MAC Layer Techniques for Cognitive Radio : A Survey[1]

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Abstract

Heavy utilization of a certain portion of spectrum results from significant competence of the free spectrum such as ISM (industrial, scientific, and medical) bands. On the other hand, some bands of spectrum are highly under-utilized because of rare usage of the band. This necessitates a new communication paradigm referred to as Cognitive Radio to exploit the existing wireless spectrum opportunistically. In this paper, we survey medium access control (MAC) layer technologies and discuss necessary core functions and challenges for the cognitive radio MAC.

1. Introduction

According to Federal Communications Commission (FCC), temporal and geographical variations in utilization of the assigned spectrum range from 15% to 85% [1,6]. Heavy utilization of a certain portion of spectrum results from significant competence of the free spectrum such as ISM (industrial, scientific, and medical) bands. For example, recent development of wireless technologies such as IEEE 802.11 and 802.15 has concentrated on free ISM bands, which exacerbates coexistence problem among IEEE 802 devices. This trend will continue as more and more wireless technologies are developed. On the other hand, some bands of spectrum are under-utilized because of rare usage of the band. For example, UHF bands in range between 300 kHz and 3 MHz are under-utilized due to advent of CATV and satellite TV broadcasting.

Therefore, more efficient spectrum allocation or management comes to be necessary and this necessitates a new communication paradigm to exploit the existing wireless spectrum opportunistically [13]. J. Mitola [7] coined a new terminology, *Cognitive Radio* that concretizes this paradigm. A cognitive radio system is the one where a unlicensed user (or *secondary user*) can opportunistically use a licensed spectral band as long as the secondary user does not do harmful affect to a licensed user (or *primary user* or *incumbent user*).

FCC officially announced a mitigation policy where temporally vacant licensed spectrum can be utilized by other unlicensed users through notice of proposed rule marketing (NPRM) in 2003 [9]. The Defense Advanced Research Projects Agency (DARPA) has started the next generation (XG) communications program to develop new technologies which allow multiple users to share the spectrum through adaptive mechanisms. The US army has also been researching adaptive spectrum exploitation (ASE) for real-time spectrum management in the battlefield [8]. New standardization activities, such as IEEE 802.22, have also targeted the use of TV bands for spectral-agile wireless regional access networks (WRANs) [2]. These techniques have different name, but have same basic concept as follows:

- Radio devices are allowed to explore the wireless spectrum.
- Radio devices may be able to exploit unused spectral bands as long as the exploitation does not cause interference to primary users of the bands.

This research effort can improve efficient spectrum usage along with development of new wireless devices. Furthermore, it opens a new wireless communication

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environment and a new market according to the relaxed FCC radio resource policy.

In this paper, we survey medium access control (MAC) layer technologies and discuss necessary core functions and challenges for the cognitive radio MAC.

This paper is organized as follows: in section 2, we describe the cognitive radio system. Then, taxonomy of various dynamic spectrum access (DSA) techniques in MAC layer is provided in section 3. Finally, we conclude this paper with conclusions in section 4.

2. Cognitive Radio System

In this section, we describe the medium access control (MAC) layer architecture and its behavior. A cognitive radio MAC (or CR-MAC) is a radio frequency transmitter and receiver pair that is designed to intelligently detect whether a particular segment of the radio spectrum is in currently use, and to jump into (or out of, as necessary) the temporarily-unused spectrum very rapidly, without interfering with the transmissions of primary users.

Fig.1. depicts cognitive radio cycle diagram of two parts (PHY and MAC layer) [15]. The physical (PHY) entity of the CR system periodically senses the spectrum (referred to as *observe* state) and transmits/ receives (called as *communication* state) data to/from other device with RF equipments.

Using PHY functionality, MAC entity receives sensing data from PHY entity. When it receives data from PHY entity, the MAC entity starts its task (*called as Initiate* state). The *Initiate* state transits based on the following three scenarios:

- In normal case, the MAC entity generates alternatives such as candidate set of spectrum resources and prioritizes the candidate set based on the sensing information provided by *Learn* state (*referred to as Plan* state) and then allocates radio resource to the device (*called as Decide* state). Next, the MAC entity performs data communication with the specific radio resource (*called as Perform* state).
- If the *Initiate* state detects an occurrence of a primary user, the MAC entity transits to *Decide* state to allocate another available channel from the learned information for its communication and then goes to *Perform* state for communication
- If the device receives shut down command (e.g., device's battery happens to be removed), MAC entity transits to *Perform* state to save its data and inform release of the spectrum in use.

