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MAC Layer strategies in Cognitive Radio Networks DSA protocols for cognitive networks

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Abstract: *the main objective of the cognitive radio is to obtain the best available spectrum through cognitive capability and reconfigurable ability. the key component of dynamic spectrum access in Cognitive radio network is dynamic spectrum sharing, which is responsible for providing efficient and fair spectrum allocation or scheduling solutions among primary and secondary users. Spectrum sharing was generally regarded as similar to generic medium access control (MAC) problems in existing wireless systems. The function of MAC is to coordinate the access among the competing nodes in an orderly and efficient manner to maximize throughput, guarantee an acceptable delay and fair access which consider as a big challenge in CR networks with a dynamic environment. The purpose of this paper is to provide the essential concepts and background related to MAC layer for Cognitive Radio networks, classification of cognitive MAC protocols, advantages, drawbacks and design challenges of cognitive MAC protocols.*

Keywords: *Keywords: Cognitive Radio; Dynamic Spectrum Access; medium access control;*

I. Introduction

Wireless communications growth has contributed to a huge demand on the deployment of new wireless services in both the licensed and unlicensed frequency spectrum. Hence, we have been facing a critical spectrum shortage problem even though several measurements have indicated that most licensed radio spectrum is very underutilized. Cognitive radio (CR) or Dynamic Spectrum Access (DSA) for next generation network (xG) has emerged as a promising technology to enable the access of the intermittent periods of unoccupied frequency bands, called white space or spectrum holes, and thereby increases the spectral efficiency. Ian F. Akyildiz et al. [1] defines cognitive radio as: "The radio that can change its transmitter parameters based on interaction with the environment in which it operates". The fundamental task of each CR user in CR networks is to determine which portions of the spectrum are available and detect the presence of licensed users (spectrum sensing), Select the best available channel (spectrum management), Coordinate access to channel with other users (spectrum sharing), Vacate the channel when a licensed user is detected (spectrum mobility). 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). Designing an efficient MAC protocol for successful deployment of CR network motivates research in CR MAC protocols. 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 in current MAC designs and their merits and demerits. DSA protocols can be classified according to different criteria, such as spectrum sharing modes, spectrum allocation behaviors, spectrum access modes, the usage of common number of radios, spectrum usage strategies, spectrum sensing techniques, etc so detailed classifications of the existing MAC protocols are described.

The rest of this paper is organized as follows. Firstly, we present an overview of spectrum sharing concepts in CR network, then presenting cognitive radio MAC layer role and address the challenges and requirements in CR MAC design. Secondly, classifications of the existing MAC protocols are described. Finally, future research directions are illustrated.

II. Cognive Radio MAC Functions

In the seven-layer OSI model of computer networking, (MAC) data communication protocol is a sub layer of the data link layer. It provides addressing and channel access control mechanisms that make it possible for several terminals or network nodes to communicate within a multiple access network that incorporates a shared medium. The hardware that implements the MAC is referred to as a medium access controller. It is also capable of providing security (data encryption, message authentication, and replay attack protection), hibernation, aggregation and fragmentation, retransmission management (through a variety of acknowledgment policies), mobility management (through beacon management), fair reservation management, and ranging. Obviously, provide such capabilities in a robust fashion require a sophisticated MAC protocol. To coexist with primary networks CR networks equip their CR users with dynamic spectrum access five main functions: Spectrum sensing, Spectrum sharing, Spectrum allocation, Spectrum access, and Spectrum mobility. The whole five functions will be investigated with their challenges, design issues and the MAC protocols classifications that based on each one.

III. CR MAC Design Requirements

Based on the close coupling with the physical layer and the hardware support on the device the CR MAC protocols are differentiated from their classical MAC schemes [7]. During past years, a large number of distributed Dynamic Spectrum Access (DSA) protocols for CR are investigated, but an efficient DSA protocol for Cognitive wireless networks (CWNs) should support the following four functions:

- *Transparency for PUs*: The essential of CR is that SUs should be transparent to PUs.
- *Collision avoidance*: the DSA protocols need to avoid the collisions between SUs and Pus and also collisions among different SUs through coordinating their spectrum access; this can be implemented by applying accurate spectrum sensing or imposing the stringent interference power constraints [5].
- *Accurate spectrum sensing*: The accuracy of spectrum sensing will significantly affect the performance of CWNs. some novel mechanisms, such as cooperative spectrum sensing, are desirable since the local spectrum sensing is often unreliable due to the impact of path loss, channel fading, shadowing, noise uncertainty [6].
- *Efficient dynamic spectrum allocation*: the average network throughput can be increased, the fairness can be improved and collisions among different SUs can be reduced if spectrum resources are efficiently allocated.

The cognitive radio MAC protocols suffering from serious performance degradation that might be caused by certain problems such as multichannel hidden terminal problem, sensing error, selection of common control channel, sensing delay, interference with PUs and network coordination problem.

