon interval consists of *Announcement Traffic Indication Message* (*ATIM*) window and data window. During an ATIM window, all nodes will wake up and switch their transceiver to a predefined channel so that all of them can rendezvous with each other. In the ATIM window, the sender and receiver will compete to exchange the control packets, aiming at reserving the data slots. After the ATIM window, the sender and receiver exchange data in the reserved data slot.

Based on CCB and CPB channel models, a number of CR studies have been proposed in literature. Jia, Zhang, and Shen proposed the CR MAC protocol [10] based on the CCB channel model, called *HC-MAC*. The common control channel of HC-MAC is applied on the unlicensed band. The HC-MAC consists of three periods, including contention, sensing, and transmission periods. In the contention period, each node contends for the transmission opportunity by applying *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) mechanism. Then, in the sensing period, any communication pair that wins the contention can exchange control packets to determine which data channel should be sensed. Based on this negotiation, both sender and receiver switch to the data channel and sense if the channel is accessed by any PU or SU. In case the channel is idle, they start to exchange data in the transmission period.

Since each SU is equipped with only one transceiver, control packets exchanged on the common control channel cannot be overheard when the SU is accessing the data channel. That is, the SU is unable to maintain the complete information exchanged on the common control channel, leading to collision problem. To avoid this problem, previous approaches [11, 12] assume that the SU is equipped with two half-duplex transceivers. One transceiver stays on the common control channel to maintain the complete information of channel usage and the other transceiver switches to the data channel for data exchange. When a PU is detected, the SUs should send the alarm message to the other SUs on the common control channel. Based on the alarm message, all SUs will not select the data channels that are currently accessed by the PU. Nevertheless, the assumption is that each SU is equipped with two transceivers, leading to the problem of high hardware cost.

Based on the CPB channel model, in studies [15, 16], each SU switches its transceiver to the ATIM window of a specific channel and exchanges the control packets to reserve the data windows for further data transmission. Once the SU obtains the transmission opportunity, it can transmit data on the designated data window. To avoid interference with PU, the SU should terminate its data transmission when PU is detected. On the other hand, the SU can continue its data exchange on the original channel when the transmission of PU is finished. Since all SUs should switch to a default channel for participating in ATIM window, the ATIM windows of all channels other than the default channel will not be used, resulting in poor network performance. Table 1 summarizes the parameters of the compared CR MAC protocols. In Table 1, each column presents the considered parameters in the proposed SMC-CR-MAC protocol and existing CR MAC protocols.

This paper aims to propose a multichannel MAC protocol for CR networks, called *SMC-CR-MAC*. The proposed SMC-CR-MAC protocol applies the *Staggered Multichannel Model* (*SMM*) [17] which efficiently copes with the rendezvous problem. In addition, the proposed SMC-CR-MAC protocol further exploits the spectrum resource for enhancing the channel utilization and thus improving the network performance without interfering with the transmission of PU. The following summarizes the contributions of this paper.

1. *Alleviating the collision and contention phenomena*. Most of the previous works only ask that SU pairs should immediately vacate the channel where PU is detected. This might lead to collisions and contentions which reduce the network throughput and increase the SU transmission delay. In the proposed SMC-CR-MAC protocol, the SU pair will be distributed over different available channels when PU is detected such that the collision and contention phenomena can be alleviated.

Table 1 Comparison of CR MAC protocols

Reference	Channel model	PU detection scenarios	Number of transceivers	Cooperative transmission	Uninterrupted data transmission	Channel switching type (when PU is detected)
HC-MAC [10]	CCB	×	1	×	○	SU continuously switches to one of the channels in the selected set
[11]	CCB	×	2	×	×	N/A
[12]	CCB	×	2	×	×	N/A
[13]	CCB	×	1	×	×	Hopping
[14]	CCB	×	1	×	×	DOSS
CR-MAC [15]	CPB (Sensing before ATIM)	×	1	×	×	N/A
[16]	CPB (Sensing before *DW*)	×	1	×	×	Opportunistic access
The proposed SMC-CR-MAC	SMM [17]	○	1	○	○	SU continuously switches to the next available channel

2. Significantly improving the channel utilization. In previous works, the CCB-based MAC protocols might raise the well-known multichannel hidden problem while the CPB-based MAC protocols might result in serious collision, contention, and bandwidth wastage problems whether PU is detected or not. In the proposed SMC-CR-MAC protocol, when PU is detected, the SU pairs are distributed over all available channels and then their unfinished transmission is restarted. Consequently, any spectrum hole will be efficiently utilized, improving the channel utilization.
3. *Considering CR hidden terminal problem*. Most of the related works only consider how the SU pairs vacate the channel when PU is detected. However, these works do not consider the location of PU appearance. This might raise a CR hidden terminal problem where one of the sender and receiver cannot detect the appearance of PU. The proposed SMC-CR MAC takes into consideration the CR hidden terminal problem.
4. *Avoidance of re-rendezvous*. Based on the location and timing of PU appearance, the proposed SMC-CR-MAC protocol has different designing policies such that the SU sender and receiver can actively meet with each other on an available channel without exchanging additional control packets.
5. *Cooperative transmission mechanism.* When the channel is occupied by PU, each SU should vacate that channel and seek the other transmission opportunities. To achieve this, the proposed SMC-CR-MAC protocol allows that each SU sender selects a proper cooperative node to cope with the rendezvous problem. Thus, SMC-CR-MAC protocol guarantees that the SU sender and receiver can successfully meet with each other on an available channel.

The remaining part of this paper is organized as follows. Section 2 illustrates the network environment and problem formulation. Section 3 reviews the staggered multichannel model and frame structure. Section 4 shows the design of the proposed SMC-CR-MAC protocol. Section 5 depicts the pseudocode and state diagram of the proposed SMC-CR-MAC protocol. Section 6 examines the performance of the proposed SMC-CR-MAC protocol against existing studies. Finally, the conclusions of the proposed SMC-CR-MAC protocol are drawn in Section 7.

2 Network environment and problem formulation

This section initially gives the assumptions of the given wireless network. Then, the problem formulation of our approach is proposed.

2.1 Network environment

Assume that there exist z non-overlapping licensed bands. Every SU s_k is equipped with one half-duplex transceiver and has a unique MAC address. Similar to SMM [17], to cope with the rendezvous problem, each s_k is assigned with a home channel, denoted by $s_k.home$, which is determined by applying the following channel hashing function ρ. Therefore, node s_k is said to be the *home node* of channel $s_k.home$.

$$s_k.home = \rho(s_k.\mathrm{MAC},\ z)$$

The mapping from each node to its home channel can balance the load of each channel since all SUs can be distributed over all channels. Each SU is aware of its neighbors' MAC address by periodically exchanging the beacon packet and thus knows the home channel of each neighboring node. To accomplish this, the node which initially joins the network should broadcast the *Hello* packet at the beginning of the beacon interval on each channel. The Hello packet includes the MAC address such that all the other nodes can maintain the neighboring information and calculate the home channel of that node. Similarly, any node which intends to leave the network should broadcast the *Leave* packet at the beginning of the beacon interval on each channel. To achieve time synchronization, all nodes apply the multichannel synchronization mechanism [18] when they exchange their MAC addresses.