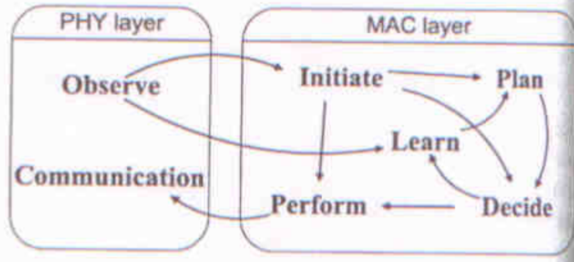

Fig.1. Cognitive Radio cycle

The device monitors characteristics of spectral channel which is updated (as in *Learn* state). This information is used to *plan* state as stated above.

3. Dynamic Spectrum Access

The key enabling technology of the cognitive radio is the dynamic spectrum access scheme. Cognitive radio techniques provide the capability to use or share the spectrum in an opportunistic manner. Dynamic spectrum access (DSA) techniques allow the cognitive radio to operate in the best available channel. More specifically, the cognitive radio MAC entity will enable the users to (1) select the best available channel (*spectrum management*), (2) coordinate access to this channel with other users (*spectrum sharing*), and (3) vacate the channel when a licensed user is detected (*spectrum mobility*) [6].

Once a cognitive radio supports the capability to select the best available channel, the next challenge is to make the network protocols adaptive to the available spectrum. Hence, new functionalities are required to support this adaptively. In summary, the main functions for cognitive radios can be summarized as follows:

- Spectrum management: Capturing the best available spectrum to meet user communication requirements.
- Spectrum mobility: Maintaining seamless communication requirements during the transition to better spectrum.
- Spectrum sharing: Providing the fair spectrum scheduling method among other co-existing users [6].

3.1 Spectrum Management

To guarantee quality of service (QoS) of each node, spectrum management is a core function of the MAC entity. Since the status of spectral resources varies over time, spectrum management continuously requires searching the optimum resources for its communication. For efficient spectrum management, measurement of spectral characteristic is of importance described as follows:

- Interference: Some spectrum bands are more crowded compared to others. Hence, the spectrum band in use determines the interference characteristics of the channel. From the amount of the interference at the primary receiver, the permissible power of user can be derived, which is used for the estimation of the channel capacity.
- Path loss: The path loss increases as the operating frequency increases. Therefore, if the transmission power of user remains the same, then its transmission range decreases at higher frequencies. Similarly, if transmission power is increased to compensate for the increased path loss, then this results in higher interference for other users.
- Holding time: The activities of primary users can affect the channel quality in networks. Holding time refers to the expected time duration that the user can occupy a licensed band before getting interrupted. Obviously, the longer the holding time, the better the quality would be. Since frequent spectrum handoff can decrease the holding time, previous statistical patterns of handoff should be considered while designing networks with large expected holding time.

Channel capacity, which can be derived from the parameters explained above, is the most important factor for spectrum characterization. Usually signal-to-noise ratio (SNR) at the receiver has been used for the capacity estimation. However, since SNR considers only local observations of users, it is not enough to avoid interference at the primary users. Thus, spectrum characterization is focused on the capacity estimation based on the interference at the licensed receivers [6].

In [2,8], CR user monitors the spectral information that contains the sensing data from PHY layer as a form of set of map. Table 1 shows an example of the spectral opportunity map (SOM) proposed in [8]. User collects this map to get spectral information and to decrease interference with primary user. The fields in SOM are described as the followings:

- *Index*: channel index,
- *Idle*: status of channel usage,
- *T_Duration*: scan duration,
- *Avg_P_utilization*: the average occurrence percentage of the primary user during the scan duration,
- *Avg_S_utilization*: the average occurrence percentage of the secondary user during the scan duration, and
- *Power*: the average transmit power of the primary user

Table 1. Spectral Opportunity Map (SOM)

Index	Idle	T_Duration	Avg_P_util	Avg_S_util	P_power
0	1	10	0.85	0.23	-20db
1	0	0	0	0	0
2	0	N/A	N/A	N/A	N/A
N	1	N/A	N/A	N/A	N/A

If we choose the channel whose avg_S_util value is less than avg_P_util value, we can at least reduce interference with the primary user.