IV. Spectrum Sensing

The sensing scheduler at the MAC layer can determine the sensing and transmission times based on the radio frequency (RF) stimuli from the physical layer environment. The spectrum sensing block plays a crucial role, both in terms of channel characterization and availability at the time of actual data transmission. Both PHY and MAC layers cooperate with each other to enhance spectrum efficiency by adaptively adjusting the data rate, transmission power, modulation level, spectrum usage and slot scheduling. Apart from that, MAC layer also receives information from the Application layer (APP). Based on all these information, MAC will optimize and decide the best action to suit requirements set by the APP layer and also varying channel conditions. Reconfiguration will be done by the adaptation module at the PHY layer Fig.1. In CR based networks the MAC layer protocols must have the ability to utilize the information from the physical layer to assign the resources for radio nodes. Available reconfigurable parameters can be determined through cognitive process. These parameters allow CR to change setting for physical and MAC layer according to requirements [4].

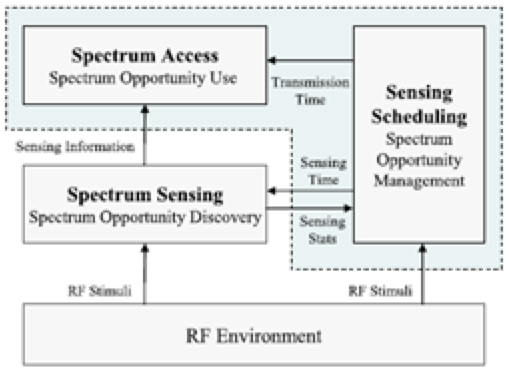

Fig 1. Spectrum functions at the CR MAC.

A. Classification of MAC protocols based on Spectrum sensing technique

The accurate sensing in dynamic spectrum sharing techniques classified into; local and cooperative spectrum sensing.

- *Local spectrum sensing*: only local sensing results are used to exploit available spectrum opportunities. These protocols design are simpler than the cooperative spectrum sensing based protocols. However, it has drawbacks: results may be incorrect due to the impacts of channel fading, shadowing, path loss, etc. also it will consume large amount of time to collect the whole spectrum information only based on the local spectrum sensing.
- *Cooperative spectrum*: sensing multiple SUs need to share their local sensing results causing much more complexity than the local spectrum sensing based protocol, but efficiently solve the above two problems. These protocols used either to improve the accuracy of the local sensing results or to collect the whole spectrum information. How different SUs exchange their spectrum sensing results, and how many SUs should be involved for cooperative sensing also a tight synchronization between CR users is required so that all CR users keep quiet and sense the target channel at the same time. In [38] the authors propose a multi channel MAC protocol for CR ad-hoc network in which a dedicated control channel is used IEEE 802.11 time synchronization function [42].

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. The primary transmitter detection is based on the detection of the weak signal from a primary transmitter through the local observations of CR users .The Primary receiver detection aims at finding the PUs that are receiving data within the communication range of a CR user. The local oscillator leakage power emitted by the radio frequency front-end of the primary receiver is exploited, which is only feasible in the detection of the TV receivers. 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 [7]. Current research mainly focused on primary transmitter detection. 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. There are two important metrics used in spectrum sensing: false alarm probability and detection probability [8]. Also 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 [9].

B. spectrum sencing design Challenges

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. Clearly, spectrum sensing will consumes a certain amount of time, which decreases data transmission time. If the spectrum-sensing time is too long, the network throughput of CWNs will be severely degraded. In addition to providing sensing coordination support at the MAC layer, the challenges that should investigated are: how long the optimal sensing and transmission durations must be, and the order in which the spectrum bangs must be searched to minimize the time for finding the available spectrum. Sensing performance is limited by hardware and physical constraints of SU nodes so delays and errors cannot be completely avoided for example, with CR terminals that equipped with multiple radio sensing process can be conducted in parallel with the data transmission process. The problem in that case is how to schedule the sensing time so that as many sensing channels are sensed as possible. On the other hand CR user that equipped with only single radio, spectrum sensing and spectrum access process should be implemented alternately. The MAC layer must provide an optimal schedule so that the sensing time and spectrum access time are balanced. 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.

V. Spectrum Sharing in Cognitive radio

Spectrum sharing is mainly located in the MAC layer and is used to schedule spectrum assignment among secondary users. Spectrum sharing involves with spectrum allocation, spectrum access and spectrum mobility (switch from one spectrum to another). Spectrum sharing plays a key role in DSA, since its design greatly affects the performance of CR networks. The dynamic spectrum sharing process consists of five major steps: spectrum access, spectrum allocation, transmitter-receiver handshake and spectrum mobility.

A. ***Spectrum access***

Access should be coordinated in order to prevent multiple users colliding in overlapping portions.

