Smart Computing Review

Cognitive Radio MAC Protocols: A Survey, Research Issues, and Challenges

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Abstract: In cognitive radio networks, methods to allow the efficient sharing of the radio spectrum without causing any harmful interference to the primary users and to solve the spectrum scarcity problem are necessary. Identifying the available spectrum resources through spectrum sensing, coordinating with other users for spectrum access, improving channel utility, reducing collision rates, and improving sensing overhead are the major factors in cognitive radio medium access control protocols. Efficient use of radio spectrum largely depends on accurate spectrum sensing, spectrum sharing, spectrum mobility, and spectrum decisions. Hence, cognitive radio technology can significantly solve the spectrum scarcity problem by exploiting radio spectrum unused by licensed users. However, many technical problems still need to be solved for the proper functioning of cognitive radio networks. The medium access control protocols for cognitive radio networks should provide a comprehensive description of common control channels, spectrum sensing, harmful interference to primary users, variation of the spectrum availability, infrastructure support, the need for time synchronization, and the number of radio transceivers. In this paper, we present an overview of current medium access control protocols. Moreover, the classifications of medium access control protocols with their relative advantages and disadvantages are thoroughly investigated. We also highlight and explore some important research issues and challenges that could drive future research in this area.

Keywords: Cognitive Radio, Medium Access Control, Spectrum Sensing, Spectrum Access

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Introduction

Due to an increase in demand of spectrum for new applications, there has been an increasing interest in designing dynamic spectrum access networks that allow unlicensed users to access a radio spectrum when not in use by licensed users. This technology is called Cognitive Radio (CR). A CR user is allowed to use only unused spectrum opportunistically to prevent any interference or collision with the primary users (PUs) [1]. The CR network refers to a wireless network that is based on CR technology [2]. It is important to consider the control and coordination of communication over wireless channels. Due to the availability of/influx of heterogeneous spectrum, designing a medium access control (MAC) protocol that offers good coordination among secondary users (SUs) is not an easy task. One of the most difficult but important design problems is how the SUs determine when and which channels they should use to transmit/receive SU packets without affecting communication among the primary users (PUs) [3]. This motivates research in CR MAC protocols, which is based on designing an efficient MAC protocol for successful deployment of any CR network. The main goal of CR is to obtain the best available spectrum through cognitive capability and reconfigurability. The MAC protocol should be able to solve the problems of hidden primary users. Most CR MAC protocols use a CCC which facilitates neighbor discovery by sending signals in CR networks. CCCs are also prone to jamming attacks by malicious users. Other important issues to consider for MAC protocols are the design of control channels and sensing delays in optimization. Many MAC protocols have already been proposed for CR networks, but research shows us that none of them work efficiently in a dynamic environment. In this paper, we present research challenges prevalent in current MAC designs and their merits and demerits.

The rest of this paper is organized as follows. Firstly, we present an overview of CR network architectures and characteristics, critical design issues and investigate challenges in CR MAC design. Secondly, detailed classifications of the existing MAC protocols are described. Thirdly, future research directions are illustrated. And finally, we conclude this paper by summarizing the key points of this work.

Literature Review

Cognitive Radio Network Architecture

CR networks can either be centralized or distributed. In a centralized CR network, a central entity controls spectrum allocation and spectrum access, and also gathers information about the radio environment. In distributed CR networks (DCRNs), there is no central unit to gather information about radio environment. A centralized CR network is also known as an infrastructure-based network, whereas a distributed CR network is known as a CR ad-hoc network. In a centralized CR network, functions such as spectrum allocation and spectrum sensing become difficult when the number of CR devices increases. It is also plagued by a maximum number of delays. In DCRNs, CR users or SUs are either fixed or mobile, and spectrum is allocated either cooperatively or non-cooperatively. In cooperative distributed CR networks, CR users share information related to sensing and signaling, so sensing delays are tolerable. Furthermore, in DCRNs, available channels are generally discontinuous and may lie anywhere in the entire spectrum. The availability of these channels may vary with time. Therefore, the SUs must have the capability to cope with a dynamic environment, since the availability of channels for SUs at any time and location depends on PU activity.