2.2 Problem formulation

This paper aims at improving the utilization of the licensed bands without interfering with the PU. Let S and C denote the set of SUs and set of channels, respectively. Let notation $t^{s}_{i,j}$ denote the total time required for data exchange between SUs s_i and s_j within time interval T, including data retransmission. Let notations $t^{\text{sensing}}_{i,k}$ and $t^{\text{sensing}}_{j,k}$ denote the total time required for nodes s_i and s_j to perform spectrum-sensing operation on channel ch_k within time interval T, respectively. Let $t^{\text{control}}_{i,j,k}$ and $t^{\text{data}}_{i,j,k}$ denote the time required for exchanging control and data packets between SUs s_i and s_j on ch_k, respectively. Let notations $t^{\text{switch}}_{i,k}$ and $t^{\text{switch}}_{j,k}$ denote the total time required for channel switching of nodes s_i and s_j within time interval T, respectively. The value of $t^{s}_{i,j}$ can be evaluated by applying Exp. (1), where α and β denote the number of packets exchanged between s_i and s_j during time interval T.

$$\begin{aligned} t^{s}_{i,j} = & \sum_{k=1}^{z} t^{\text{sensing}}_{i,k} + \sum_{k=1}^{z} t^{\text{sensing}}_{j,k} \\ & + \sum_{k=1}^{z} \left(t^{\text{control}}_{i,j,k} \times \alpha + t^{\text{data}}_{i,j,k} \times \beta \right) \\ & + \max \left(\sum_{k=1}^{z-1} t^{\text{switch}}_{i,k}, \sum_{k=1}^{z-1} t^{\text{switch}}_{j,k} \right), \forall i,j \in S, k \in C \end{aligned} \tag{1}$$

Let $p_{i,j}$ denote the PU node which neighbors to nodes s_i or s_j and P denote the set of $p_{i,j}$. To evaluate the total duration of the spectrum hole, the following measures the total time required for P. Let notation $N(s_i)$ denote the neighboring nodes, including PUs and SUs, of s_i, where $s_i \in S$. Let $d^{k}_{i,j}$ denote the total duration that PU node $p_{i,j}$ accesses channel ch_k within a given period T. Let notation T^P denote the time required for all PU pairs in set P to exchange data on all channels. The value of T^P can be calculated by applying Exp. (2).

$$T^P = \bigcup_{k=1}^{z} d^{k}_{i,j} \tag{2}$$

Let T^S denote the set of durations that are not accessed by any PU. Accordingly, the remaining durations, called *spectrum hole*, can be expressed by applying Exp. (3).

$$T^S = T - T^P \tag{3}$$

The problem considered in this paper can be formulated as an integer linear programming labeled from Exps. (4) to (10). Let notation $|T^S|$ denote the sum of all durations in set T^S. This paper aims at designing a CR MAC protocol to maximize the channel utilization index F, as shown in Exp. (4), of the licensed bands.

$$\text{maximum } (F), \text{ where } F = \frac{\sum_{\forall i,j \in S} t^{s}_{i,j}}{|T^S|} \tag{4}$$

Expression (6) to (10) show the constraints in achieving the goal of this work. Let t^{d}_{k} denote the duration that SU nodes s_i and s_j stay on the same channel ch_k. Expression (5) evaluates the total duration $t^{rend}_{i,j}$ that SU nodes s_i and s_j rendezvous with each other on the same channel within time interval T.

$$t^{rend}_{i,j} = \sum_{k=1}^{z} t^{d}_{k}, \forall k \in C \tag{5}$$

Expression (6) depicts the *Rendezvous Constraint* which asks that nodes s_i and s_j should rendezvous with each other on the same channel for the duration larger than the time required for data exchange.

Rendezvous Constraint

$$t^{rend}_{i,j} \geq t^{s}_{i,j} \tag{6}$$

Since each node is equipped with single half-duplex transceiver, the *Transceiver Constraint* asks any node s_i staying at most one channel ch_k at any given time point t, denoted by $ch^{i}_{k,t}$.

Transceiver Constraint

$$\sum_{k=1}^{z} ch^{i}_{k,t} \leq 1, \forall k \in C \tag{7}$$

Let Boolean variable $x^{t,k}_{i,j}$ denote whether the SU pair (s_i, s_j) exchanges data on channel ch_k at the given time t. That is,

$$x^{t,k}_{i,j} = \begin{cases} 1, & \text{nodes } s_i \text{ and } s_j \text{ exchange data on channel } ch_k \text{ at time } t. \\ 0, & \text{otherwise.} \end{cases}$$

Let Boolean variable $y^{t,k}_{p,q}$ denote whether the PU pair (p, q) exchanges data on channel ch_k at time t. That is,

$$y^{t,k}_{p,q} = \begin{cases} 1, & \text{PU nodes } p \text{ and } q \text{ exchange data on channel } ch_k \text{ at time } t. \\ 0, & \text{otherwise.} \end{cases}$$

The *SU Interference Constraint*, as given in Exp. (8), asks that the SU pair (s_i, s_j) should terminate their data exchange when PU is detected on channel ch_k at time t.

SU Interference Constraint

$$x_{i,j}^{t,k} + y_{p,q}^{t,k} \leq 1, \forall p, q \in N(s_i) \cup N(s_j) \tag{8}$$

Assume that SU pair (s_i, s_j) exchanges data on channel ch_k at time t. The *Collision Constraint*, as given in Exp. (9), asks that the SU nodes located within the communication range of SU nodes s_i or s_j cannot exchange data on channel ch_k at time t.

Collision Constraint

$$x_{i,j}^{t,k} + \sum_{u,u' \in N(s_i)} x_{u,u'}^{t,k} + \sum_{v,v' \in N(s_j)} x_{v,v'}^{t,k} \leq 1, \forall i,j \in S, u \in N(s_{v'}), v \in N(s_{u'}) \tag{9}$$

Let notations i_{sending}^t, $i_{\text{receiving}}^t$ and i_{sensing}^t be Boolean variables which denote whether node s_i executes data sending, data receiving, and spectrum-sensing operations at time t, respectively. The *Transceiver Operation Constraint* asks that node s_i can only execute one operation of sending, receiving or spectrum-sensing at any given time t.

Transceiver Operation Constraint

$$i_{\text{sending}}^t + i_{\text{receiving}}^t + i_{\text{sensing}}^t \leq 1 \tag{10}$$

As depicted in Exp. (4), the goal of this paper is to maximize the channel utilization while constraints given in Exps. (6) to (10) are satisfied.

3 Overview of the applied staggered multichannel model

The proposed SMC-CR-MAC protocol highly relies on the *Staggered Multichannel Model* (*SMM*) [17]. This section reviews the SMM channel model and its corresponding frame structure. Recall that there are z non-overlapping licensed channels. Each channel is divided into many beacon intervals with equal length and each beacon interval consists of *Negotiation Window* (*NW*) and *Data Window* (*DW*). In this channel model, the *NW*s of contiguous channels are arranged to be staggered. That is, the end of *NW* of channel ch_h is the beginning of *NW* of channel ch_{h+1}, as shown in Fig. 1. As a result, each node can be distributed over all channels, decreasing the collision and congestion problems.

In the SMM channel model, the *NW* is further partitioned into *Receiver Declaration Period* (*RDP*) and *Control Period* (*CP*). The *RDP* is mainly used for home nodes to broadcast their own scheduling information, as defined in SMM [17], which assists the corresponding senders

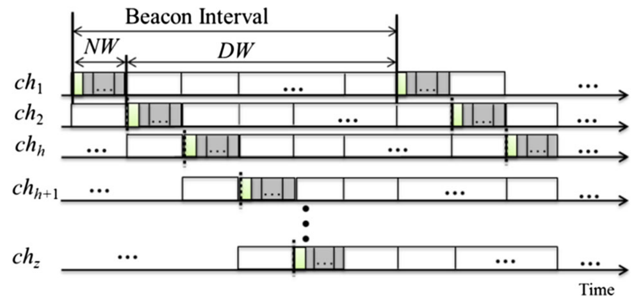

Fig. 1 Staggered multichannel model [17]

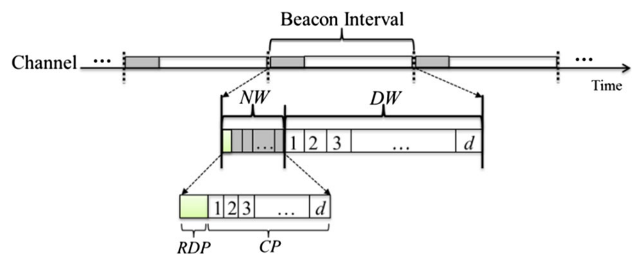

Fig. 2 The frame structure of SMM channel model proposed in [17]

become aware of the available slots. The *CP* provides opportunities for sender and receiver to rendezvous with each other and then negotiate for reserving a data slot. The *CP* and *DW* are further divided into d slots, called *control slots* and *data slots*, respectively. All senders contend the m-th control slot in *CP* for reserving the m-th data slot. In *DW*, sender and receiver exchange data in the reserved slot. Figure 2 depicts the frame structure of applied SMM channel model.