3.2 Spectrum Mobility

Each device wants to operate in the best available spectrum band. Hence, if communication channel becomes worse or the primary user appears on the communication channel, spectrum mobility is initiated. Spectrum mobility is defined as the process when user changes its spectrum band to the other for its communication. When spectrum mobility occurs, it is important to synchronize between transmitter and receiver (refer to as *spectrum handoff*). If the spectrum handoff duration is longer than a threshold value, users can perceive serious disruption of the communication. Therefore, fast spectrum handoff technique is necessary. The purpose of spectrum mobility management is to make sure that such transitions are made smoothly and as soon as possible such that the applications running on user perceive minimum performance degradation during a spectrum handoff. It is essential for the mobility management protocols to learn in advance during the spectrum handoff.

In [2], users have channel to hop next time (*called as backup channel)*. To have *backup channel* between communication users, they can decrease *spectrum handoff* control message

3.3 Spectrum Sharing

The existing MAC schemes for CR systems can be categorized by different taxonomies. In the following, we analyze various types of MAC protocols.

3.3.1 By Existence of Control Entity

CR MAC schemes can be divided by centralized or decentralized approaches based on who is given the control of the network as follows:

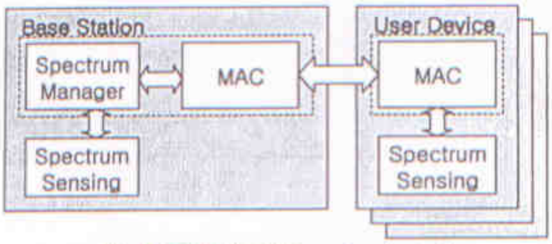

Fig.2. IEEE 802.22 protocol stack

A. Centralized Approaches

In the centralized approach, a base station (BS) allocates spectrum channel to devices. IEEE 802.22 is an example of this approach. In IEEE 802.22, spectrum manager performs spectrum management, mobility, and sharing.

As shown in Fig. 2, spectrum manager in base station communicates and controls user devices through MAC layer. Spectrum manager collect user's sensing data, and allocates the best spectrum available to devices using collected spectrum sensing data.

B. Decentralized Approaches

The decentralized approaches do not require base station. Instead, spectrum resource are shared and managed by distributed nodes in the network. In the protocol proposed in [8], every node has resource management entity (RME) and measurement management entity (MME) which monitors and manages spectral information from PHY layer. The RME manages information of whole spectrum usage in the network. The spectral information is periodically updated by MME or RME in other nodes. The RME allocates (or reserves) a spectral channel to it and delivers the spectral information gathered to other entity. From this, nodes can dynamically share in spectrum access.

C. Comparison

Table 2 shows comparison of the two architectural approaches. The centralized approach requires coordination device like a base station while decentralized approach just needs more cognitive spectrum sharing functionality. Since more cognitive sharing functionality is required in the decentralized approach, communication overhead for the decentralized will be much larger and thus spectrum utilization is harder to be realized against the centralized one.

Table 2. Comparison of Centralized and Decentralized Approaches

	Centralized	**Decentralized**
Infrastructure	Need	Don't need
Overhead	Low	High
Spectrum utilization	Easy	Difficult

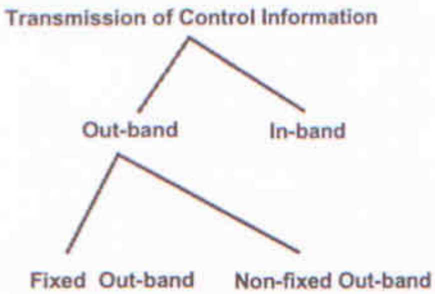

Fig.3. Transmission methods of control message

3.3.2 Transmission Methods of Control Message

Cognitive radio (CR) user requires not only a necessary traffic channel to transmit/receive data, but also information sharing such as spectrum allocation and sensing information exchange. To realize this, CR MAC system can be categorized by (1) *in-band* (both data traffic and control information are conveyed on the same channel) and (2) *out-band* (data traffic channel and control channel are separated) as shown in Fig. 3.