Cognitive Radio MAC Design: Issues and Challenges

This section deals with issues related to CR research, challenges to overcome spectrum scarcity, multichannel hidden terminal problem (MHTP), difficulties in common control channel (CCC) design, and CR MAC operation. We need to develop an efficient and robust MAC protocol to provide SUs with the maximum chance to access the unused spectrum, while respecting the PU's priority rights.

Spectrum Sensing and Availability

Spectrum sensing aims to find vacant spectrum options and avoids interference with the PUs. The detection technique that is used to find PUs in CR networks follows three stages: detection of primary transmitter, detection of primary receiver, and maintaining interference temperature. Local observations of CR users are necessary to detect weak signals from a primary transmitter. A primary receiver finds PUs that are receiving data from within the communication range of a CR user [4]. The interference temperature cannot distinguish between actual signals from a PU and noise/interference caused by cumulative radio frequencies let out/transmitted by multiple transmissions. Most of the current research focuses on transmitter detection methods. Three different schemes have been proposed to detect transmitters: matched filter detection, energy detection, and feature detection. Energy detection is the easiest scheme to implement. If the strength of a detected signal is above a certain threshold, it is considered busy. However, energy detection requires coordinated quiet periods to avoid false alarms. As the availability of radio resources is uncertain and depends on a PU network, sensing PU channels becomes necessary. In order to do so, an efficient sensing mechanism should be implemented. Accurate sensing is impossible in practice, but efforts should be made to keep sensing errors to a minimum. An inaccurate result increases the uncertainty of finding available resources. It is important to note that high sensing performance creates more opportunities for SUs to use a licensed spectrum, while longer data transmission time guarantees the efficient use of PU resources by SUs [5].

■ Optimization of Spectrum Sensing Duration and Level of Interference

The primary objectives of the MAC design are minimizing interference on PU and optimizing the duration of channel sensing. Due to the hardware limitations of SU nodes, delays and errors cannot be completely avoided. Implementation of a cooperative sensing scheme may improve sensing performance. In a CR network, the spectrum sensing phase is followed by the data transmission phase. So, careful consideration should be taken when specifying the duration and frequency of the sensing phase in MAC. There are two existing approaches: fine sensing and fast sensing. Fine sensing ensures proper detection of the spectrum, but provides a short duration for data transmission. On the contrary, fast sensing ensures optimal detection of the spectrum, but provides a short time for sensing. There are two important metrics used in spectrum sensing: false alarm probability and detection probability [6].

■ Negotiation Mechanism and Time Synchronization

There must be an efficient mechanism for a transmitter and its intended receiver to select a common available channel for transmission. In distributed CR networks, there is no central authority, which makes it necessary for SUs to go through a channel negotiation process. Many CR MAC protocols use CCC in an initial control message exchange, which is shared by many or all SUs. Some MAC protocols incorporate time synchronization among SUs. Selection of CCC is not easy and may also cause a loss of resources. Therefore, the channel negotiation mechanism should be designed properly. If not, it may be troublesome to manage the proper utilization of resources and overhead time. Without time synchronization, it is difficult to implement channel negotiation. It leads to improper coordination between network establishment and SUs. Therefore, network-wide time synchronization is a major research challenge at present, because of the uncertainty of spectrum availability.

■ Problems in Common Control Channels

Two SUs in a CR network can be connected if they have a common control channel for communication. For example, if Node A wants to transmit to Node B, A and B should negotiate their channel sets and exchange a control message to reserve a channel for communication in a manner outlined in IEEE 802.11 DCF. But a dedicated CCC has several drawbacks. First, a channel dedicated to control signals is a wasteful use of channel resources. Second, a control channel will become saturated as the number of users increase [2]. And finally, an adversary node can cripple the dedicated control channel by intentionally flooding the control channel. This leads to a decrease in the number of channels available to all users. Available channels may vary in the frequency of operation, bandwidth, and transmission range. Due to heterogeneity in the transmission range, a channel with a shorter transmission range may not cover all areas, but a channel with a longer transmission range may cover all the areas.

■Problems in Multichannel Hidden Terminal

Problems in multichannel hidden terminals have been identified in multi-channel networks [2]. A SU equipped with single radio can listen to only one channel at any time, and therefore can miss control messages when its radio is busy transmitting or receiving data. This SU might initiate communication with another SU node in an already allocated channel, resulting in a collision. This is called the MHTP. It can be better addressed in a multi-transceiver MAC protocol. But multiple radios at each SU node make the system more complex and expensive. However, single radio MAC protocols are much cheaper and less complex to implement.

