An Opportunistic Pervasive Networking Paradigm: Multi-hop Cognitive Radio Networks

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Abstract

Cognitive radio networks enable ubiquitous communications both in frequency and time domain, and hence enable opportunistic pervasive communications. Multi-hop cognitive radio networks are appealing to the researchers due to their wide range of application potential in commercial, emergency communication, and military tactical networks. However, the multi-hop nature of the network coupled with the varying spectrum availability owing to the opportunistic spectrum access introduce many design challenges. Medium access control (MAC) layer in multi-hop cognitive radio networks needs to make distributed spectrum sensing and accessing decisions without disturbing the communications of the licensed users, while at the same time determining the communication frequency with the neighboring unlicensed users. Various MAC protocols for multi-hop cognitive radio networks have hitherto been proposed in the literature. In this chapter, we first outline the design challenges for the MAC layer protocols. Subsequently, we describe several MAC protocols proposed for multi-hop cognitive radio networks, emphasizing their strengths and weaknesses. Finally, we point out open research issues with regard to the MAC design of these networks.[1]

I. INTRODUCTION

The proliferation of wireless applications and services has intensified the demand for the radio spectrum. Although the licensed spectrum is at a premium, a large portion of the spectrum is used sporadically with a high variance of geographical and temporal usage. This ineffective utilization constitutes the very 'raison d'être' of *dynamic spectrum access (DSA)* concept, which refers to the opportunistic utilization of the spatiotemporally unoccupied portions of the spectrum. The key and jump-start enabler for DSA is *cognitive radio*, which is the next evolution of adaptive/aware/software-defined radios through a supplemental intelligent layer providing the DSA capability.

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[1] This work is supported by the State Planning Organization of Turkey (DPT) under grant number DPT-2007K 120610, Scientific and Technological Research Council of Turkey (TUBITAK) under grant number 109E256, and by Boğaziçi University Research Fund (BAP) under grant number 09A108P.

Cognitive radio devices can operate anywhere and using any portion of the spectrum as long as they guarantee that the licensed owners of the spectrum portion are not disturbed. This ubiquitous and opportunistic nature of cognitive radio devices renders the cognitive radio networks a vital paradigm in opportunistic pervasive communications.

A cognitive radio network (CRN) is comprised of primary (PU) and secondary (SU) users. The former is the licensed owner of a frequency band, whereas the latter utilizes the spectrum opportunities during the inactive times of the PUs. A CRN may have a single-hop or multi-hop structure. The emerging IEEE 802.22 standard-based wireless regional area network (WRAN) technology is based on the single-hop CRN concept, in which a centralized cognitive base station (BS) manages the SUs that opportunistically use the TV bands when they are unoccupied by the incumbent TV services. On the other hand, multi-hop CRNs (MHCRN) have no fixed network infrastructure or central controller with an additional requirement that the information needs to be relayed over multiple wireless links. Thus, the SUs in a MHCRN have to coordinate themselves in a distributed manner.

Multi-hop wireless networks gain increasing popularity as multi-hop connections inevitably become necessary to maintain high degree of network connectivity and achieve higher data rates for larger distances. Furthermore, the difficulty of providing infrastructure in certain applications such as emergency situations and battlefields necessitates the network to have an ad hoc structure. Moreover, CRNs are promising to obviate the radio inter-operability problems with the ultimate goal of providing a "universal wireless device". For instance, the Joint Tactical Radio System (JTRS) attempts to provide a common architecture to solve the formidable radio interoperability problem of the US military [1]. Inter-operability problems are also an impediment in joint operations, where each nation typically has its own radio system. Lately, emphasis on peacekeeping, disaster relief, homeland security, and other non-combat military operations has produced additional problems. In these roles, military units have to communicate with humanitarian organizations and public safety agencies, as well as the civilian population. Consequently, emergency communication networks and military tactical networks of the future are anticipated to be based on MHCRNs. Moreover, the pivotal role of the multi-hop wireless networks in sustaining high degree of network connectivity and attaining increased data rates coupled with the enhanced spectrum efficiency and radio inter-operability benefit of CRNs make MHCRNs a strong candidate technology for commercial applications as well.

The primary function of a medium access control (MAC) protocol is to govern the physical layer data transmissions and to provide access service to the error control and recovery at the link layer. The design of MAC layer for CRNs has additional challenges such as ensuring that the communications of the PUs are not disturbed, and collisions among the SUs are avoided so that channel utilization is improved. Unlike the single-hop CRNs, which have the emerging IEEE 802.22 standard, the MAC layer of MHCRNs has hitherto been unstandardized. Furthermore, the MAC design of MHCRNs introduces challenges that are non-existent in single-hop CRNs, such as transceiver synchronization, group communication, hidden incumbent node problem, as well as the Clear to Send (CTS) timeout problem in addressing the hidden and exposed terminal problems.