A. Method Using Out-band

For transmission methods of control message using out-band, we can further categorize them into (a) *fixed out-band* and (b) *non-fixed out-band*. The fixed out-band is a dedicated spectrum to be utilized for control information while schemes using non-fixed out-band do not employ a specific spectrum.

a. Fixed Out-band

Many spectrum sharing solutions, either centralized or decentralized, assume a fixed common control channel (CCC) [16,17] to transmit control message. Jing, *et al.* proposed common spectrum coordination channel (CSCC) Etiquette protocol [11] to exchange control messages between different radio systems. The CSCC resides at the edge of spectrum bands in a fixed fashion for announcement of radio parameters such as frequency, power, modulation, duration, interference margin, service type, etc. Each node is equipped with a low bit-rate, narrow-band control radio for listening to announcements and broadcasting its own parameters at the CSCC channel. Nodes receiving CSCC control information can then initiate appropriate spectrum sharing policies and priority to resolve conflicts in spectrum demand and share the resource more efficiently.

Buddhikot, *et al.* proposed a dynamic intelligent management of spectrum for ubiquitous mobile networks (DIMSUMnet)[18] based on IP. DIMSUMnet has DIMSUM base station (BS) to control mobile devices. DIMSUM BS allocates appropriate spectrum to mobile devices from a spectrum information and management (SPIM) server through Internet. DIMSUM BS and mobile devices communicate over a dedicated spectrum information channel (SPIC) to exchange information such as sensing information and channel allocation.

b. Non-fixed Out-band

Zhao, *et al.* proposed a decentralized cognitive MAC (DC-MAC) [14] which transmits control message over a non-fixed channel. In the DC-MAC, when a device has data traffic to transmit, the device transmits handshake signal over one of its available channels. A corresponding node receiving the handshake signal responds to the transmitting device, and negotiates data channel to use for their data communication.

IEEE 802.22 utilizes the similar approach when a CPE requests a data channel from the BS. When the CPE detects BS's beacon, it analyzes the control message in the beacon and compare its available channel set with BS's available channels. Then, the CPE requests an optimum channel for its communication with the BS.

B. Method Using In-band

These methods transmit/receive both data traffic and control information over the same spectral bands. IEEE 802.22 is one of the schemes that utilize in-band where control information such as backup channel, spectral map, etc is conveyed over MAC PDU (protocol data unit). Beacon MAC header also contains control message such as the number of available backup channels, allocated slots, upstream and downstream channel allocation information.

3.3.3 Admission Control

Although secondary users compete among themselves, they can utilize admission control function to share the spectrum efficiently. In the centralized approach, base station can perform the admission control functionality where it prioritizes user demands. As more users share the common spectrum bands, previously admitted users do not perceive degradation of their QoS using admission control. This type of approach also referred to as cooperative. In the decentralized approach, however, this methodology will not be easy since users are competing among themselves for accessing the spectrum. Their access will be more selfish (or non-cooperative)

3.3.4 Coexistence

Although the secondary user competes with other users to obtain spectrum, each user also needs to exchange spectrum and control information for efficient dynamic spectrum access,

IEEE 802.22 [2] proposes coexistence beacon protocol (CBP). The CBP is MAC control message to solve coexistence problem. To solve the coexistence problem, a CBP message generated from a specific WRAN can be broadcasted to bordering devices in other WRAN. If the edge (or bordering) devices receive the CBP message, the devices transmit the information of CBP to their base station. Then, base station can infer the characteristics of other WRAN system based on the CBP message. So, the base station can limit the transmit power or mange spectrum allocation accordingly. Lastly, the base station transmits the same CBP message to inform other base station in different WRAN.

Common spectrum coordination channel (CSCC) protocol in [11] proposes a use of CCC to inform existence of other service user. However, every device needs to be equipped with common control channel.

4. Conclusion

Heavy utilization of a certain portion of spectrum results from significant competence of the free spectrum such as ISM (industrial, scientific, and medical) bands. On the other hand, some bands of spectrum are highly under-utilized because of rare usage of the band. This necessitates a new communication paradigm referred to as Cognitive Radio to exploit the existing wireless spectrum opportunistically. In this paper, we survey medium access control (MAC) layer technologies and discuss necessary core functions and challenges for the cognitive radio MAC. The centralized approach can facilitate relative simple deployment. However, it does not effectively solve the hidden node problem in the network. The decentralized approach, on the other hand, needs new techniques to overcome problem of overhead and common control channel. There remain a large number of unsolved challenges to be resolved such as admission control and interference mitigation protocols, etc.

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