■ Network Coordination and Reconfiguration

Without moderate coordination and reconfiguration among SUs, deciding spectrum and maintaining it is very difficult. A good network coordination and reconfiguration is free from control signal overhead, sensing error, sensing delay, and interference to PU. In addition to the distributed architecture of CR, which is set up without proper network coordination and maintenance, the varying time in the availability of spectrum makes it more difficult to provide support for quality of service (QoS).

■ Energy Efficient MAC Protocol

The CR MAC design approach must address mechanisms that are energy efficient, since most of the devices are battery powered. The number of sensed channels must also be minimized through efficient mechanisms. Lightweight protocols are required for estimation, learning, and decision-making operations[1].

■ Self-interference Problem

The main challenge for active SU's is to detect a PU's presence during the data transmission phase. It is really difficult for active SUs to sense/detect and transmit at the same time and in the same channel. But without undergoing simultaneous sensing/detection and transmission, we cannot predict the presence of PUs. A multi-antenna-based system suffers from the self-interference problem created by both sensing/detection and transmission antennas [25]. Usually, a multi-antenna system suffers from the self-interference problem. That's why different sets of sensing/detection and transmission antennas were needed to avoid self-interference. Hardware implementations and detailed descriptions of antenna isolation are discussed in [25]-[28]. The cancellation of active antennas based on spatial filtering to combat the self-interference problem is proposed in [29]. They show that transmitted power cancels spatially in the direction of detection before reaching the detection antenna. They claim that a wideband isolation level of ~60 dB is obtained through their proposed system. Another method to improve the self-interference problem is proposed in [26].

■ Handling Primary User's Sudden Appearance

During the data transmission phase, SUs should sense the spectrum and vacate the channel upon the detection of the PU. During this phase, one of the main concerns of SUs is to protect PUs from harmful interference. Licensed users should always get priority.

Detailed Classification of MAC Protocols

■ MAC Protocols for CR Networks

In this section, we provide a thorough description of MAC protocols for both centralized and distributed CR networks. To facilitate the discussion, we investigated the characteristic of several existing CR MAC protocols. Depending on central support (base station), CR MAC can be divided into centralized and distributed networks. Each can be further divided into (i) random access, (ii) time slotted, and (iii) hybrid protocols, as shown in Fig. 1. Moreover, the number of radio transceivers has an impact on the operation of the MAC protocols.

■ MAC Protocols for Centralized CR Networks

A central entity such as a base station (BS) is needed for this protocol to manage network activities. Synchronization and coordinating operations among nodes are also managed by the central entity. A thorough information/insight on CR Centralized MAC protocols is given as follows:

- *Random Access Protocol:* Random access protocol is based on CSMA/CA mechanism. A CSMA-based protocol [7] uses a single transceiver, and PUs coexist with CR users. CR users require a longer sensing/detection period than PUs. Therefore, the priority for spectrum access is given to the PUs. CR base stations and users cannot find out if the PUs experience multiple failed transmission attempts. Also, a coding scheme for transmission power and transmission rate of the users are not assigned properly in this protocol.
- *Time slotted protocol:* A time slotted protocol like IEEE 802.22 as mentioned in [8] needs network wide time synchronization, where time is divided into slots for control channels and data transmission. A super frame is defined, which is further divided into a super frame header and a MAC frame. A MAC frame is comprised of an upstream and downstream sub frame. The main disadvantages of this protocol are the exchange of a high volume

of control messages and lower data throughput. It is difficult to maintain time synchronization as well. Back up channels are used to restore communication after PU interference.

- *Hybrid protocol*: Hybrid protocols are basically implemented as a game theoretic dynamic spectrum access [9]. These protocols use control signals over synchronized time slots, and data transmission may have schemes for random channel access. Mechanisms for dynamic spectrum access with clustering, negotiation, and collision avoidance are used in the game theoretic approach. One of the major drawbacks is that negotiation delay increases with the number of players. Difficulty in synchronization and possible collisions among game information packets makes the game theoretic hybrid approach more challenging.