The authors in [2] present an overview of existing work and research challenges about the ad hoc CRNs in general. They outline the research issues about spectrum sensing, decision, sharing, and mobility on different layers of the protocol stack. On the other hand, the authors in [3] present a survey on the MAC protocols in CRNs in general, where they discuss about both infrastructure based and ad hoc CRNs. In contrast, we focus in this chapter on the MAC protocols specifically in MHCRNs. In this respect, the domain of study in this chapter can be regarded as the intersection of the domains of [2] and [3]. Hence, we provide a deeper discussion on a narrower and more specific topic.

The rest of this paper is organized as follows: In Section II, we outline the challenges in the MAC design of MHCRNs, accompanied by a comparison of multi-channel networks and MHCRNs. In Section III, we briefly discuss about the key MAC protocols for MHCRNs, listing their advantages and disadvantages. We make a comparison of the investigated protocols in Section IV, and provide future directions for researchers with regard to open issues that have not been thoroughly addressed. Finally, we conclude the survey in Section V.

II. OVERVIEW OF MULTI-HOP COGNITIVE RADIO NETWORKS MAC LAYER

A. MAC Design Challenges in MHCRN

1) Common Control Channel (CCC) Problem: In a MHCRN, the SUs need to communicate with each other through control messages for accomplishing tasks like the negotiation of a common channel available to both parties. For this purpose, a common control channel is needed. A separate dedicated control channel would seem to be a proper solution. Although a CCC facilitates numerous spectrum sharing functions such as sender and receiver handshake or sensing information exchange, a dedicated CCC has several drawbacks. Firstly, it is a waste of channel resources. Secondly, a control channel can quickly saturate as the number of SUs increases, which constitutes a big problem especially for MHCRNs. Thirdly, an adversary can cripple the CCC by flooding it on purpose and can thus severely obstruct the channel negotiation and allocation process, hence causing Denial of Service (DoS) attacks [4]. These three problems also exist in multi-channel networks. MHCRNs have the additional problem of the possibility of a PU appearance in the CCC. If an incumbent signal is detected in the same band, CCC needs to switch to another band by applying a control channel policy. In order for this control channel hopping pattern to be identical in all the nodes in the MHCRN, a channel selection policy that guarantees this requirement needs to be applied. Furthermore, each SU has to constantly sense the CCC band for a prompt detection of PU appearance. Another approach to obviate the need for a CCC is to choose a channel among the available channels as the control channel. When the PU of that channel returns, a new channel which is available to all users is chosen. Nevertheless, the probability that a certain channel is available to all SUs in a MHCRN is quite low. Furthermore, the available channels may differ in the transmission range, operation frequency and bandwidth. Owing to this heterogeneity in the transmission range, the scalability and connectivity of the network is subject to change in accordance with the control channel since a channel with a shorter transmission range may not provide service to all the areas served by a channel with a longer transmission range. Therefore, a better protocol that avoids the use of a CCC, while at the same time taking the network heterogeneity into account is essential.

2) Transceiver Synchronization: In order to establish communication and data exchange between two pairs of SUs, both the sender and the receiver node have to tune to the same channel at the same time. Since the nodes do not know which channels are available and which one of the available channels the other node is going to tune to, they need to establish the communication frequency and time period prior to the incipient communication. Transmitter-receiver synchronization challenge is unique to the MAC in opportunistic spectrum access (OSA) networks and maintaining this without introducing extra control message exchange is a nontrivial task. The problem becomes even more complicated in MHCRNs because of the lack of a centralized controller to govern the transmissions from all nodes.

3) CTS Timeout and Undecodable CTS Problems: The existence of hidden and exposed terminals is a classical problem in MAC design for multi-hop ad hoc networks. In a MHCRN, the hidden terminals are SUs outside the secondary transmitter's range, but inside the secondary receiver's range, while exposed terminals are SUs within the secondary transmitter's range but outside the secondary receiver's range. Since hidden terminals can result in collisions and exposed terminals may lead to wasted opportunities, they need to be addressed properly. IEEE 802.11 Request to Send (RTS)/Clear to Send (CTS) like approaches might alleviate the problem; nevertheless, this scheme possesses two problems in the MHCRN domain. Firstly, the conventional RTS/CTS approach fails when the RTS/CTS packet is not decodable; e.g., when the received signal power is just below what is needed for decoding. In a MHCRN, this might happen when there is a collision due to the PU activity. Secondly, unlike in traditional MAC protocols, the sender in a MHCRN cannot merely set a fixed timeout while expecting a CTS in MHCRNs because the PU activity can inevitably prevent the SU control channel transmissions. Therefore, a more sophisticated mechanism is needed to address this problem in MHCRNs more effectively.

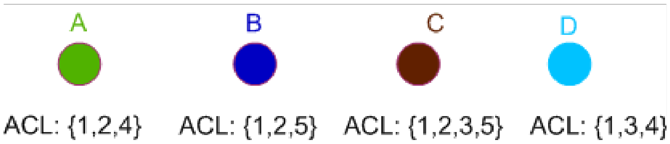

Fig. 1: Multi-channel hidden terminal problem.