To simplify the presentation, throughout this paper, we consider the communication pair to be (s_i, s_j), where s_i and s_j are sender and receiver, respectively. Let the home channels of sender and receiver s_j are ch_a and ch_b, respectively. In the SMM channel model, each node should switch to its home channel at the start of each beacon interval and participate in the whole *NW*. Meanwhile, any sender s_i intending to exchange data with its receiver s_j will switch to *NW* of receiver's home channel ch_b, denoted by NW_b, to reserve the data slot for data exchange. Then nodes s_i and s_j exchange data in *DW* of receiver's home channel ch_b, denoted by DW_b.

As stated in the Related Work section, CCB channel model has serious contention and collision problem since all nodes compete transmission opportunities for exchanging control packets simultaneously. The applied SMM channel model distributes all nodes over all channels by applying the home node concept and hence alleviates the collision and contention phenomena. On the other hand, in the CPB model, all SUs should switch to the default channel for participating in the ATIM window, resulting in the situation that the ATIM windows of all channels other than the default channel will not be used. In this paper, the applied SMM channel model shifts *NW*s such that all *NW*s will not overlap. In this way, all *NW*s will be fully utilized for exchanging control packets and hence the channel utilization is significantly improved.

4 The proposed SMC-CR-MAC protocol

In CR networks, PU has the highest priority to access the licensed channels. To avoid interference with any PU, each SU pair should instantly vacate the channel when PU is detected by applying a spectrum-sensing mechanism. Thus, the data transmission of SU will be terminated. This section illustrates how the SU continues its unfinished transmission on an available channel. Since the PU can be detected at any given time, two cases will be discussed. The first case is that PU is simultaneously detected by both sender and receiver. This case is referred to as *Homogeneous Sensing Situation* (*HOSS*). Another case is that PU is only detected by sender or receiver. This case is referred to as *Heterogeneous Sensing Situation* (*HESS*). The following subsections give the detailed solutions of two situations.

4.1 Homogeneous sensing situation (HOSS)

According to the duration of PU appearing, two problems need to be addressed in HOSS.

The Negotiation Blocking (NB) Problem *Node s_i fails to rendezvous with s_j in NW_b if PU appears in NW_b, leading to a rendezvous problem.*

The Data Blocking (DB) Problem *The pair (s_i,s_j) should terminate their data exchange and immediately vacate the channel if PU appears in the m-th data slot of DW_b, resulting in failure data exchange.*

In the NB-Problem, a node cannot exchange control packets on the channel where PU is detected, resulting in rendezvous problem. On the contrary, DB-Problem is raised after the completion of rendezvous procedure. Therefore, the NB-Problem has more challenges than the DB-Problem. The following subsections discuss solutions to the NB and DB problems.

4.1.1 Solution to the NB-problem

Two rules of SMC-CR-MAC protocol have been proposed to cope with the above-mentioned problems: *Contiguous Channel Switching* (*CCS*) rule and *Sender-Receiver Channel Swap* (*SRCS*) rule. The CCS rule aims to find an appropriate channel where no PU is detected so that the rendezvous between sender and receiver can be achieved.

The CCS rule *Both sender s_i and receiver s_j repeatedly switch to the next channel and detect whether there exists PUs on that channel until they reach an appropriate channel where no PU is detected.*

However, all SU pairs might switch to the next channel one by one and finally stay on the same channel, say ch_k, where no PU is detected by applying the CCS rule. The collision and congestion problems will occur. To prevent collision and congestion problems, these SU pairs should exchange data on different channels. Recall that the channels ch_a and ch_b are the home channels of sender s_i and receiver s_j, respectively. To totally distribute the data exchanges over all available channels, the channel for data exchange between sender and receiver should be changed to channel ch_a, rather than ch_k. The following presents the procedure of *Sender-Receiver Channel Swap* (*SRCS*) rule.

The SRCS rule *Both sender s_i and receiver s_j switch to ch_a and then exchange control packets in the control slot for reserving a data slot to continue their unfinished data exchange.*

The following introduces how to execute SRCS rule. Let channel ch_k represents the new channel where nodes s_i and s_j arrive by applying the CCS rule. On ch_k, node s_i broadcasts the *Channel-Swapping-Request* (*CSR*) packet in any control slot of CP_k, where CPk denotes the *CP* of ch_k. The CSR packet aims to inform node s_j that both s_i and s_j should apply the SRCS rule to continue their unfinished data exchange. Upon receiving the CSR packet, node s_j replies to node s_i with the *CSR-ACK* packet. Once node s_i receives the CSR-ACK packet, both s_i and s_j apply the SRCS rule.

By applying the SRCS rule, the SU pair with unfinished data exchange can be totally distributed over all channels because the senders' home channels might be different. Therefore, collision and congestion problems can be overcome. On ch_a, nodes s_i and s_j firstly detect if there exists any PU. If it is not the case, they exchange RTS/CTS packets in CP_a and then exchange DATA/ACK in the corresponding data slot of ch_a. However, if they detect the appearance of PU, both of them apply the CCS rule to find another available channel to continue the unfinished data exchange. Since applying the SRCS rule can distribute all possible pairs to different channels, the congestion and collision problems are resolved.

The following illustrates how the proposed SMC-CR-MAC copes with the NB-Problem. As shown in Fig. 3, let the home channels of sender s_3 and receiver s_1 be channels ch_3 and ch_1, respectively. Assume that sender s_3 and receiver s_1 negotiate in the first control slot of channel ch_1 in the first beacon interval for further data exchange. However, they detect the appearance of PU (marked in green ink) on ch_1. Hence, both of them apply the CCS rule

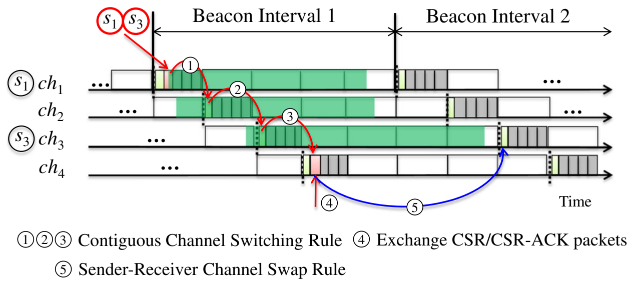

Fig. 3 The solution to the NB-Problem

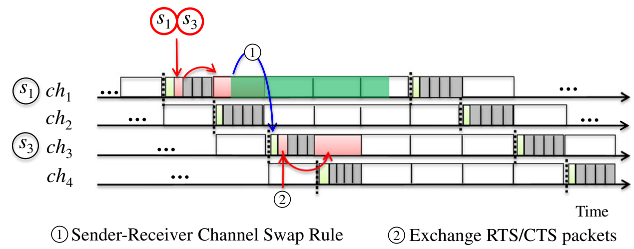

Fig. 4 The solution to the DB-Problem

to switch from ch_1 to ch_2. Then they perform the spectrum-sensing operation and further detect the appearance of PU on ch_2 and ch_3. Execution of the CCS rule will be terminated when they arrive on ch_4 where no PU is detected. On ch_4, they broadcast their own scheduling information in the *RDP* of ch_4 and exchange CSR/CSR-ACK packets in the first control slot of ch_4 for further applying the SRCS rule. By applying the SRCS rule, sender s_3 and receiver s_1 switch to ch_3 and aim to participate in CP_3 of the second beacon interval. Since no PU is detected on ch_3, nodes s_3 and s_1 will exchange RTS/CTS and DATA/ACK in CP_3 and DW_3, respectively.

In summary, the CCS and SRCS rules can efficiently overcome the NB-Problem in such a way that the contention and collision problems are prevented. The next subsection presents the solution to the DB-Problem.