- *Spectrum Access Mode Based Classification*
  - *Contention-based*: spectrum access is usually implemented by carrier sense multiple access with collision avoidance (CSMA/CA) mechanism, which is similar as the mechanism in IEEE 802.11.
  - *Time Slotted*: a unique slot is assigned for each second user (SU), thus interference free transmissions are available for SUs.
  - *Hybrid protocols*: aim to derive the tradeoff between the contention- based protocols and slotted protocols. In each slot, SUs compete for the spectrum according to the contention-based protocols. Table 1 shows the characteristic of the three types.

Table 1 Spectrum accsess mode based classification

	Contention based	**Time slotted**	**Hybrid**
Mechanism	(CSMA/CA) mechanism, which is similar as in IEEE 802.11 DCF standard	A unique slot is assigned for each SU, thus interference-free transmissions are available for SUs	In each slot, SUs compete for the spectrum according to the CSMA protocols.
Architectures	Have the simplest architectures	The most complex, due to synchronization mechanism and slot allocation strategy	The complexity is lower than that of the slotted protocols.
Network Performance	The lowest due to the packet collisions and inefficient spectrum competitions	Achieve the best network performance compared with the contention-based and hybrid protocols	performance of hybrid protocols usually outperforms that of the contention-based protocols

- ***Challenges in spectrum access***

a) Distributed collision avoidance mechanism.

The collision avoidance mechanism is used to reduce the collisions among different users among SUs and PUs through spectrum access scheduling, channel allocation, and power control. The collision avoidance mechanism is more complex in distributed CWNs. In CR network where the priority for using channel belongs to PUs and there are some hidden/exposed terminal problems the (CSMA/CA) mechanism is not enough. Therefore, the distributed collision avoidance mechanism is worth for further studying.

b) Time synchronization

Network- wide time synchronization can be obtained usually through synchronization signaling on the control channel. Since there is a difficulty of allocating a common CC in CR network, time synchronization is a critical issue in a time slot-based spectrum access protocol.

c) Multi-flow for distributed MAC Protocol.

CR MAC design needs a huge amount of control signaling in distributed CR network to deal with the multiple data flows in the network in the same time. Therefore CR MAC requires an effective CC management mechanism.

B. Spectrum allocation

Allocation depends on spectrum availability and determined based on internal (and possibly external) policies.

- *Spectrum Allocation Behavior Based Classification*

  DSA protocols can be divided into two categories, which are Cooperative and Non-cooperative as.
  - *Cooperative approach* aims to maximize the whole network performance through the cooperation among SUs. Although cooperative approach need to solve complex optimization problems, the performance of the cooperation is usually better than non-cooperation [40].
  - *Non-cooperative approach aims to optimize their own* performance independently through their local observations and decisions, moreover it has simple architectures and low computation complexity [31,38].

- ***spectrum access scheduling and channel allocation design challenges***

a) Channel negotiation.

It is necessary for the SUs to undergo a channel negotiation mechanism among themselves to select common available channels before transmission [21]. Therefore, a MAC design must incorporate an efficient negotiation mechanism for the proper coordination among the SUs. Inefficient mechanism could consume significant amount of resources itself due to messaging and time overhead. How to design a channel negotiation mechanism in the MAC protocol so that resources available for data transmission are minimally affected, remains a critical issue for CRNs.

b) Cooperative channel allocation.

As mentioned above a center will perform channel allocation for CR user. The critical issue is to maximize the total network throughput and balancing fairness channel allocation that guarantee the QoS for each CR user under the limits of hardware, power consumption and primary user protection level.

C. Spectrum Sharing Mode

DSA protocols can be classified into three categories, spectrum *overlay* and spectrum *underlay*.

1) In *overlay* protocols; **Error! Reference source not found.** SUs can only access the spectrum that is not currently occupied by PUs so its Interference avoidance which causes that spectrum sensing is especially important also SUs cannot transmit their data packets all the time because spectrum sensing will be performed periodically, which will degrade the network throughput in some degree

2) In the *underlay protocols,* SUs are Access part of spectrum when there are *PUs (interference)* transmitting at very low power to ensure that the interference temperature of the primary user does not exceed a predefined limit so the protocols do not perform spectrum sensing thus Increase band width and has very low SNR (Signal to Noise Ratio). [45, 46] shows that this model is suitable for the scenario that the spectrum usage status of PUs changes quickly.

3) *Interweave protocols*: Uses opportunistic spectrum access technique. Secondary user utilizes available spectrum holes thus avoiding simultaneous transmission. To identify spectral holes, SUs must employ a suitable spectrum sensing strategy. Upon correctly discovering spectrum holes on the licensed spectrum, SUs can transmit at high power levels without subject to the interference constraints at SUs as in the underlay spectrum sharing paradigm. For the case where the SUs can synchronize their transmissions with PUs' idle time intervals and perfect sensing can be achieved, SUs will not create any interference to active PUs. However, half-duplex SUs cannot sense the spectrum and transmit simultaneously; therefore, SUs could not detect the event in which a PU changes its status from idle to active during their transmissions. Consequently, SUs employing half-duplex radios may cause interference to active Pus.