4) Multichannel Hidden Terminal Problem (MCHTP): Multi-channel hidden terminal problem (MCHTP) was initially identified in multi-channel networks; however, the same problem also exists in MHCRNs. Figure 1 illustrates four nodes with their respective Available Channel Lists (ACL). Assume that only the adjacent nodes are in the transmission range. Since channel 1 is available to all nodes, suppose that channel 1 is chosen as the CCC and that node C and D are already communicating through channel 3. When node A wants to send a packet to node B using channel 2, it sends an RTS to B on the CCC, which is channel 1 in this case. B suggests channel 2 for data communication by sending a CTS packet. Subsequently, node A sends a confirmation message to node B and to its neighbors indicating that it has reserved channel 2 for data communication. Nevertheless, since C has been communicating using channel 3, it fails to receive the CTS from B. Therefore, it presumes that channel 2 is available and might commence communication with node B using channel 2, and hence yielding a collision. This is called the MCHTP.

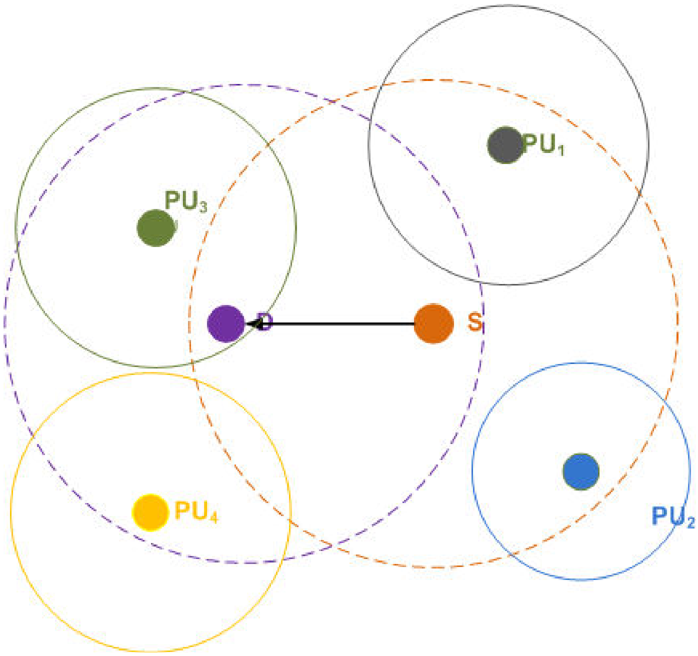

Fig. 2: Hidden incumbent node problem [5].

5) Hidden Incumbent Node Problem (HINP): In MHCRNs, when the sender and receiver nodes negotiate to determine an available channel, they select a data channel based on their ACLs in order to avoid causing interference to the PUs. Hidden incumbent node problem (HINP) that arises in this situation was introduced by the authors in [5]. In Figure 1, node S is the source node with an ACL of $\{1, 2, 3, 4\}$, which indicates that no signal was detected on that channel, implying the absence of any PU or other SU activity. The circles in the figure represent the transmission range of the nodes in the center. Besides, PU_i indicates that the PU is operating on channel i. Node S sends its ACL in the RTS packet to the destination node D using the CCC. The incumbent nodes PU_1 and PU_2 are operating inside the transmission range of the source node S. However, node S cannot detect the signals of these incumbent systems since the radio waves from these signals cannot reach the source S. It is possible that after the RTS and CTS exchange between S and D, D may choose channel 1 as the data channel, which will directly cause interference to the incumbent system working on channel 1. The same case also applies for channel 2. Similarly, within the transmission range of the destination node D, channels 3 and 4 are occupied by the incumbent devices. The incumbent signal on channel 3 can be sensed by D; therefore, the ACL of D excludes channel 3. In the case of channel 4, the signal from the incumbent system cannot reach node D or it can be ignored by the destination node as a background noise due to weak signal strength. If node D selects channel 4 and includes this in the CTS that it sends to S, then PU_4 will receive harmful interference from the destination node D. This problem is called the Hidden Incumbent Node Problem (HINP).

6) Number of Transceivers: In the single transceiver model, the CR nodes utilize the same transceiver for both control and data channel transmissions. Since the nodes have to periodically switch back to the control channel, this model results in longer transmission delay than the dual transceiver model. Furthermore, single transceiver model requires exact synchronization between the nodes. Although the dual transceiver model eliminates these drawbacks since one of the transceivers is dedicated to the control channel, this model possesses hardware implementation complexity. A similar situation exists for the sensing task. If a dedicated radio continually senses the spectrum while another radio is involved with the data transmission tasks, more transmission opportunities can be detected and the sensing results have better accuracy. Furthermore, the multi-channel hidden node problem illustrated in Figure 1 can be avoided, since node C does not miss the CTS message transmitted by node B due to its dedicated control channel transceiver. Nevertheless, more radios imply hardware implementation complexity. If a single radio is used for both sensing and accessing, then the data transmission has to be periodically interrupted, which incurs more latency.