4.1.2 Solution to the DB-problem

During CP_b, nodes s_i and s_j execute negotiation process in the proper control slot to further reserve the corresponding data slot. Then nodes s_i and s_j exchange DATA/ACK packets in the reserved data slot. However, if any PU appears on ch_b during the data exchange of nodes s_i and s_j, the DB-Problem occurs. Selecting another available channel to continue the unfinished data exchange is a big challenge. The proposed SMC-CR-MAC protocol applies the SRCS rule to cope with the DB-Problem. By applying the SRCS rule, nodes s_i and s_j simultaneously switch to s_i's home channel ch_a to continue their unfinished data exchange. After switching to ch_a, nodes s_i and s_j scan ch_a to check if there exists any PU. If no PU is detected, they follow the multichannel MAC protocol [17] to exchange data, as presented in Sect. 3. If they detect PU on ch_a, both of them will apply the CCS rule until they find an available channel.

The following illustrates how to cope with the DB-Problem by applying the SRCS rule. As shown in Fig. 4, assume that the home channels of sender s_3 and receiver s_1 are channels ch_3 and ch_1, respectively. Consider that sender s_3 and receiver s_1 exchange data in the first data slot of ch_1. If PU appears in that slot, nodes s_1 and s_3 immediately vacate ch_1 and apply the SRCS rule to switch to ch_3. If no PU is detected on ch_3, nodes s_1 and s_3 follow the multichannel MAC protocol [17] to exchange data with each other. In this way, the DB-Problem can be eliminated.

4.2 Heterogeneous sensing situation (HESS)

This subsection mainly considers the situation that only one of the sender s_i or receiver s_j detects the appearance of PU, referred to as HESS. The HESS might occur in *NW* or *DW*. According to the location of PU appearance, two cases can be discussed: *Receiver Aware Case* and *Sender Aware Case*. The receiver aware case occurs if the PU can only be detected by receiver s_j. On the contrary, the sender aware case depicts that the PU can only be detected by sender s_i. Although the CCS and SRCS rules have been applied to cope with NB and DB problems, they cannot handle *HESS*. Applying the CCS rule will raise two additional problems: *Receiver-Asynchronous Problem* (*RA-Problem*) and *Sender-Asynchronous Problem* (*SA-Problem*). The following defines the two problems.

The RA-Problem *The RA-Problem occurs if PU appears on* ch_b *and is only detected by receiver* s_j*. Herein the receiver* s_j *applies the CCS rule. The sender* s_i *cannot meet its receiver* s_j *on* ch_b*.*

The SA-Problem *The SA-Problem occurs if PU appears on* ch_b *and is only detected by sender* s_i*. Herein the sender* s_i *applies the CCS rule. The sender* s_i *cannot meet its receiver* s_j *on the other available channels.*

To cope with RA and SA problems, two approaches of SMC-CR-MAC protocol will be proposed: *Receiver-Asynchronous-Avoidance Approach* (*RAA*) and *Sender-Asynchronous-Avoidance Approach* (*SAA*). The following subsections give a detailed description of the proposed two approaches.

4.2.1 Receiver-asynchronous-avoidance approach (RAA)

In this case, receiver s_j cannot broadcast its scheduling information and also cannot receive a packet from sender

s_i. Without receiving ACK packet from receiver s_j, sender s_i is aware of the RA-Problem which has occurred. To produce more rendezvous opportunities, s_j repeatedly switches to the next channel $ch_{(b \bmod z)+1}$, providing rendezvous opportunities to s_i on the other available channels, say ch_k. Because s_i did not receive the scheduling information from s_j, it applies the CCS rule to repeatedly switch to the next channel and attempt to receive the scheduling information from s_j. On each switched channel, if s_j detects no PU on channel ch_k, it broadcasts its scheduling information. Two cases can occur, depending on whether s_i can successfully receive the scheduling information. If s_i detects no PU on ch_k, it receives the scheduling information from s_j. The sender s_i observes that both nodes are switched to the same available channel. In the case in which no PU is detected on the sender's home channel ch_a, s_i and s_j exchange CSR/CSR-ACK packets with the highest priority on ch_k. Then s_j switches to the home channel of s_i to reserve the data slot. Subsequently, s_i and s_j participate in CP_a to reserve a data slot for further data exchange. As a result, the second challenge is overcome.

In the second case, the RA-Problem occurs in DW_b. The receiver s_j cannot reply the ACK packet to the sender s_i. To continue the unfinished data exchange, s_i applies the CCS rule to repeatedly participate in *NW* of next channel until it successfully receives s_j's scheduling information. Then nodes s_i and s_j follow the multichannel MAC protocol [17] to continue their unfinished data exchange.

4.2.2 Sender-asynchronous-avoidance approach (SAA)

This subsection describes the SAA approach and illustrates how it overcomes the SA-Problem. Similar to the RA-Problem, two cases can be discussed depending on whether the PU is detected in NW_b or DW_b.

The motivation of cooperative transmission can be explained by giving the following example, as shown in Fig. 5. In Fig. 5(a), the SU sender s_1 aims to transmit data to a SU receiver s_2. Assume that the home channel of s_2 is ch_1. Nodes s_4 and s_5 located within the intersection of nodes s_1 and s_2's transmission range. If sender s_1 detects PU appearance in *NW* on ch_1, it cannot negotiate with the receiver s_2 on this channel. Suppose that the appearance of the PU might block ch_1 for ten beacon intervals, the SA-problem occurs. Without applying cooperative transmission, sender s_1 should wait ten beacon intervals and then execute negotiation task with receiver s_2. The following illustrates an example to show the advantages of applying cooperative transmission.

As shown in Fig. 5(b), there exists a cooperative node of nodes s_1 and s_2 on ch_2, which satisfies the following three conditions: (i) The cooperative node located within the intersection of both nodes s_1 and s_2' transmission range; (ii) The cooperative node is not blocked by PU on ch_1; (iii) The cooperative node can exchange data with s_1 on ch_2. In Fig. 5(b), let node s_4 function as the cooperative node of nodes s_1 and s_2. Cooperative node s_4 can receive the sender s_1's data on ch_2 and then forward the data to receiver s_2 on ch_1. As a result, the data can be successfully sent from s_1 to s_4 on ch_2 and then sent from s_4 to s_2 on ch_1. In this example, only three beacon intervals are needed to exchange data between nodes s_1, s_2, and s_4. The transmission delay can be significantly reduced from ten to three beacon intervals. The following illustrates how the sender, cooperative node, and receiver apply the cooperative transmission.

Because receiver s_j does not detect the PU in *NW* of beacon interval x, it can broadcast the scheduling information at the start of the beacon interval. However, sender s_i cannot receive the broadcast message because it detects the PU in the *NW*. At this point, s_i is unaware whether s_j also detects the PU. Node s_i assumes that s_j did not detect the appearance of PU, and it attempts to find another opportunity to contact s_j. To achieve this, s_i switches to the next channel $ch_{(b \bmod z)+1}$ to find a cooperative node. In the *NW* of channel $ch_{(b \bmod z)+1}$, s_i broadcasts the *Help-Request* (*H-REQ*) packet. Upon receiving *H-REQ*, the node (e.g., s_c), which can function as the cooperative node, replies with the H-ACK packet to s_i. Subsequently, s_i and s_c apply the multichannel MAC protocol [17] to exchange data on $ch_{(b \bmod z)+1}$. Subsequently, both s_i and s_c revert to ch_b to participate in the *NW* of beacon interval $x + 1$ and perform the spectrum-sensing operation. Based on the spectrum-sensing results, s_i and s_c determine their own backoff timers which are configured to ensure that the node without detecting PU has a high priority for transmitting data to s_j. If s_i continues detecting PU on ch_b, s_c has a higher priority to negotiate with s_j for further data exchange. Conversely, if s_i does not detect the PU, it has a higher priority to negotiate with s_j. In this case, s_c receives the RTS packet from s_i. Consequently, s_c abandons the cooperative transmission process and drops the data. If no SU node can function as the cooperative node, the sender will apply the CCS rule to continuously switch to the next channel to seek a cooperative candidate. In the worst case scenario, when the SU switches to every channel within a beacon interval but no cooperative node exists, it will give up the cooperative transmission and continue to perform the spectrum-sensing operation at the next beacon interval of receiver's home channel until that channel is ready for use.