Both underlay and overlay techniques allow simultaneous transmission of primary and secondary users, overlay paradigm requires codebook and message information while underlay paradigm require interference information at primary receiver to adjust its transmission power. Interweaver paradigm avoids simultaneous transmission and uses opportunistic spectrum access method [3]. In comparison with the underlay and overlay paradigms, the interweave approach requires to acquire less information about the PUs and it can also utilize the spectrum more efficiently since there is no transmit power constraint. Moreover, PUs are not required to change or adapt their communication strategies or parameters to realize the spectrum sharing with SUs. Inspired by these advantages, many researchers focus on the MAC protocol design issues for interweave spectrum sharing paradigm.

D. Spectrum mobility or Handoff

If a licensed user requires the portion of the spectrum in use the communication needs to be continued in another vacant portion. Mobility of SUs may result changes of available spectrum sources, thus CR protocols cannot perform efficient resource allocation and access coordination. 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.

VI. CR MAC Design Infrastructure

Designing MAC protocol in CR networks is strongly affected by infrastructure of the network such as network architecture, the number of radio on each CR user and the transmission model, and control channel management.

A. Common Control Channel

Using CCC is an effective method to guarantee the reliable control information exchanges in CR networks. Users share a dedicated channel to exchange signaling information, sensing outcome, and perform channel selection. This scheme does not require time synchronization, hence, in order to avoid that network nodes miss control messages, a dedicated transceiver should be tuned on the common channel. There are three possible approaches for managing control information: out-of-band CC, in-band CC and underlay CC.

Out-of-band control channel: (dedicated channel) *CC* is separated from data channels and exchange only control information [43,48]. This can efficiently simplify the protocol architectures. But dedicated channel may suffer from saturation problem and be vulnerable to attack by hackers. The CCC can be implemented by two approaches, licensed CCC and unlicensed CCC [14]. In the licensed CCC approach a dedicated CCC is assumed to exist to control and exchanged packets without interference from other systems. However, such licensed CCC may not exist in practical CWNs due to the spectrum allocation policy. Determining which channel is used as the CCC in distributed CWNs is more difficult due to the time-varying spectrum resources and the absence of central controller[13, 19]. In unlicensed CCC [47] CR network users select available unlicensed channel for CC. However, it may not be fixed because the available spectrum resources of different SUs may be totally different [10, 12]. This efficiently solves CCC channel problems but usually have more complex architecture.. There are two approaches to manage out-of-band control channel:

1) *Split phase-based CC:* CR users use rendezvous channel to exchange signaling during beacon periods of a super frame which include data transmission periods and beacon periods. This method causes waste of spectrum utilization and need strict synchronization.
2) Common CC: control message can be exchanged in a dedicated CC along with data channel. More than one radio needs to be equipped to observe the CC.

- *In-band Control Channel*: Transmission data and control messages are in the same channel. This type of signaling is suitable for distributed ad-hoc CR network. Control packets can be transmitted separately on different channels, such as the hopping based CC [11, 12].CC has several drawbacks like a waste of spectrum and vulnerability to jamming attacks by malicious also a control channel will become saturated as the number of users increase, this leads to a decrease in the number of channels available to all users.
- *Underlay Control channel*: Control messages are transmitted in low power over a large bandwidth so that it's appear as noise to the primary user. Comparing to the previous approaches this model is more reliable, but it require complicated power control algorithm and specific hardware for spread spectrum communication.

B. Number of radios based classification

Based on the number of radios for each SU, the DSA protocols can be divided into:

- *Single radio based protocols*: only one radio is equipped for each SU. [14, 50, 10].
- *Multi-radios based protocols: at least two radios are needed* for each SU.[11, 13, 14, 19].

Compared with the single radio based protocols, the multi-radios based protocols usually allow the SUs to listening to the control packets exchanges all the time, thus reducing the packet collisions. Moreover, multiple channels can be used simultaneously if multiple data radios are equipped. However, generally speaking, the multi-radios based protocols have higher cost than the single radio based protocols. Although the single radio based protocols have lower cost and power consumption, how to schedule the radio to listen to control packets exchanges and to transmit data packets is a challenging task. In addition, the single radio based protocols are often suffered from the multi-channel hidden terminal problem.