7) Coordination of Spectrum Sensing and Accessing Decisions: To achieve optimal performance in a MHCRN, the MAC protocol has to determine a set of channels to sense and a set of channels to access. In a single-hop CRN with a central coordinator, the coordinating node can decide on which nodes will sense and guide a cooperative spectrum sensing process in addition to making the spectrum accessing decisions. Nonetheless, since there is no central coordinator in a MHCRN, the nodes have to make the spectrum sensing and accessing decisions in a distributed manner. Moreover, the spectrum access decisions should take not only the availability of a sensed channel, but also the channel fading condition and the nodes' energy constraints into account. Furthermore, the cognitive nodes have to determine the optimal sensing time and optimal transmission time in a distributed manner.

Distinguishing the PU activity from the transmissions of other SUs is an important problem in CRNs because the PU statistics play an important role in various decision criteria, especially during channel access. That is to say, "carrier sensing" and "PU sensing" are two different phenomena in the MHCRN context, and hence, both of them have to be handled separately and effectively. To this end, IEEE 802.22 protocol establishes quiet periods to coordinate the spectrum sensing process. However, unlike the IEEE 802.22 network, MHCRNs lack a central coordinator. Therefore, the coordination of the quiet periods without a central coordinator is a challenging research issue in MHCRNs.

8) Group Communication: The proper operation of higher layer protocols in carrying out mechanisms such as address resolution depends on the existence of a group communication mechanism at the MAC layer. Per contra, finding a channel available to all the nodes in the group to communicate is a daunting task in a MHCRN, especially when taking into account the fact that even the communication between a pair of CR nodes requires significant control message exchanges.

9) MAC Layer Authentication: In a single-hop CRN, confidentiality and authentication across the network can be provided by applying cryptographic transforms to the MAC frames. For instance, IEEE 802.22 contains a security sub-layer. Unfortunately, such a protocol cannot be implemented in a MHCRN because there is no trusted entity that can act as a server to control the distribution of keying material. Therefore, an adversary node can send spurious control frames to saturate the CCC. If the control frames are exchanged in an unencrypted form, the candidate channel list in the control channel hopping pattern can also be acquired by the adversary. Thus, even if the control channel ceaselessly hops among different frequency bands due to the presence of the incumbent signals, the adversaries still have the capability to continually saturate the CCC [4].

B. Comparison of Multi-channel Networks and MHCRN

Multi-channel networks and MHCRNs share a plenty of common features. In both networks, each user has a set of channels available for communication. When two users want to communicate, they negotiate possibly via a common control channel (CCC). Furthermore, the CCC and MCHTPs, which are related to a multi-channel network, are common to a MHCRN. Therefore, many MHCRN MAC proposals in the literature are inspired by the work about MAC designs in multi-channel networks [5][6][7].

There are two major differences between these two networking environments. Firstly, the number of channels available at each node is fixed in a multi-channel network, while it is variable in a MHCRN. Hence, it is probable that an SU in a MHCRN has no available channels owing to the complete occupancy of the spectrum by the PUs. Secondly, the channels in a multi-channel network generally have equal bandwidths and transmission ranges; however, the environment is heterogenous in a MHCRN. In this respect, a MHCRN may be considered as an amalgamation of multi-hop and multi-channel networks together with the additional challenge of varying spectrum availability.

III. PROPOSED MAC LAYER PROTOCOLS

In this section, we briefly describe a wide range of MAC protocols designed for MHCRNs by stating the essential behavior of the protocols wherever possible. Moreover, we also present the advantages and disadvantages of the protocols.

A. POMDP Framework for Decentralized Cognitive MAC (DC-MAC)

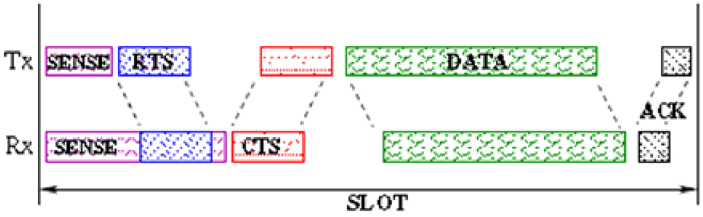

Fig. 3: DC-MAC operation phases [8].

The authors in [8] formulate a Partially Observable Markov Decision Process (POMDP) framework for modeling the channel sensing and access decisions in a MHCRN. They model the PU activity as a two state (occupied/idle) Markov chain. Since in general the network state cannot be completely observed due to partial spectrum monitoring or sensing error, the model is a POMDP. At the beginning of each time slot, each user firstly determines a set of channels to sense. On the basis of the sensing observations, each node then selects a subset of the available channels to access. At the end of the time-slot, in response to these sequential sensing and accessing actions, each user obtains a reward, which is equal to the number of bits delivered. The objective is to maximize the total expected reward accumulated over a certain number of slots, where the spectrum occupancy statistics remain unaltered. The constraint is to bound the probability of collision below the permissible maximum value. Depending on the received reward, each user updates its *belief vector*, which represents its knowledge about the network state. Figure 3 illustrates the sequence of operations in this protocol.