The following example shows the SAA approach. As shown in Fig. 5(a), assume that nodes s_1 and s_2 are sender and receiver, respectively. The home channel of node s_2 is ch_1. Nodes s_4 and s_5 located within the intersection of nodes s_1 and s_2's transmission range. Figure 5(a) depicts the occurrence of SA-Problem where PU is only detected

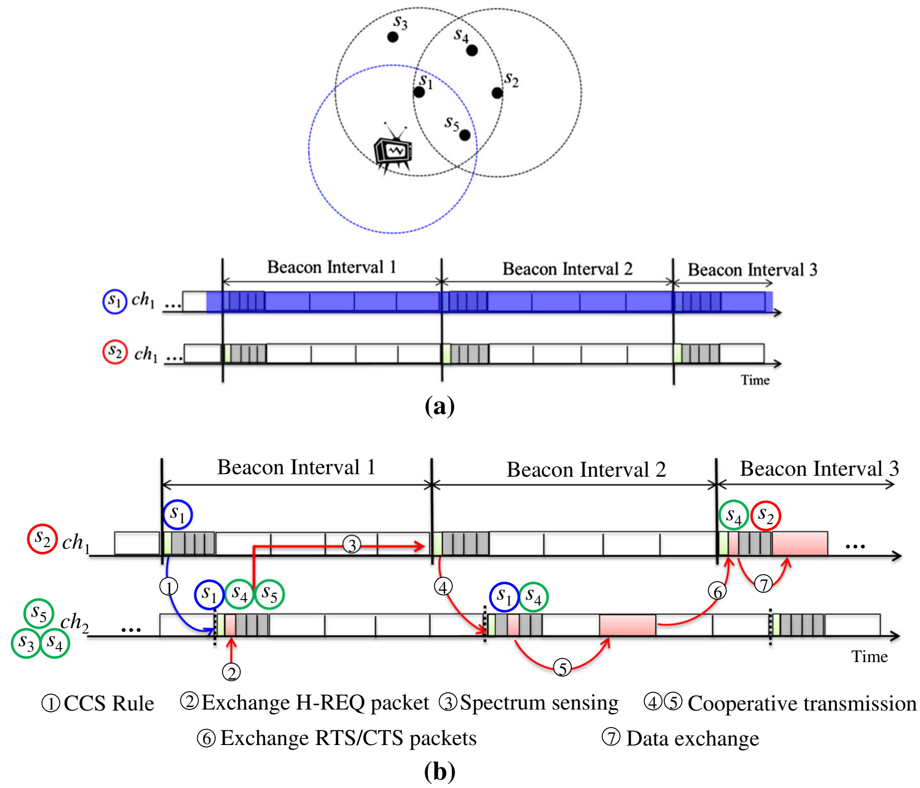

Fig. 5 The solution to the SA-Problem. **a** The scenario of the SA-Problem, **b** The procedure of the SAA approach

by node s_1. Figure 5(b) illustrates how the SAA approach copes with the SA-Problem. When node s_1 detects the PU appearance, it applies the CCS rule and thus switches to ch_2. However, node s_1 cannot receive s_2's scheduling information in the *RDP* of NW_2. Thus, it broadcasts the H-REQ packet to the home nodes of ch_2 in the first control slot of the first beacon interval. Upon receiving the H-REQ packet, nodes s_4 and s_5 switch to ch_1 and perform the spectrum-sensing operation. In this case, only node s_4 can be the candidate of cooperative node since it does not interfere with PU. After that, node s_4 switches to ch_2 and then exchanges RTS/CTS packets with node s_1 in the second control slot of the second beacon interval. Once nodes s_1 and s_4 successfully exchange data in the second data slot of ch_2, both of them switch to ch_1 to seek the opportunities for sending the data to receiver s_2 in the third beacon interval. If the PU is detected by node s_1 on ch_1, node s_1 will terminate its negotiation process and apply the cooperative transmission. In this example, node s_1 detects PU on ch_1 of the third beacon interval and hence the cooperative transmission is executed. Meanwhile, cooperative node s_4 does not detect the appearance of PU on ch_1. It exchanges RTS/CTS/DATA/ACK packets with receiver s_2 and hence the data of s_1 has been successfully relayed from s_4 to s_2.

In the second case, the PU is detected on DW_b. The sender s_i should vacate that channel and then apply the CCS rule for switching to other available channels. Since the PU appearance after the SU pair (s_i, s_j) finished the negotiation procedure, receiver s_j is aware that sender s_i intends to send data to itself. Therefore, sender s_i has high priority to exchange data with receiver s_j in the next beacon interval of channel ch_b.

5 The pseudocode of the SMC-CR-MAC protocol

Figure 6 presents the procedure of HOSS which aims to cope with NB and DB problems. Consider that nodes s_i and s_j are sender and receiver, respectively. The home channels of s_i and s_j are ch_a and ch_b, respectively. In lines 2–9, the NB-Problem can be resolved by applying the CCS and SRCS rules. As shown in lines 4 and 5, if both nodes s_i and s_j detect PU appearance on $ch_{(b \bmod z)+1}$, they apply the CCS rule. If it is not the case, nodes s_i and s_j exchange CSR/CSR-ACK packets and apply the SRCS rule for switching to sender's home channel, as depicted in lines 7 and 8. On the contrary, if the DB-Problem occurs, nodes s_i and s_j execute the SRCS rule and then applies protocol [17], as shown in lines 8 and 9.

Figure 7 further illustrates the procedure of HESS. Lines 2–7 show the RA-Problem. In line 4, Sender s_i applies the CCS rule until it receives s_j's scheduling information. Both nodes apply the SRCS rule and then follow the

Fig. 6 The HOSS procedure

Algorithm I: The procedure of HOSS

1. **if** $P \cap N(s_i)$ and $P \cap N(s_j) = \{\phi\}$ **do**{
2. **if** *NB-Problem occurs* on ch_b **do**{
3. nodes s_i and s_j switch to $ch_{(b \bmod z)+1}$
4. **if** PU appears **do**
5. **execute** CCS rule
6. **else**{
7. nodes s_i and s_j exchange CSR/CSR-ACK
8. nodes s_i and s_j execute SRCS rule
9. both of them apply protocol [17]}}
10. **if** *DB-Problem occurs* on ch_b **do**
11. **execute** lines 8 and 9}

Fig. 7 The HESS procedure

Algorithm II: The procedure of HESS

1. **if** $P \cap N(s_i) = \{\phi\}$ and $P \cap N(s_j) \neq \{\phi\}$ **do**{/*RA-Problem*/
2. **if** node s_i cannot receive s_j's scheduling information **do**{
3. /*PU is detected in NW_b*/
4. node s_i applies CCS rule until it receives s_j' scheduling information in CP_k
5. nodes s_i and s_j exchange CSR/CSR-ACK packets and apply the SRCS rule
6. both of them apply protocol [17]
7. **if** node s_i cannot receive ACK packet **do** /*PU is detected in DW_b*/
8. **execute** lines 4, 6 and 7}}
9. **if** $P \cap N(s_i) \neq \{\phi\}$ and $P \cap N(s_j) = \{\phi\}$ **do**{/*SA-Problem*/
10. **if** PU is detected in NW_b **do**{
11. **execute** line 4
12. nodes s_i broadcasts H-REQ packet in CP_k
13. node s_u switches to ch_b and perform spectrum-sensing operation
14. node s_u replies H-ACK to node s_i in CP_k
15. nodes s_i and s_u switch to CP_b for negotiating with node s_j
16. **execute** lines 6 and 7}
17. **else**{/*PU is detected in DW_b*/
18. node s_i has high priority to exchange data with node s_j on ch_b in next beacon interval
19. **execute** line 8}}}

multichannel MAC protocol [17] to exchange data with each other, as shown in lines 5 and 6. On the other hand, if PU is detected in DW_b, sender s_i and receiver s_j apply line 8. In lines 9 and 10, if the SA-Problem occurs in NW_b, node s_i firstly applies line 4 to switch to an available channel ch_k. Then node s_i selects the cooperative node s_u for further cooperative transmission, as shown in lines 12–16. On the contrary, if PU is detected in DW_b, node s_i applies the CCS rule to switch to an available channel ch_k, as depicted in lines 18 and 19. In line 19, node s_i will participate in CP_b of next beacon interval with high priority for exchanging data with node s_j.