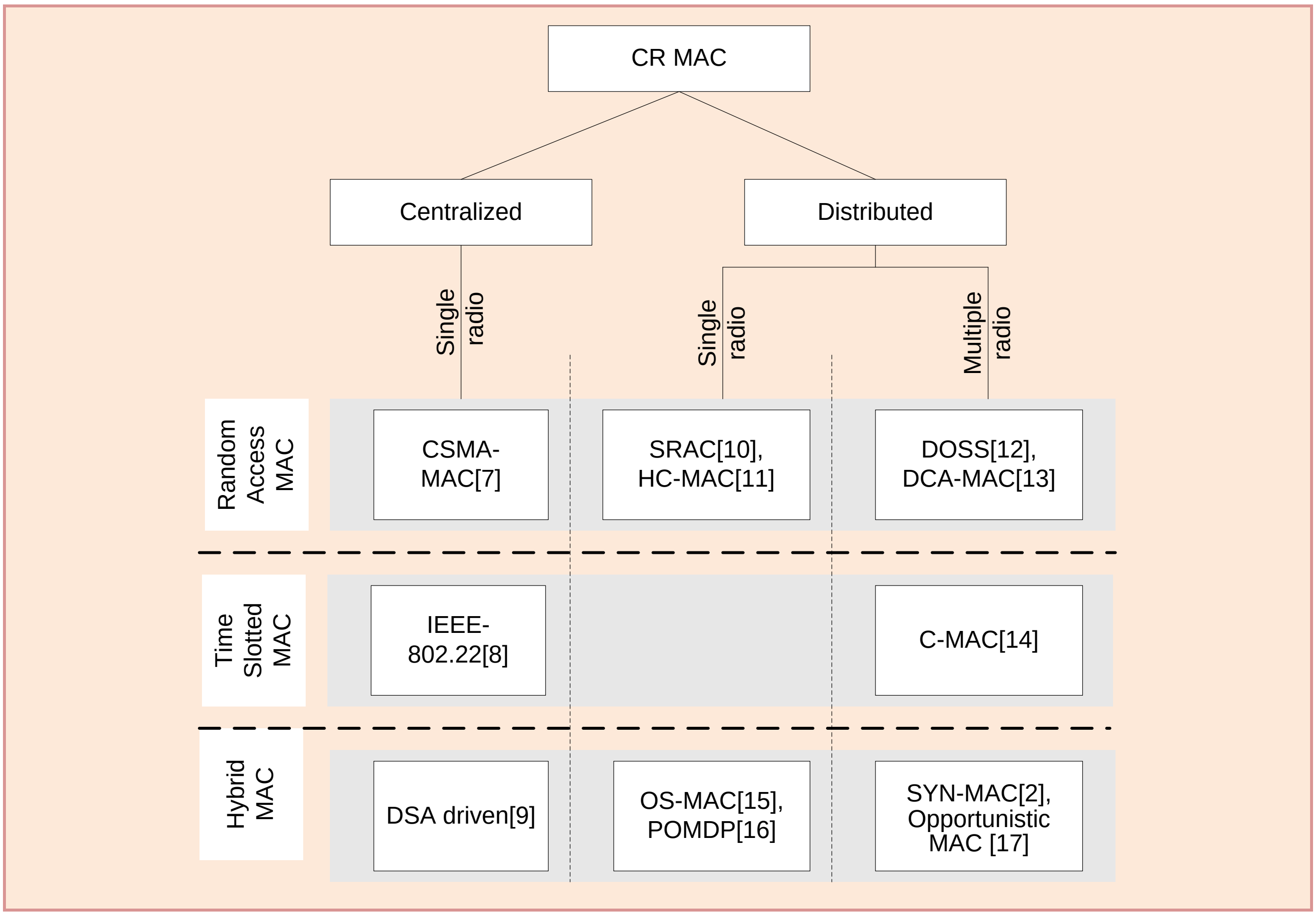

Figure 1. Classifications of CR MAC protocols.