In order to ensure transceiver synchronization, both the transmitter and the receiver nodes update their belief vector using only the common information. This way, they tune to the same channel in the next time-slot. Moreover, this framework addresses the CCC problem since it does not require a dedicated communication channel. Additionally, the proposed framework deals with the conventional hidden and exposed terminal problems using an RTS/CTS exchange mechanism.

Advantages: Spectrum sensing and accessing decisions are coordinated in a distributed manner without additional control message exchanges through a CCC. When the sender and receiver nodes are neighbors to the same PU, they are guaranteed to access the same channel without explicit synchronization. However, when this is not the case, they still need a handshaking procedure because a PU that is idle for one party may be occupied for the other one. The authors implement this handshaking procedure through RTS/CTS exchanges. Furthermore, the proposed protocol can be implemented using a single transceiver at each SU.

Disadvantages: The transmission pairs need RTS/CTS messages not only to handle the conventional hidden and exposed terminal problems, but also to negotiate the communication channel when they do not have a common neighboring PU. Since

RTS/CTS message exchanges require a common communication channel, the authors do not completely solve the CCC problem, although they partially address it. Furthermore, the authors also do not address the CTS timeout problem mentioned in Section II, which is specific to MHCRNs.

B. DCR-MAC

The authors in [5] primarily focus on dealing with the HINP discussed in Section II. They state that it is necessary to exchange the incumbent system information with one-hop neighbors from the source and destination nodes. To this end, they propose a reactive and collision-free reporting mechanism. The neighbor nodes of the source overhear the RTS message. If they detect an incumbent signal at the p^{th} listed sub-channel in the ACL of the RTS, they transmit a short pulse at the p^{th} reporting slot of the reporting phase in the CCC, which is right after the RTS phase. For a certain reporting slot, if the source node detects a pulse signal, then it indicates that there exists an incumbent system around the neighbor of the source that uses the corresponding sub-channel in spite of the fact that the source did not sense it. Therefore, the source node updates the ACL and transmits an RTSu (RTS-updated) signal. Similarly, the neighbor nodes around the destination overhear the CTS and report the incumbent system information to the destination node through short pulses. The RTS/CTS exchange also serves the purposes of maintaining transceiver synchronization and resolving the conventional hidden and exposed terminal problems. The authors consider both single and dual transceiver models. The dual transceiver helps in combatting the MCHTP. The single transceiver model that the authors consider adapts the MMAC ad hoc traffic indication message (ATIM) mechanism, originally proposed by the authors in [9] for multichannel networks. Besides, the authors assume a CCC in the ISM band.

Advantages: The authors address the HINP, which previously received little attention. Since the proposed sensing information exchange mechanism between the neighbor nodes and the source/destination nodes is reactive, it does not require periodic MAC control message transmissions, which would occur in a proactive protocol.

Disadvantages: Because of the additional reporting slots in the RTS/CTS exchange, the proposed protocol incurs a greater access delay than a conventional RTS/CTS message exchange. Furthermore, the usage of a CCC makes the protocol prone to DoS attacks and the reporting slots in the CCC exacerbates the CCC saturation problem. It is also noteworthy to mention that the proposed protocol does not entirely solve the HINP because the one-hop neighbors also may not be in the transmission range of the PU. It may even be the case that no SU is in the transmission range of the PU. Therefore, a more sophisticated transmission power control mechanism needs to be employed by the SUs in order to completely solve the HINP.

C. Cross-Layer Based Opportunistic MAC (O-MAC)

The authors in [10] propose PHY and MAC layer integrated spectrum sensing policies for MHCRNs. Each SU is equipped with two transceivers: one transceiver for spectrum sensing and data transmission and one transceiver for control channel transmissions. Firstly, the authors make a Markovian analysis of a simple random sensing policy, where each SU randomly selects one of the licensed channels to sense. The authors prove that when the number of SUs is large enough, the SUs can sense all of the licensed channels even using the simple random sensing policy. Nonetheless, this policy is inadequate when the number of SUs is smaller than or close to the number of licensed channels. To amend this weakness, the authors then propose a negotiation based sensing policy and analyze it through an $M/G^Y/1$ queueing model. The basic idea is to let the SUs know which channels are already sensed by their neighboring SUs and then select different channels to sense in the next time-slot. At the very beginning, the SUs randomly select a licensed channel to sense and report the channel state by sending beacons in the reporting phase of the control channel. During the negotiation phase, the SUs encapsulate the channel sensing information into the RTS/CTS packets. The neighboring nodes that overhear these packets learn about whether they have sensed the same channel. If there are neighboring SUs that sense the same channels as the sender in a particular time slot, each of them will sense another different licensed channel in the subsequent time slot, which is randomly picked up from the rest of the channels that have not been sensed. If the number of SUs is larger than or equal to the number of licensed channels, the negotiation based sensing policy eventually reaches the desired state where all the licensed channels are sensed by all the SUs.

Advantages: The rigorous throughput and delay analysis provides insights into under which circumstances a simple random sensing policy is enough and when a more sophisticated negotiation based sensing policy is needed.