Figure 8 depicts the state diagram of the proposed SMC-CR-MAC protocol. In particular, when the SA-problem is occurred, the SU pair will switch to the *Cooperative transmission state* and then apply the cooperative transmission.

6 Performance evaluation

This section presents the performance evaluation of the proposed SMC-CR-MAC protocol against related works HC-MAC [10], CR-MAC [15], and the optimal approach. Assume that applying the optimal mechanism can obtain an optimal solution where the spectrum hole will be fully utilized and hence the channel utilization is maximized. In this study, the ns-2.34 [19] simulator was used, which combined with multichannel model [20]. Table 2 lists the parameters of simulation environment. In our simulation, nodes are randomly placed in a plane area sized 1500 m × 1500 m. Each performance result was obtained from the average results of 1,500 experiments. The 98 % confidence interval is always smaller than 2 % of the reported values in the experiments.

Figure 9 investigates the probabilities of successful rendezvous of two compared approaches by varying the probability of PU appearance in the *NW*. Generally, when the PU is detected on a licensed channel, the SU nodes should immediately vacate that channel. As shown in Fig. 9, when no PU appears on the licensed bands, the probabilities of successful rendezvous of two CR MAC protocols are 100 %. However, the probabilities of successful rendezvous of two MAC protocols are decreased with the probability of PU appearance. As shown in Fig. 9, the curve of CR-MAC sharply drops because it does not cope with the rendezvous problem when PU is detected in the *NW*. On the contrary, the proposed SMC-CR-MAC

Table 2 Simulation parameters

The number of channels	1–6
The bandwidth of each channel	2 Mbps
The number of SU communication pairs	1–50
Each simulation duration	100 s
Traffic arrival model	Constant-bit rate (CBR)
The probability of the PU appearance	0–100 %
Transmission range	250 m
Data packet size	512 bytes
Control period/data period size	20 ms/20 ms
SIFS/DIFS	16/24 µs
Simulation time	50 s

protocol applies the CCS rule and exchanges CSR/CSR-ACK packets to handle the rendezvous problem when PU is detected in the *NW*. In particular, when the probability of PU appearance achieves to 60 %, the proposed SMC-CR-MAC protocol is greater than 61 times of CR-MAC.

Figure 10 depicts the impact of PU appearance in the *NW* on the average network throughput. In general, the average network throughput is decreased with the probability of PU appearance. This occurs because of the fact that any data exchange of SU should be terminated when PU is detected, leading to low average network throughput. The optimal approach has the highest average network throughput since it applies exhaustive algorithm to select the best available channel for data exchange. The CR-MAC protocol has the lowest average network throughput since it does not continue the unfinished data exchange of SU pair when PU is detected. Moreover, CR-MAC cannot utilize the spectrum holes which appear in the following data window, leading to low average network throughput. To continue the unfinished data transmission, the proposed SMC-CR-MAC protocol

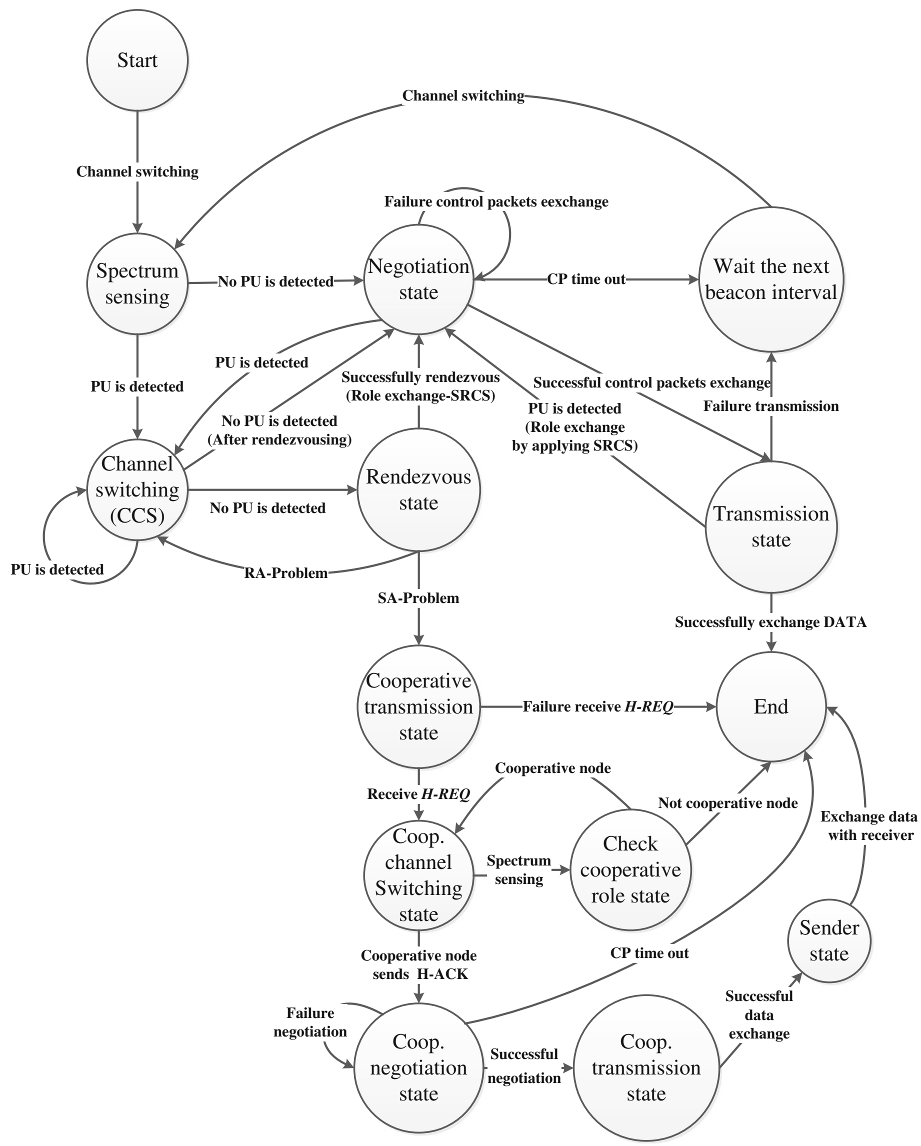

Fig. 8 Depicts the state diagram of the proposed SMC-CR-MAC protocol

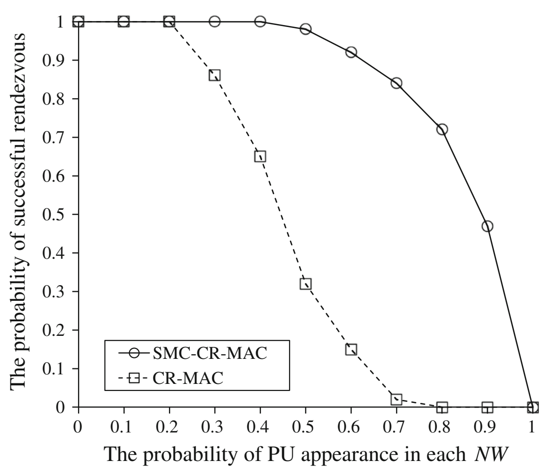

Fig. 9 The probability of the successful rendezvous versus the probability of PU appearance in the *NW*

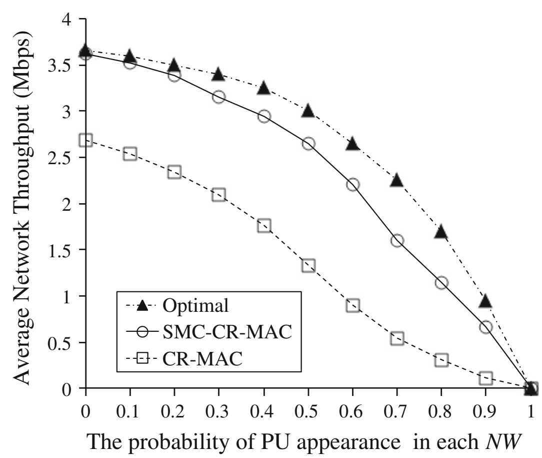

Fig. 10 The average network throughput by varying probability of PU appearance in the *NW*

applies CCS and SRCS rules. Consequently, the SMC-CR-MAC protocol outperforms CR-MAC protocol in terms of the average network throughput.