MAC Protocols for Distributed CR Networks

DCRN MAC protocols do not have a central entity such as a base station (BS). Usually most of the distributed MAC protocols are more scalable, efficient, and dynamic in nature than a centralized approach. That is why many researchers now focus on DCRNs. DCRN MAC protocols can be divided into random access, time slotted, and hybrid approaches as shown in Fig. 1. Configuring and maintaining network wide time synchronization, less sensing/detection errors and sensing delays are some of the factors that need to be considered while designing DCRN MAC. We explain the types of DCRNs as follows:

- *Random Access Protocol:* Single-radio adaptive channel (SRAC) MAC [10] protocol based on cross channel communication and dynamic channelization. As a result, signaling overhead is maximized. HC-MAC [11] aims at spectrum access by considering the hardware constraints. Dynamic open spectrum sharing (DOSS) MAC [12] protocol provides an innovative solution to address problems caused by hidden and exposed nodes. In the distributed channel assignment (DCA) [13] based scheme, the use of separate CCC results in CCC saturation.
- Time slotted protocol: C-MAC [14] is one of the time slotted protocols and is based on two key concepts: rendezvous channel and back up channel. A rendezvous channel is used for node coordination. The backup channel

provides a choice of alternate spectrum bands in case of an appearance of a PU. The main advantages of this protocol are inter-channel coordination and load balancing. The major drawbacks of C-MAC are non-instantaneous spectrum switching and low scalability.

- Hybrid protocol: Hybrid protocols like OS MAC [15] use predetermined window periods. It uses a single radio that switches between the data band and CCC. The OS MAC protocol has several drawbacks: there is no consideration of protection of PUs either by adapting transmission or by power control. In [16], a hybrid single radio MAC protocol based on the theory of a partially-observable Markov decision process (POMDP) is proposed. The POMDP is a generalization of the Markov chain process. Multi-radio hybrid protocols such as SYN-MAC and Opportunistic MAC are proposed in [2] and [17], respectively.

The common control channel design also plays an important role in DCRNs. The detailed classifications of the DCRN MAC protocols based on CCC are shown in Fig. 2. Based on a design approach, distributed MAC protocols are divided into single and multi-transceiver groups. Some of the MAC protocols [11, 16, and 18] that work with a single transceiver are more vulnerable to MHTP. Hence, a SU equipped with only a transceiver can miss control messages when it is busy transmitting or receiving data [2]. These problems can be dealt with by using multiple transceivers and keeping one continuously tuned to the control channel. Most CR MAC protocols differ according to the presence or absence of CCC. For the transmission of each data packet, the SU sender and receiver have to agree upon the certain timeslot and channel they will use for their transmission. This coordination is typically implemented with a CCC.

The authors in [19] and [20] divide the CCC schemes into four categories: dedicated control channel (DCC), common hopping, split phase, and multiple rendezvous control channel (MRCC). Among the four in DCC, one SU channel is dedicated solely to the transport/transmission of control messages. The drawback of the DCC approach is that if a PU is active on the CCC, all communications are obstructed. Hopping CCC has the ability to use all the channels for data transmission and sending control signals, whereas in DCC, CCC can only be used to transfer control packets. In split phase CCC, during the control phases, all nodes switch their radio frequency front ends (RFEs) to the dedicated CC and decide channels for data transmission.

The advantage is that CCC can be used during the data phases. No extra RFE for CCC is needed as with DCC, but it needs a stronger synchronization mechanism to identify and control data channels. In MRCC, multiple nodes can exchange control information at the same time while using all the available channels. MRCC seems to be most appropriate for PU activities, but requires more synchronization between hopping users. Single and multiple transceiver MACs are further divided based on the presence or absence of CCC. CCC offers better coordination among SUs and reduces collision during data transmission. The CREAM-MAC protocol as proposed in [3] employs a CCC like rendezvous where the SUs exchange control packets for resource reservation. From the viewpoint of reliability, the control channel is a very crucial design element of the MAC design, since no data communication is possible when it is obstructed. Some MAC protocols (OSA-MAC, C-MAC, and HC-MAC) work well with a dedicated CC. But dedicated CC has several drawbacks like a waste of spectrum and vulnerability to jamming attacks by malicious users. POMDP has a higher reconfiguration overhead and does not have a CCC.

To avoid these problems, some MAC protocols (POMDP, SYN-MAC) that work without a CCC but use PU data channels are proposed. In POMDP, a sender continuously visits the channels where the intended receiver is expected to be tuned at a higher probability. The SYN-MAC protocol proposed in [2] does not need a CCC, but has a dedicated radio to track the channel for control messages. Here, time is divided into a number of slots, and each time slot is dedicated to one channel to control the signal exchange.