C. Transmission Channels

The number of spectrum channel that are used for transmitting data is an important factor that a ffects the communication techniques. Existing DSA protocols can be divided into two categories:

1) Single channel based: each source-destination pair can only use one channel for their data transmissions. Although it has lower date rate but , a low requirement for spectrum recourses results in a longer connection for CR SUs and low cost.[11,13,19,35,38,40,43,47].
2) Multi-channel based protocols: allow the source and destination nodes to utilize multiple channels simultaneously so it need to design more complex mechanisms to guarantee the fairness of protocols and efficiently allocate spectrum and transmit power. However, this mechanism higher cost than the single-channel based protocols because more radios are needed. The multi-channel based protocols can be further divided into two sub-categories, *hardware-based* and *software-based protocols*. In the hardware-based protocols [20], multiple data radios are equipped for one SU with each radio operating on one channel. On the contrary, the software-based protocols only need one data radio per SU based on the channel aggregation technique [14, 16, 37, 49].

- *Problems in Multichannel Hidden and exposedTerminal*

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. Some protocols solved the MHTP by using a control radio to operate on the CCC [13,14,15], but additional costs will be caused. Another protocol CREAM-MAC [16] only allows the SU, which just finished the data transmission, can only reserve the same channels that are used during the last transmission within a pre-defined interval. In this way, although only one radio is equipped for each SU, the multi-channel hidden terminal problem can be solved. Moreover, the multi-channel hidden terminal problem is not well solved in the distributed CWNs without using the dedicated CCC [17,18].In DCR-MAC protocol[19], the neighbor nodes of the source and destination nodes will notify the source and destination nodes whether the channels selected by them is occupied by PUs while receiving the RTS and the CTS packets. This mechanism can solve the hidden PU problem. However, the throughput and delay will be degraded due to the additional control information exchanges.

In the distributed CWNs, multi-channel exposed terminal problem [15] is that, when one sending node discovers its neighbor nodes are sending data packets in some data channels through carrier sense, the sending node will give up choosing those channels for transmission. Obviously, the available channels for the sending node are remarkably reduced. Therefore, the network throughput will be seriously degraded.

D. Power control mechanism

The power control mechanism is a critically important component for the spectrum access protocols. Designing efficient power control mechanism can reduce the mutual interferences among neighbor nodes; it can improve the spatial reuse efficiency and significantly increase the network throughput. Moreover, it can also help users save energy, which is very important to the system with limited energy 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.

Compared with the centralized networks, the power control mechanism for distributed CWNs will be implemented through a completely distributed manner, which makes the interference coordination among multiple SUs more difficult [15,20]. Moreover the transmit power of the SU will also impact the occurrence of the available spectrum opportunity, [15] Therefore, the power control mechanism is a challenge for distributed DSA protocols.

E. Network Architecture

Network architecture assumptions have major influence on the design of CR MAC protocols. There are two categories of CR Network architecture:

a) *Centralized spectrum sharing:* In a centralized CR network (known as an infrastructure-based network), a central entity controls spectrum allocation and spectrum access, and also gathers information about the radio environment. Centralized approaches simplify the design of spectrum sharing but 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.

b) *Distributed spectrum sharing*:

In distributed CR networks (DCRNs)(known as a CR ad-hoc network), there is no central unit to gather information about radio environment each node is responsible for the spectrum. Distributed, cooperative spectrum sharing that uses common control channel (CCC) does not require any infrastructure and is more scalable compared to centralized spectrum. Distributed MAC protocols without CCC needs to be modified to support control traffic information exchange within and between groups, neighbor discovery takes longer time compared to approaches with CCC, since SUs periodically broadcast beacons rotating through all available channels and do spectrum scanning to obtain spectrum availability information about their neighbors. Also, spectrum sharing overhead is higher compared to the ones with CCC and multiple radio interfaces due to selection of within-group control channels and group maintenance.

VII. MAC layer Standards

A. IEEE standards

The first worldwide air interface based on CR techniques is IEEE 802.22 for the wireless regional area network (WRAN) [22,23]. The 802.22 standard not only specifies the PHY and MAC protocols, but also includes many cognitive functions, such as spectrum management, sensing interface, geo-location and database access. This standard aims to provide broadband wireless access in the TVWS and the data transmission is designed to be 1.5 Mb/s for the downlink and 384 kb/s for the uplink.802.16h is IEEE standard which specify improved mechanisms, as policies and MAC enhancements, to enable coexistence among license-exempt systems based on IEEE Standard 802.16 and to facilitate the coexistence of such systems with primary users.802.22 is mostly targeted at rural and remote areas, its coverage range is considerably larger than 802.16 to allow for a good business case, and this is why 802.22 is the first standard ever for WRANs. Also, 802.16 does not include incumbent protection techniques necessary to operate in licensed bands, while it has an ongoing project (802.16h) currently concentrating on coexistence among 802.16 systems only.

Another CR standard that allows personal/portable devices to dynamically access the TVWS is the IEEE 802.11 AF standard [24]. Because the spectrum bands licensed to TVWS have better propagation characteristics than the ISM bands, this standard is expected to provide higher data transmission rate than current IEEE 802.11 standards. In the IEEE 802.11 AF standard, the access point (AP) is embedded with CR function and can dynamically obtain the available spectrum bands in the TVWS according to the specific spectrum trading schemes. Besides the IEEE 802.22, Ecma 392, and IEEE 802.11 AF standards, some new CR standards are exploiting, see table 7.