Disadvantages: In addition to the inclusion of the channel sensing information into the RTS/CTS packets, the usage of the control channel for the reporting and negotiation phases aggravates the CCC saturation problem. Furthermore, the authors assume that the licensed channel availability information is consistent among all SUs; i.e., all SUs utilize the licensed channels used by the same set of PUs. This assumption may hold only for small scale MHCRNs. The entire analysis in this paper is invalid for situations where a licensed channel is occupied by a PU and hence unavailable for the SUs in some part of the MHCRN, but it is available in another part of the MHCRN.

D. HC-MAC

The authors in [11] propose a cognitive MAC protocol that determines the optimal spectrum sensing decision for a single secondary transmission pair with single radios that cannot sense and transmit simultaneously. If more channels are sensed in a certain time period, more channels may be available for transmission. Nevertheless, sensing consumes time and if the

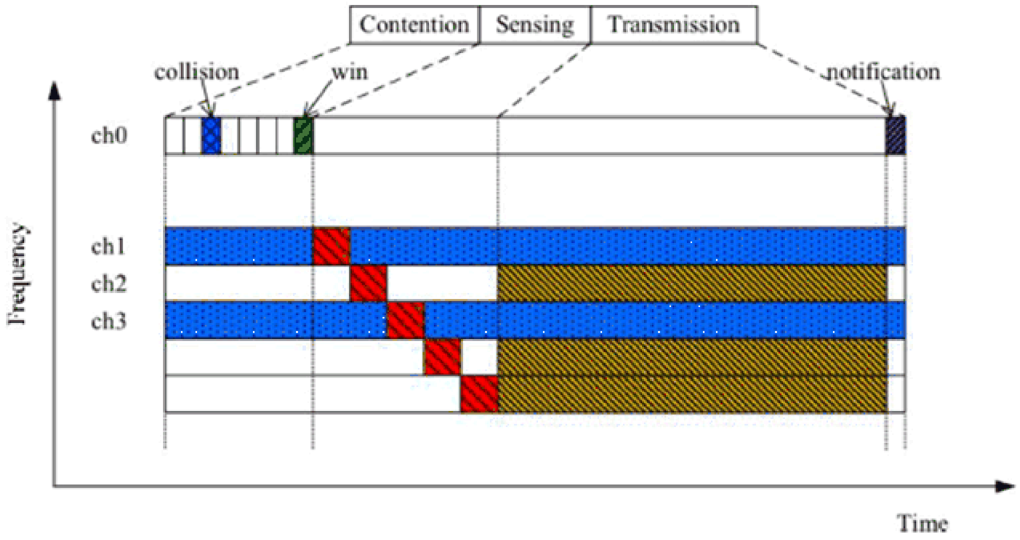

Fig. 4: HC-MAC operation phases [11].

additionally sensed channels are unavailable, it is a waste of time since this time could be used for data transmissions instead. The contention, channel sensing and data transmission phases are sequential, as illustrated in Figure 4. The authors formulate this spectrum sensing decision problem as an optimal stopping problem, which can be solved by backward induction. Three types of control messages are used. C-RTS/C-CTS messages are used for contention and spectrum reservation. Any SU hearing either of these two messages defers its operation and waits for the notification message. S-RTS/S-CTS messages are used to exchange the channel availability information between the sender and receiver in each sensing slot. T-RTS/T-CTS messages are used to notify the neighboring nodes the completion of the transmission.

Advantages: The influence of sensing overhead for the multi-channel opportunity is considered. The approach requires little hardware complexity, since the hardware constraints such as a single radio for both spectrum sensing and data transmission, as well as partial spectrum sensing ability are taken into account.

Disadvantages: Additional control message exchanges in the decentralized version of the approach have a detrimental impact on the CCC. Furthermore, HC-MAC does not take the impact of SU spectrum usage into account. A secondary pair A-B who wins the contention period senses the spectrum with the neighboring nodes silenced. Nevertheless, the two hop away nodes that do not receive the C-RTS/C-CTS messages can still perform their operations. If these two hop away nodes operate on the same channels as the ones sensed by the pair A-B, then the sensing results of these A-B nodes will inaccurately indicate that there is a PU transmission on these channels. This situation is referred to as the *sensing exposed terminal problem* and it is not handled effectively by HC-MAC.

E. C-MAC

The major component of the Cognitive MAC (C-MAC) protocol proposed by the authors in [6] is the rendezvous channel (RC). In the C-MAC protocol, each channel has a superframe structure and one channel is identified as the RC, which is decided dynamically and in a distributed manner. The RC has functionalities such as synchronization among the available channels, discovery of the neighbor nodes, channel load balancing, group communication support (multicast and broadcast), and mitigation of the conventional hidden terminal problem as well as the MCHTP. The superframe structure also includes a slotted beaconing period, through which the nodes exchange information during the channel negotiation.

Advantages: One of the major merits of the RC is the support for group communication, which is often neglected in other existing work in the literature. Although not explicitly stated by the authors, the proposed distributed beaconing approach can help alleviate the HINP because the nodes acquire the information about their neighbors' neighbors such as occupied beacon slot and transmission schedules through this approach.