Furthermore, time synchronization among SUs is another design issue to be considered for a single transceiver MAC, designed with a CCC (HC-MAC, OSA-MAC). The duration of control signaling and the data transmission schedule are made known to CR users through local or global time synchronization. Global time synchronization is usually network wide, whereas local time synchronization is limited to neighboring nodes. In global time synchronization, all SUs in the network have the knowledge of sensing, negotiation, and data transmission period. Also duration of sensing is independent of any transmission from SUs. Some MAC protocols like HC-MAC have considered the possibility of problems arising due to an exposed terminal, while working with local time synchronization. Hence, good network coordination is not possible with local CCCs. But it is easier to reconfigure a local CCC than a global one. Globally available CCC is not yet possible in dynamic CR environments. Hence, the effect of CCC protocols can be compromised, or there will be less denial of service (DoS) attacks in local CCC than in global CCC. The level of interference to PUs is an important issue to be considered while designing a MAC. It has not been considered in most existing protocols except OSA-MAC, OP-MAC [21]. CogMesh [22] can achieve better coordination with dynamic local CCC. Only few MAC proposals such as [1] have considered the energy efficiency issue.

Statistical MAC [23] is a CSMA/CA based protocol that exploits statistics of spectrum usage for decision making for accessing channels. HC-MAC performs channel detection before selecting the channel and also considers/studies the hardware limitations of practical SU nodes. In the novel MAC scheme designed for multichannel cognitive radio ad-hoc networks [24], time allotted for detecting channel is not regularly arranged on a channel time. Whenever the secondary node data transceiver is not used for data transmission/reception, a CR node selects the idle channel with the highest sensing/detection capability and carries on detection for the selected channel independent of other nodes.