Figure 11 shows the impact of probability of PU appearance in *DW* on average network throughput. Generally, the average network throughput is decreased with the probability of PU appearance. Since the optimal approach has the complete channel information, it can select the channel which has the best channel condition such that the SU pair has the highest average network throughput. The HC-MAC has lower network throughput than CR-MAC when the probability of PU appearance achieves to 0 %. This occurs because HC-MAC allows SU pair to reserve a set of available channels in the sensing period for further data exchange. In this case, only one SU pair can exchange

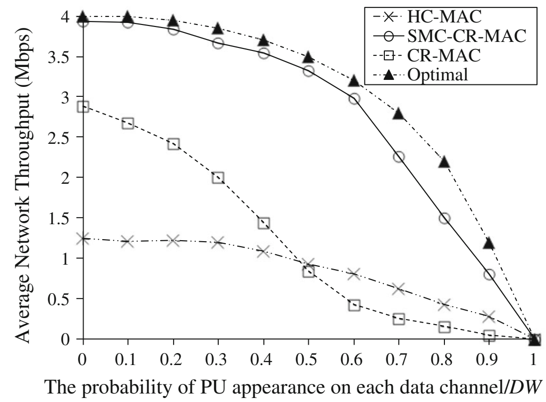

Fig. 11 The average network throughput by varying the probability of PU appearance on the data channel/*DW*

data in data transmission period. As shown in Fig. 11, the proposed SMC-CR-MAC protocol outperforms HC-MAC and CR-MAC protocols because the proposed SMC-CR-MAC protocol applies SMM channel model to improve the average network throughput. Moreover, it applies SRCS rule to distribute the network loads over all channels, achieving the purpose of load balance on each channel.

When the PU appears frequently, all of the CR MAC protocols (including the proposed SMR-CR-MAC) are affected; hence, the network performance of all of the CR MAC protocols decreases. Figures 9, 10, and 11 show that the probability of successful rendezvous and the average network throughput of all of the compared CR MAC protocols decrease with the probability of the PU appearing. However, the proposed SMC-CR-MAC protocol yields a higher average network throughput and greater probability of successful rendezvous than HC-MAC [10] and CR-MAC [15] when the PU is detected in the *NW* or *DW* with a high probability that the PU appears. This occurs because the proposed SMC-CR-MAC protocol considers various PU detection scenarios and proposes corresponding solutions to continue the unfinished data exchange of the SU.

Figure 12 depicts the impact of probability of PU on spectrum hole utilization *F*, as calculated in Exp. (4). The high value of *F* shows that the applied CR MAC protocol is able to efficiently utilize the spectrum hole within time interval *T*. In general, all compared CR MAC protocols have high spectrum hole utilization when the probability of PU appearance is low. The optimal approach has the highest spectrum hole since it applies exhaustive algorithm to select the available channel which has the best channel condition. The HC-MAC selects a set of channels to continue the unfinished data exchange when PU is detected. Nevertheless, the duration that PU accesses the data channel may be short and the remaining part of that channel will not be used, resulting in low channel

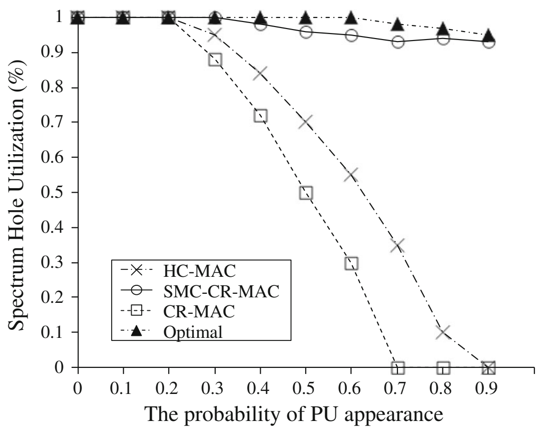

Fig. 12 The impact of probability of PU appearance on spectrum hole utilization

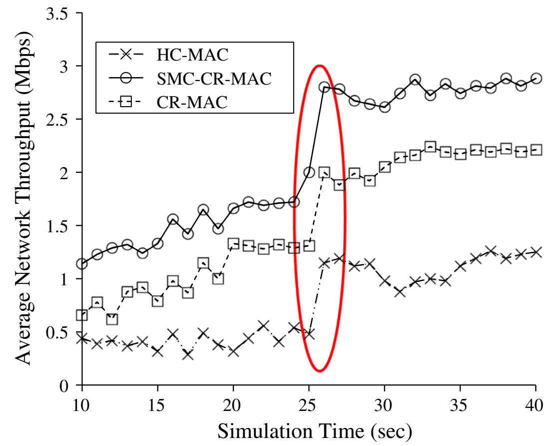

Fig. 13 Network throughput comparison of three MAC protocols by varying the probability of PUs appearance

utilization. On the other hand, CR-MAC does not consider restarting the transmission of SU pair and it also leads to low channel utilization. The proposed SMC-CR-MAC protocol applies the CCS and SRCS rules when PU is detected in *NW* or *DW*. By applying two rules, all spectrum holes can be efficiently utilized. As shown in Fig. 12, the proposed SMC-CR-MAC protocol has better network performance than HC-MAC and CR-MAC protocols in terms of the spectrum hole utilization.

Figure 13 compares three CR MAC protocols in terms of the average network throughput. The simulation controls the behaviors of PUs and observes the network throughput from 10 to 40 s. From 10 to 25 s, all PUs have high appearance probability (80 %) of. This indicates that the SUs have fewer chances to access the licensed channels. On the other hand, during 25 to 40 s, the PUs have low appearance probability (20 %) and hence the SUs have more chances to access the licensed channels. As shown in Fig. 13, the curves of three compared CR MAC protocols sharply grow when the probability of PU appearance is low, as depicted in the red circle. The compared CR MAC protocols perform spectrum-sensing operation to find opportunities for data exchange on available channels. The SMC-CR-MAC protocol takes into the consideration two detection situations, including HOSS and HESS, and further copes with NB, DB, RA, and SA problems by applying the CCS, SRCS, and cooperative transmission. As a result, the SMC-CR-MAC protocol is greater than 1.5 times and 4.2 times of CR-MAC and HC-MAC protocols in terms of the average network throughput, respectively.

Figure 14 depicts the effect of average network throughput on the number of SU communication pairs. Assume that the probability of PU appearance is set by 20 %. In general, the network throughputs of three compared MAC protocols are increased with the number of SU communication pairs. To avoid interference with PU, HC-MAC allows SU pair to reserve a set of channels in the sensing period and the reserved channels cannot be used by other SU pairs even if these channels are idle. Therefore, only one SU pair can exchange control packets in sensing period, resulting in poor network performance. The CR-MAC has better performance than HC-MAC because it allows multiple SU pairs to access licensed channels simultaneously. In Fig. 14, the proposed SMC-CR-MAC protocol has the best network performance since it applies SMM channel model. The contention phenomenon can be alleviated because all control packets are distributed over *NW*s of all channels. As shown in Fig. 14, when the number of SU communication pairs is twenty, the SMC-CR-MAC protocol is greater than 144 and 263 % of CR-MAC and HC-MAC in terms of network throughputs, respectively.