Disadvantages: C-MAC overcomes the MCHTP by having one transceiver perpetually tuned to a pre-determined RC. In other words, only when at least two transceivers are available, C-MAC can mitigate this problem. With a single transceiver, SUs have to periodically switch back to the RC both for control messages and re-synchronization. Therefore, when C-MAC is employed with a single transceiver, the nodes can miss the control frames informing them about the data transmissions among their neighboring nodes, which can possibly lead to a MCHTP.

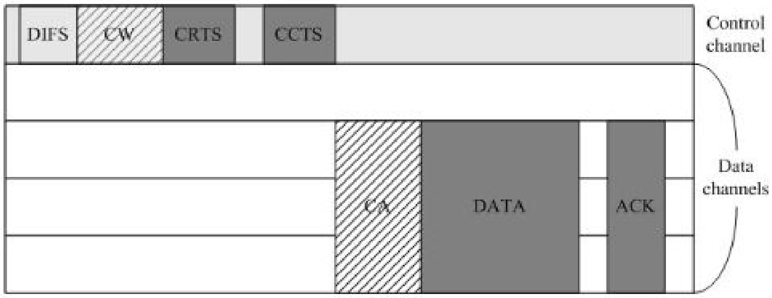

Fig. 5: SCA-MAC operation phases [12].

F. DOSS-MAC

Dynamic Open Spectrum Sharing MAC (DOSS-MAC) protocol proposed by the authors in [13] is based on the *busy tone* concept. Each node has three transceivers; i.e., for the busy tone channel, control channel and the data channel. When a node is receiving data on a particular frequency band, it also transmits a busy tone signal in another narrow-band frequency, which is found by mapping the wide-band data channel via utilizing a transformation function. A node that has data to transmit observes these busy tone bands and hence it is apprised of all the data reception activities in its neighborhood. This way, hidden and exposed terminal problems are eliminated.

Advantages: Since the receiver node sends the busy tone, DOSS-MAC successfully overcomes the problem that arises when the RTS/CTS packet is not decodable while trying to handle the conventional hidden node problem.

Disadvantages: The major drawback of this protocol is the need for three dedicated transceivers, which yields a costly hardware implementation. Besides, if a PU appears on the busy tone band after a data receiving SU turns on its busy tone signal or if a PU already occupies that frequency band at the time that the data receiving SU implements the spectrum mapping, then the data receiving SUs cannot send their busy tone signals in the corresponding band. The SUs have the additional burden of being obliged to continuously monitor the busy tone bands in order to ensure that the busy tone signals are turned off in a timely manner as soon as a PU appears in that band. Moreover, when a PU is operating on the busy tone band, the other SUs that observe this band may erroneously decide that an SU is receiving data in the corresponding wide-band data channel and refrain from using the data channel. Therefore, these situations constitute a waste of opportunities and additional complexity on the SUs.

The authors also state that multicasting and broadcasting are addressed by having the transmitter send a multicast/broadcast request packet over the CCC and all the pertinent nodes adjust their receivers accordingly. No busy tone is used in these message exchanges. However, if the spectrum declared by the transmitting node is not available at some recipients of the broadcasting request packet, then this message exchange process fails to address this problem. Determining a frequency band that is available for all the recipients of the multicast/broadcast packet is a nontrivial task that has not been handled by the DOSS-MAC protocol.

G. SCA-MAC

The authors in [12] propose a channel allocation strategy for ad hoc cognitive radio networks. Their proposed method predicts the successful rate of a channel by first calculating the probability of that particular spectrum band being idle and then the probability that a packet with a specific length will fit the spectrum hole during the idle PU period. Subsequently, they bundle several continuous idle channels to expedite the data transmission. This way, the authors ensure the interference to the PUs to be limited by a predetermined acceptable rate. The cognitive nodes use Control-channel-Request-to-Send (CRTS) and Control-channel-Clear-to-Send (CCTS) messages to coordinate the access to the channel through the control channel. The access to this control channel is implemented by a CSMA/CA mechanism. The control packets carry the information of packet length and channel aggregation, whose expected successful rate meets the interference limit. After the exchange of the control packets, the sender and receiver nodes tune their transceivers to the agreed channels. Figure 5 depicts the operation phases of the SCA-MAC protocol.

Advantages: The ability of the protocol to guarantee that the interference imposed to the PUs is bounded is an essential feature for CRNs, since it ensures that there is no noticeable deteriorating impact on the QoS of the PUs. Furthermore, incorporating the channel statistics into the decision criteria for channel access enables the quality assessments of the channels. This way, the SU acquires the ability to intelligently wait for a busy channel with high successful rate to become idle again when the currently existing idle channels have low successful rate.

Disadvantages: The authors assume that a CCC exists. When the CRTS/CCTS packets fail due to collision among the other SUs when they are trying to be transmitted over the CCC, SCA-MAC protocol simply restarts the negotiation process. Nevertheless, this renegotiation exacerbates the CCC saturation problem.