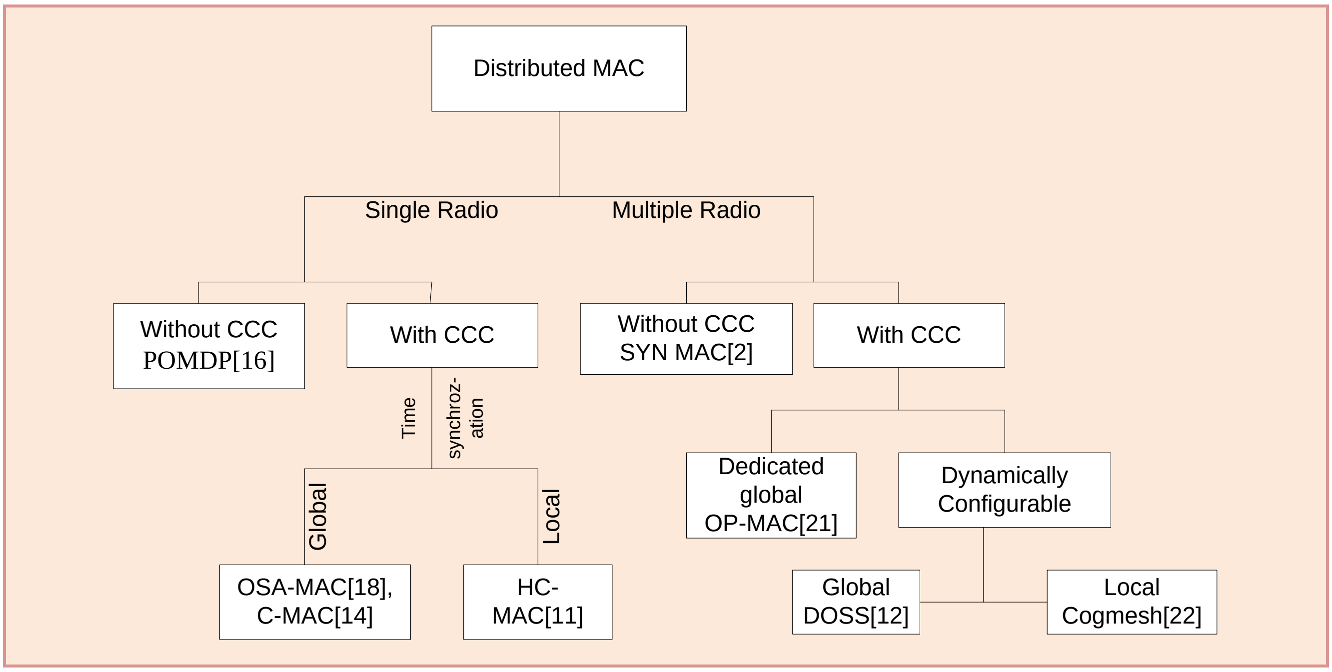

Figure 2. Detailed classifications of distributed MAC protocols considering CCC.

Comparison Details

■ Distinguishing Features of the MAC Protocols

The distinguishing characteristics of different existing MAC protocols, both centralized and distributed, are tabulated in Tables 1, 2, and 3. In Table 1, the CR network model type, presence/absence of control channel, number of radio transceivers, and spectrum access techniques are listed for different types of MAC protocols.

In Table 2, we show the comparison of different MAC protocols by considering different characteristics such as energy efficiency, awareness of sensing errors, existence of backup channels, and QoS provisioning. The MHTP, network coordination and configuration overhead, sensing error, time synchronization and interference to PUs are listed in Table 3 for different types of MAC protocols.

Table 1. Classification of existing MAC characteristics.

Proposal	Network Model	Control channel and no. of radio	Spectrum access
SYN-MAC[2]	ad hoc	no, 2	hybrid
CSMA-MAC[7]	infrastructure	no, 1	random
HC-MAC[11]	ad hoc	yes, 1	random
DOSS[12]	ad hoc	yes, 3	random
DCA-MAC[13]	ad hoc	yes, 2	random
C-MAC[14]	ad hoc	no, multiple	time slotted
POMDP[16]	ad hoc	no, 1	hybrid
OSA-MAC[18]	any	yes, 1	time slotted

Table 2. Optimizations of MAC proposals.

Proposal	Energy efficiency	Sensing error aware	Backup channel	QoS provisioning
ECRQ-MAC [1]	yes	no	no	yes
SYN-MAC[2]	no	no	no	no
DSA-MAC**[9]**	no	no	no	yes
SRAC**[10]**	no	no	no	yes
HC-MAC**[11]**	no	yes	no	no
DOSS[12**]**	no	no	no	yes
DCA-MAC**[13]**	no	yes	no	yes
C-MAC**[14]**	yes	no	no	yes
POMDP[16]	no	no	no	no
OSA- MAC**[18]**	no	yes	no	yes

Table 3. Comparison of existing MAC characteristics.

Proposal	MHTP	Network coordination, reconfiguration overhead	Sensing error	Time synchronization	Interference to PUs
ECRQ-MAC **[1]**	addressed	high, high	addressed	addressed	not addressed
SYN-MAC**[2]**	addressed	high, moderate	not addressed	global	not addressed
SRAC**[10]**	not addressed	high, high	addressed	not addressed	not addressed
HC-MAC**[11]**	not addressed	local, low	not addressed	local	not addressed
DOSS**[12]**	addressed	dynamic(global),moderate	not addressed	global	not addressed
POMDP **[16]**	addressed	not required, high	addressed	global	addressed
OSA-MAC**[**18**]**	addressed	dedicated(global),low	addressed	global	addressed
OP-MAC**[21]**	addressed	dynamic, low	not addressed	addressed	not addressed
Cog**M**esh**[22]**	Not addressed	dynamic, moderate	not addressed	global	not addressed