- ***Other Institutions***

Several other institutions are also currently pursuing cognitive radio research including Ecma 392, E2R, Virginia Tech, Winlab, and BWRC. E2R is a European initiative into supporting End-to-End re-configurability with numerous participating European universities and companies. E2R is focused primarily on incorporating dynamically radio resource management schemes into existing cellular structures to achieve advanced end- user services with efficient utilization of spectrum, equipment and radio resources on multi-standard platforms. Ecma 392 standard is the first CR standard which aims to develop the communication standard for personal portable devices to exploit the TVWS [43, 44]. Ecma 392 specifies the PHY and MAC protocols for personal/portable devices. Adaption to worldwide regulatory requirements and robust support for real-time traffic are two main characteristics of Ecma 392.

TABLE 7 Comparison of various IEEE standards incorporating cognitive, DSA, and coexistence technologies [25].

Standard	Scope
IEEE 802.22 Initiation: 9/2004 Completion: Est. 9/2009	This standard specifies the air interface, including MAC and PHY layers, of fixed point-to-multipoint wireless regional area networks operating in the VHF/UHF TV broadcast bands between 54 MHz and 862 MHz The unique requirements of operating on a strict non-interference basis in spectrum assigned to, but unused by, the incumbent licensed services requires a new approach using purpose-designed cognitive radio techniques that will permeate the PHY and MAC layers.
802.19 Initiation: 3/2006 Completion: Est. 9/2008	This recommended practice describes methods for assessing coexistence of wireless networks. The document defines recommended coexistence metrics and methods of computing these coexistence metrics. The focus of the document is on IEEE 802 wireless networks, though the methods developed may be applicable to other standards development organizations and development communities.
IEEE 802.16h Initiation: 12/2004 Completion: Est. 9/2008	This amendment to the 802.16 standard will specify improved mechanisms (as policies and medium access control enhancements) to enable coexistence among license-exempt systems based on IEEE standard 802.16 and to facilitate the coexistence of such systems with primary users.
IEEE 802.16m Initiation: 12/2006 Completion: Est. 12/2009	This amendment to the 802.16 standard will provide an advanced air interface for operation in licensed bands. It will meet the cellular layer requirements of IMT-advanced next-generation mobile networks while providing continuing support for legacy Wireless MAN-OFDMA equipment. It is possible cognitive technology may be introduced in this amendment.
IEEE 802.11y Initiation: 3/2006 Completion: Est. 12/2009	This amendment to the 802.11 standard will allow application of 802.11-based systems to the 650–3700 MHz band in the U.S. It will standardize the mechanisms required to allow shared 802.11 operations with other users. Likely required mechanisms include: specification of new regulatory classes (extending 802.11j), sensing of other transmitters (extending 802.11a), transmit power control (extending 802.11h), dynamic frequency selection (extending 802.11h).

VIII. Centralized MAC Protocols for CR Networks

CR MAC can be broadly divided into two classes: centralized and distributed depending on the architecture of the CR network in consideration. In centralized spectrum sharing a centralized entity possesses detailed information about the network and handles with all the spectrum allocation and access procedures. Hence, compared to distributed, centralized approaches simplify the design of spectrum sharing. CR Centralized MAC protocols are given as follows:

• *Random Access Protocol:* The MAC protocols in this class do not need time synchronization, and are generally based on the collision sense multiple access with collision avoidance (CSMA/CA) principles. A CSMA-based protocol [26] 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.

• *Time slotted protocol:* These MAC protocols need network wide synchronization, where time is divided into slots for both the control channel and the data transmission. IEEE 802.22 as mentioned in [22] has a super frame 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. Back up channels are used to restore communication after PU interference. 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.

•*Hybrid protocol*: These protocols use a partially slotted transmission, in which the control signaling generally occurs over synchronized time slots [27], and data transmission may have schemes for random channel access. The game theoretic approach use clustering, negotiation, and collision avoidance mechanisms. One of the main disadvantages 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.

- *Further discussions*

The proposed CUCB-MAC protocol is a centralized time-slotted spectrum sharing protocol based on counting the number of collisions for each SU, predicting the ideality of the entire available channel then excluding some of the available channels at each time slot [5]. It is a modification of a MAC protocol named Collision-Based MAC protocol (CB-MAC), it depends on three parameters for the allocation of channels to the SUs; 1) counting collisions number for each SU, 2) predicting the availability probability for all the available channels and then

3) excluding some of the available channels. It has been proved that using the proposed CUCB-MAC protocol outperforms the original CB-MAC protocol on all the measured performance metrics.
The main idea of the collision based MAC protocol (CB-MAC) protocol [28] is to make a fair scheduling among SUs; this is done by not allowing some SUs to meet more collision than others. To guarantee such fairness; collision statistics such as the average number of collisions is used to prioritized SUs. Incoming SUs packets are retained in a buffer; so some of them will be served in the next time slots based on their priorities. The proposed protocol consists of channels, central spectrum manger that is equipped with both the scheduler and the buffer. This buffer contains packets requests sent by the SU,the collected inform information in its buffer to allocate the appropriate channel for the SUs' packets Fig.2.