TABLE I: Comparison of MAC protocols for multi-hop cognitive radio networks.

ISSUES +:Addressed -: Not addressed	**DC-MAC** [8]	**DCR-MAC** [5]	**O-MAC** [10]	**HC-MAC** [11]	**C-MAC** [6]	**DOSS-MAC** [13]	**SCA-MAC** [12]
CCC Problem	+	-	-	-	+	-	-
Transceiver Synchronization	+	+	+	+	+	+	+
Conventional Hidden/Exposed Terminal Problem	+	+	-	+	+	+	+
CTS Timeout Problem	-	-	-	-	-	-	-
Undecodable CTS Problem	-	-	-	-	-	+	-
Multichannel Hidden Terminal Problem (MCHTP)	-	+	-	-	+	+	-
Hidden Incumbent Node Problem (HINP)	-	+	-	-	+	-	-
Number of Transceivers	1	Both 1 and 2	2	1	1	3	1
Coordination of Spectrum Sensing and Accessing Decisions	+	-	+	+	+	-	-
Group Communication	-	-	-	-	+	+	-
MAC Layer Authentication	-	-	-	-	-	-	-

IV. OPEN ISSUES

Table I gives a comparison of the MAC protocols investigated in Section III, which address various aspects of the MHCRN specific research challenges aforementioned in Section II. Each protocol discussed is marked as either $(+)$, indicating that the corresponding research issue is addressed or $(-)$, indicating that the issue is not addressed.

MAC Layer Authentication: None of these studies completely solves all the vital aspects related to MHCRN operation. Transceiver synchronization is addressed by all the investigated protocols; however, none of these works addresses the MAC layer authentication problem, which is a challenging issue in the absence of a centralized controller.

Quiet Period Coordination in Spectrum Sensing and Accessing: The nodes in a MHCRN have to discern between the transmissions of PUs and the transmissions of other SUs. To this end, other SUs may be forced to be silent when an SU senses the channel. Coordination of these quiet periods in a distributed manner is a possible research issue. The only work that claims to have addressed this problem is C-MAC [6], where the authors mention that they use the RC for this purpose. Nevertheless, they do not discuss about how this coordination would be implemented using the RC and without the presence of a central entity.

CTS Timeout Problem: Conventional hidden and exposed terminal problems are addressed by most work through IEEE 802.11 like RTS/CTS mechanisms; nevertheless, none of these studies considers the cognitive radio specific fact that no fixed timeout can be applied while expecting the CTS message because of the PU activity. A possible research issue might be to incorporate the predicted channel usage pattern into the calculation of the CTS timeout value. In other words, a method that dynamically changes the CTS timeout value according to the predicted channel usage pattern of that frequency might be considered as a possible research issue. For instance, the work in [12] might serve as a basis and be modified to be incorporated into the CTS timeout value calculation.

Tradeoff Between MCHTP and the Number of Transceivers: MCHTP can be entirely obviated with the usage of a dedicated CCC transceiver. Nevertheless, an additional dedicated transceiver implies hardware implementation complexity. Thus, these two problems are inter-related and there is usually a tradeoff in their design and implementation. Most of the investigated protocols address either the CCC problem or the MCHTP, but not both [5][8][13]. The only protocol that addresses both problems is C-MAC [6]. Although C-MAC avoids the usage of a CCC while combatting the MCHTP, this capability comes at the hardware expense of having a dedicated transceiver tuned to a predetermined rendezvous channel. Since this extra transceiver does not exist in the actual protocol but mentioned by the authors as a possible extension to alleviate the MCHTP, we marked the number of required transceivers for C-MAC as 1 in Table I. Combatting the MCHTP without a dedicated control channel transceiver is a promising research issue.

HINP: HINP is specific to MHCRNs; therefore, there are no other previously proposed protocols in other realms, such as multi-channel networks or IEEE 802.11 MAC, that can be adapted to the MHCRN framework. HINP is also not completely solved by the investigated protocols, although it is partially addressed by the authors in [5] and [6].

Group communication: Group communication has also received little attention. Determining a communication channel for a group of SUs without introducing extra control message overhead is an open and challenging research issue. C-MAC [6] seems to be the only work that addresses the group communication, considering that the multicasting/broadcasting capability of DOSS-MAC [13] constitutes some drawbacks mentioned in Section III.

V. CONCLUSION

To put it in a nutshell, MAC design for MHCRNs carries the challenges of multi-channel networks and multi-hop networks in addition to the complications that stem from the varying spectrum availability of the cognitive radio networks. The major challenging research issues are common control channel (CCC) problem, transceiver synchronization, conventional and MCHTPs, hidden incumbent node problem (HINP), the number of transceivers, coordination of spectrum sensing and accessing decisions, group communication and MAC layer authentication. There is yet no study in the literature that addresses all of these issues concurrently and effectively. Moreover, there is currently no existing standard for MAC design of MHCRNs. Therefore, protocols that handle all of these research challenges are imperative and crucial in actualizing the opportunistic pervasive networking paradigm of multi-hop cognitive radio networks.

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