Recent Trends

Distributed cognitive radio (DCRN) MAC protocols don't have a central entity, for example, a base station (BS). Usually a large portion of the disseminated MAC protocols are more adaptable and effective in dynamic mode than in centralized approach. That is the reason why numerous specialists at present concentrate on DCRNs. DCRN MAC protocols can be divided into time division multiple access (TDMA) based MAC protocols [1], [18], [14] and contention based MAC protocols [12]. Since DCRN doesn't have any local facilitator, TDMA based MAC protocols are not effective enough for DCRN since it requires a contention based MAC protocol. CCC is another significant issue due to vulnerabilities caused by PU movement. Some MAC protocols are proposed with a CCC (e.g. [18], [14], and [11]) and some without a CCC [2], [16]. Only dedicated CCC can ensure global time synchronization [30]. Some MAC protocols work with channel hopping which is based on CCC [30]. A major problem in multichannel hidden terminal occurs when some MAC protocols proposed with single transceiver [18] may miss control signals when they are busy. However, using multiple transceivers may reduce the problem. Using multiple transceivers is not a cost effective solution either. In [11], HC-MAC protocol is proposed which is a single transceiver MAC and it is shown to suffer with spectrum wastage problem. Because of practical limitations SU's have to wait even when more accessible channels exist. In [18], the OSA-MAC is proposed which can attain better coordination among SU's within the vicinity of dedicated CCC. They propose channel selection before channel sensing. This inaccurate selection may be the reason behind the spectrum wastage problems of OSA-MAC. SWITCH [31] is a multichannel MAC protocol that uses unlicensed channel as a backup channel to adapt with the sudden appearance of the PUs in data channel. In [32], a proactive spectrum handoff framework (ProSpect) in a CR ad hoc network scenario is proposed. In [33], a fair MAC protocol (FMAC) is proposed to ensure fair and efficient coexistence of CR networks. However, FMAC [33] is designed for centralized network only and does not provide any details on monitoring of primary user appearance during the data transmission phase. In [34], a channel switching mechanism between the data and backup channels (PCR-MAC) has been proposed using historical usage of the channels for channel selection. SWITCH [31] and opportunistic spectrum access [35] may be prone to self-interference problem [25] caused by simultaneous sensing and transmission strategy. In order to overcome self-interference problem, several research works have been done [25-29]. Antenna isolation and self-interference cancellation system is proposed in [25] to combat problems due to self interference. Both sensing and transmission antennas should be mutually exclusive with echo interference cancellation by suppression which can defend up to 70-115 dB [25]. To enable simultaneous sensing and transmission, they proposed a self-interference cancellation capability of up to 70-115 dB at which self-interference signal can be eradicated satisfactorily. They have claimed that their suggested approach can suppress self-interference signal up to 90 dB. It is better to note that a radio with transmit power of 0 dBm and noise of -90 dBm needs to offset almost 95 dB of self-interference.

Future Research Directions

Most of the proposed solutions do not cover major issues related to CR dynamic environment. Therefore, some research proposals are first suggested in the context of MAC protocol entity. More research in future is required to search for accurate sensing schemes. Although the hardware limitations of CR users is a critical issue on spectrum sensing. So, more efficient and robust alternatives must be investigated in terms of CCC design. Clear assignments to deal with transmit power, coding scheme, transmission rate to the CR users must be devised. MAC Design focusing on energy introduces new challenges in CR MAC design research. QoS provisioning for SUs in a wireless network is not possible without necessary support from the MAC protocol. Further research may include QoS for SUs in the context of dynamic resource availability. However, ensuring a reliable network coordination and reconfiguration mechanism is another major issue that must be addressed efficiently. There are various cooperative sensing schemes to fuse the sensing information of SUs. Hence, when maximizing the throughput of the CR networks, we should consider optimizing the sensing time as well as the parameters of the fusion scheme. Majority of the current research has focused on improving the throughput of CR networks. Here, we list some important design issues that are necessary to be addressed in distributed CR MAC design.

- Improve time synchronization and network coordination for SUs without dedicated CCC.
- Performance comparison of both instantaneous and average false alarms and detection probability for detecting primary appearance during data transmission phase would be a good topic for future research.
- Overall overhead analysis after taking into consideration the number of transceivers.
- A need to develop more practical PU activity models by considering the characteristics of access technologies as well as types of traffic. Intelligent spectrum sharing, sensing, and power allocation policy may improve QoS in CR networks.

Conclusion

The main objective of this survey is to provide researchers with a global vision of CR MAC protocols. We believe that further modifications are required in devising an efficient MAC protocol. We have identified a lot of merits and demerits of the existing MAC protocols. We have analyzed their comparative characteristics and pointed out crucial design issues in CR networks. In summary, the field of research on CR MAC design is quite broad. This article attempts to briefly explore the CR MAC design issues and researches challenges. However, to ensure an efficient design of CR MAC, more research is needed along the lines introduced in this survey.

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