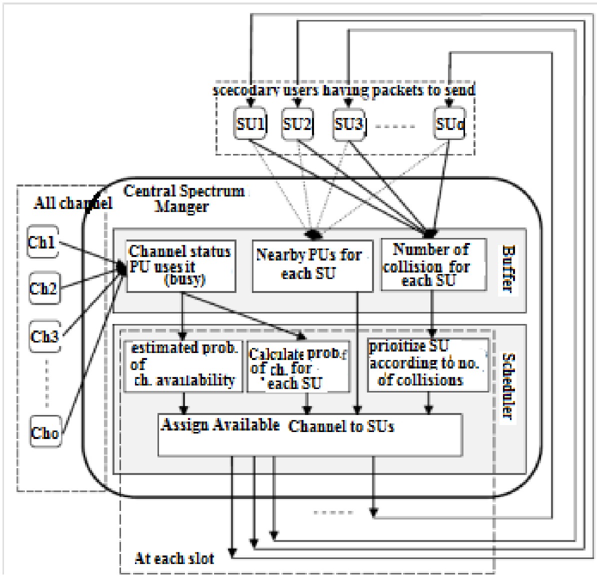

Figure.2 (CUCB-MAC) System Architecture

- ***Strengths***

Compared to the CB-MAC protocol, the proposed CUCB-MAC has some advantages: CUCB-MAC improves all the performance metrics' values. The improvements are medium on the average throughput, the average delay and the percentage of channel utilization. High improvement achieved on the average number of collided PUs' packets, the percentage of dropped packets and the average number of collided packets. The packets are stored in each SU's buffer unlike the CB-MAC protocol which stored the packets in the central control module buffer so packets are dropped if the buffer is overloaded.

- ***Limitations***

Compared to the CB-MAC protocol, the proposed CUCB-MAC has some drawbacks: As any SU with a packet to send (in the proposed CUCB-MAC), needs to sense its surrounding area for the existing PUs in its range, then send a list of these PUs to the central control module together with the sent request. The central control module uses these lists to calculate each channel usage by each SU's nearby PUs. This process leads to consuming some energy of the SUs' battery and needed extra buffering to store the list of Pus also extra processing time needed by the central control module to calculate the channel usage.

IX. MAC Protocols for Distributed CR Networks

Distributed spectrum sharing does not require any centralized entity or infrastructure, instead users self-organize and decide cooperatively or non-cooperatively the spectrum assignment due to changing environment. Distributed spectrum sharing is more scalable, According to different spectrum access modes, distributed dynamic spectrum access protocols can be divided into three categories:
• *Random Access Protocol:* some examples of this category is Dynamic open spectrum sharing (DOSS) MAC [29], the protocol provides solution to hidden and exposed nodes problems. The main drawback of this protocol is the spectrum is not efficiently utilized. Moreover, the need for multiple transceivers is not justified as two of them are not used for data communication at all. The single-radio adaptive channel (SRAC) MAC [30] protocol based on cross channel communication and dynamic channelization. As a result, signaling overhead is maximized, SRAC-MAC, also cannot handle the multi-channel hidden terminal problem. HC-MAC [31] aims at spectrum access by considering the hardware constraints. It has a single radio that simplifies the hardware

requirements but, the number of control messages is significant and may saturate the control channel earlier than classical single channel RTS-CTS based MAC protocols. The distributed channel assignment (DCA) [32] utilizes spectrum pooling which helps to enhance spectral efficiency by reliably detecting the primary network activity, thus serving as physical layer signaling, but the use of separate CCC results in CCC saturation. Distributed Cognitive Radio MAC protocol (DCR-MAC) [33] solved the hidden PU problem by using RTS and the CTS packets. However, the throughput and delay of the DCRMAC will be degraded due to the additional control information exchanges.

• *Time slotted protocol*: The distributed coordinated spectrum sharing (DCSS) MAC protocol for cognitive radio [34] time slot mechanism is used to detect incumbents. However, DCA negotiates for a data channel per packet. It fully relies on a CCC, which may incur control channel starvation. In DCSS, request to send (RTS) and clear to send (CTS) are exchanged before communications. RTS/CTS messages include the available data channel list. One of the famous slotted distributed DSA protocol is the cognitive MAC (C-MAC) protocol [35]., which is based on the well-known IEEE 802.22 standard. C-MAC has two key concepts: A rendezvous channel is used for node coordination and 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. In T-MAC [36] an efficient power control mechanism is provided, which can significantly increase the space reuse efficiency. T-MAC can efficiently reduce the multichannel hidden terminal problem and solve the multi-channel exposed terminal problem.