Figure 15 further measures the unbalanced degree of traffic load on each channel by varying the number of SU communication pairs. In general, all SUs should promptly vacate the channel when PU is detected. Those SUs switch to other available channels for data exchange. However, these SUs might switch to the same available channel, leading to traffic unbalance problem. Herein, a constant traffic is offered from each SU and the traffic load will be increased with the number of SU communication pairs. The following illustrates how the simulation calculates the unbalanced degree of traffic load for given z channels. Let notations c_k and μ denote the traffic load on ch_k and average network traffic load, respectively. The value μ can be calculated in Exp. (11).

$$\mu = \frac{1}{z}\sum_{k=1}^{z} c_k \tag{11}$$

Let notation δ denote the standard derivation of traffic load which can be measured by applying Exp. (12). The value of δ approaching to 1 indicates that the CR MAC protocol provides better balance in terms of traffic load on

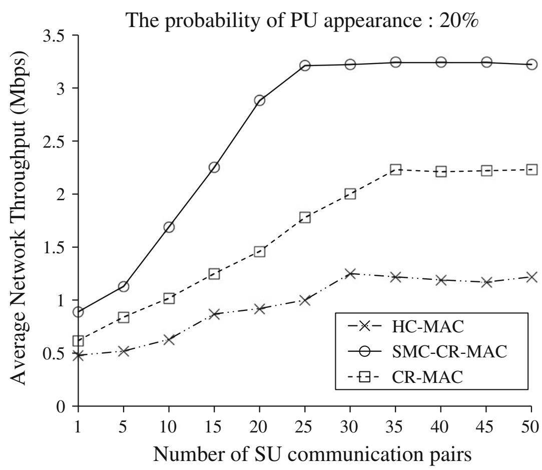

Fig. 14 The relation between number of SU communication pairs and average network throughput in the network

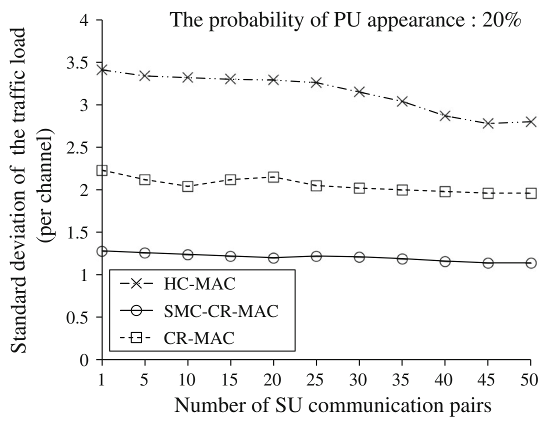

Fig. 15 The standard deviation of the traffic load associated with the number of SU communication pairs

each channel. In this case, the collision and the congestion phenomena will be alleviated.

$$\delta = \sqrt{\frac{1}{z}\sum_{k=1}^{z}(c_k - \mu)^2} \tag{12}$$

The SMC-CR-MAC protocol applies the SRCS rule which distributes all possible pairs over different channels. On the contrary, HC-MAC and CR-MAC protocols do not take into consideration the traffic balancing. As a result, the SMC-CR-MAC protocol has the lowest value of δ and achieves better load-balancing than the other two protocols.

Figure 16 investigates the aggregated network throughput by varying transmission duration of PU and probability of PU appearance. The long transmission duration of PU and high probability of PU appearance lead to the situation that the SUs have fewer opportunities to access the licensed channels. In general, the network throughputs of three compared CR MAC protocols decreased with the probabilities of PU appearance. The HC-MAC has the lowest

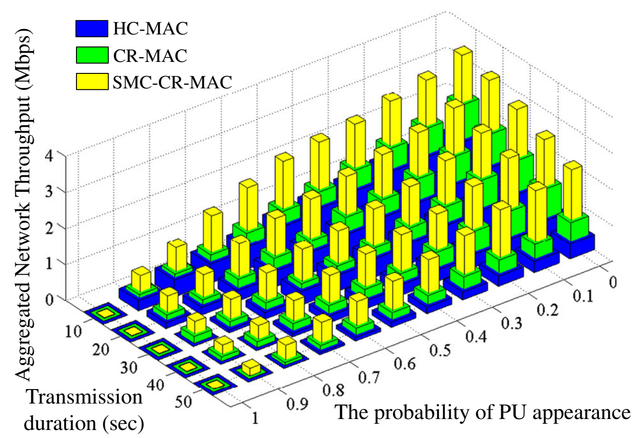

Fig. 16 The aggregated network throughput by varying transmission duration of PU and probability of PU appearance

network throughput in all cases since it can only exchange one data in each transmission period. In comparing with the HC-MAC, CR-MAC can exchange multiple packets in one beacon interval and hence it has higher aggregated network throughput. However, once a pair of PUs appears on the licensed channel, CR-MAC does not explore other opportunities for data exchange on the other available channels. On the other hand, the SMC-CR-MAC protocol employs the CCS and SRCS rules to cope with rendezvous, collision, and congestion problems. As shown in Fig. 16, the SMC-CR-MAC protocol has the best network performance than CR-MAC and HC-MAC protocols in terms of the aggregated network throughput.

Figure 17 depicts the performance comparison of the proposed SMC-CR-MAC protocol with/without applying SAA approach. The *SAA_5* and *SAA_10* show that the sender and receiver apply SAA approach, which have 5 or 10 common neighbors, respectively. The *SMC-CR-MAC_Without SAA* mechanism shows that the sender only applies the CCS and SRCS rules without applying SAA approach. In general, all curves are increased with the probability of PU appearance. *SMC-CR-MAC_Without SAA* has the highest average packet delay since the sender does not ask for assist to execute the cooperative transmission. The sender may be interfered by PU with long duration on receiver's home channel, leading to long packet transmission delay. As shown in Fig. 17, the *SAA_10* mechanism has the lowest average packet delay compared with the other two mechanisms. The major reason is that the sender has higher probability to select cooperative node when the communication pair has more common neighbors. As a result, the proposed SMC-CR-MAC protocol that applies the cooperative transmission with more common neighbors has better network performance in terms of the average packet delay.

In summary, the proposed SMC-CR-MAC protocol exhibits more favorable network performances in terms of the average network throughput, probability of a successful

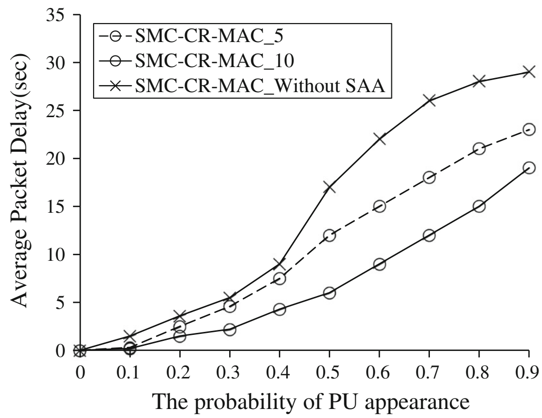

Fig. 17 The comparison of three mechanisms in terms of average packer delay by varying the probability of PU appearance

rendezvous, and standard deviation of the traffic load. Particularly, the improvements are considerable when the traffic load is heavy, the PU behaves unexpectedly, or the PU occupies the licensed band for a long time.

7 Conclusions

This paper proposes an efficient CR MAC protocol, called *SMC-CR-MAC*. Compared with prior works, the proposed SMC-CR-MAC protocol exhibits several good features. One feature is that it applies *Staggered Multichannel Model* (SMM) and hence the rendezvous and multichannel hidden terminal problems are resolved. The other feature is that the proposed SMC-CR-MAC protocol considers HOSS and HESS based on the location of PU appearance. The HOSS raises NB and DB problems while HESS raises RA and SA problems. The proposed SMC-CR MAC protocol adopts CCS and SRCS rules to cope with NB and DB problems and adopts RAA and SAA approaches to overcome RA and SA problems, improving the network performance and utilization of licensed bands. Simulation results demonstrate that the proposed SMC-CR-MAC protocol has better performance result in terms of utilization of licensed bands, standard deviation of traffic load on each channel, and probability of successful rendezvous.

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