• *Hybrid protocol:* Multi-channel MAC (MC-MAC) protocol integrates spectrum sensing, packet scheduling, and channel allocation [37]. In the MC-MAC, the channel allocation problem is solved. Although the MC-MAC can achieve higher network throughput than the O-MAC, the channel allocation in the MC-MAC is performed by a spectrum broker, which may not exist in realistic distributed CWNs.

An opportunistic MAC protocol (O-MAC) [14] integrates the spectrum sensing, In order to increase the network throughput, Hybrid protocols like OS MAC[39] 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 [40], 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 [11] and [41], respectively.

- *Further discussions*

A distributed MAC protocol for CR Ad hoc networks to opportunistically utilize multiple channels proposed in [5]. CR nodes forecast and rank channel availability observing primary users' activities on the channels for a period of time by time series analyzing using smoothing models for seasonal data by Winters' method. The proposed approach protects primary users, mitigates channel access delay, and increases network performance. In this protocol each CR device is equipped with two transceivers. One is for the control channel and another for data channels. There are {N} non-overlapping licensed channels which opportunistically accessible by secondary users (SU) and are called data channels. A common control channel is available for reliable communications and free from interference by the incumbents used for control packet exchange. Synchronization is similar to the 802.11 time synchronization function (TSF) [42]. Time is divided into beacon intervals. Each SU maintains a table to record the status of the channels by sensing each channel and overhearing channel negotiation messages from the neighbors. There are two kinds of sensing: fast sensing and fine sensing. Fast sensing is done at the beginning of each ATIM window and in the middle of the BI, fast sensing takes a very short time and the fine sensing takes a long time.

- ***Strengths***

In most of existing MAC protocols for CRNs in the literature, the CR nodes do not send data packets while channel negotiation goes on. The proposed protocol does not wait until the end of the channel negotiation and it allows sending data packets just after successful channel negotiation. The proposed protocol starts data transmission just after successful channel negotiation. Also, channel ranking and selection strategies play a vital role in decreasing average packet delay. The strategies of channel sensing in the middle of the beacon interval and repairing the broken link due to the presence of PU also help to reduce average packet delay. Channel selection is carried out based on the history of incumbents' behavior on the channel over a period of time. Using the data recorded in the channel status table, SUs estimate the channels' status based on the multiplicative seasonal model for the next time slot. In the real world, availability of the channel is seasonal. After successful channel negotiation, SUs exchange RTS/CTS before sending actual data packets to avoid the hidden terminal and exposed terminal problem. The control transceiver wakes up just before the fast sensing ends in the middle of data window to send the emergency control message and renegotiate for data channels. It enters the sleep state after the channel negotiation window. The data transceiver is turned off if the SU has no data to send or receive and no fine sensing to do. Therefore, the proposed protocol efficiently utilizes white space and achieves better aggregated good put and lower delay.

X. Challenges and Open research Issues

Some major challenges in designing opportunistic cognitive MAC protocols for CRNs are as follows: efficient joint spectrum sensing and access design; The trade of between spectrum utilization and interference to PUs; Fair spectrum access among SUs; Hardware limitations; Multi-channel hidden/exposed terminal problem; Control channel configuration; Spectrum heterogeneity seen by SUs; QoS provisioning; and a synchronicity between SU and PU networks.

Current research has focused on improving the throughput and performance of CR networks, so some important design issues that are necessary to be addressed in distributed CR MAC design are:

- 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.
- Improve time synchronization and network coordination for SUs without dedicated CCC.
- Overall overhead analysis after taking into consideration the number of transceivers.
- Future research should address performance comparison of both instantaneous and average false alarms and detection probability for detecting primary appearance during data transmission phase.

XI. Conclusion

Designing a smart and efficient MAC protocol remains a key requirement for successful deployment of any CR network. The paper has surveyed the MAC layer for Cognitive radio networks and gives an overview on MAC protocols. The design of CR MAC protocols has followed two approaches standardization efforts leading to the formation of the IEEE 802.22 working group and application/scenario specific protocols so the existing dynamic spectrum access protocols were categorized based on different criteria. Recently several medium access control protocols for the wireless network have been proposed by the researchers. However, no protocol is accepted as standard. The paper review CUCB-MAC protocol a centralized time-slotted protocol as it came with new idea to make a fair scheduling among SUs, to guarantee such fairness; collision statistics such as the average number of collisions is used to prioritize SUs. Another distributed MAC protocol for CR Ad hoc networks was reviewed the approach protects primary users, mitigates channel access delay, and increases network performance In addition, we presented the open issues for current MAC protocol we believe that MAC protocol design for cognitive radio is an open area of research and will be of interest to both the industry and the academia as this technology matures in the next few years.

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