International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2013): 4.438

Introduction to Cognitive Radio Network and survey on MAC protocols for Cognitive Radio Networks

Kiran Godara[1], Rishipal Singh[2]

[1, 2] Department of Computer Science and Engineering, Guru Jambheshwar University of Science and Technology, Hisar, Haryana, India

Abstract: ***Spectrum is a scarce resource and traditional spectrum assignment policies does not make efficient use of spectrum which leads to wastage of allocated spectrum. With increase in the number of wireless devices spectrum demand is growing rapidly. Cognitive Radio Networks (CRN) can provide solution to these problems by using the spectrum in dynamic manner. Cognitive Radio (CR) users can access the spectrum allocated to Primary Users (PUs) without affecting the primary network communication. MAC protocols are needed when multiple CR users want to access the spectrum allocated to primary users. A brief overview of the requirement of CRN is provided. Basic working and architecture of CRN is introduced. Moreover, classification of various types of MAC protocols used in CRN is given with protocols used in past. Comparison of the MAC protocols is also provided in the end.***

Keywords: Cognitive Radio Network, Medium Access Control (MAC) Protocols, Spectrum Management, Dynamic Spectrum Access, Spectrum Overlay, Spectrum Underlay, Primary user, Secondary user

1. Introduction

With increase in wireless communication, number of mobile users is rising day by day. Demand for spectrum is also increasing at very fast rate. Most of the spectrum is allocated using fixed spectrum assignment (FSA) policy and is underutilized. Federal Communication Commission (FCC), report reveals that there is wide variation in temporal and geographical usage of allocated spectrum which varies from 15% to 85% [1]. Radio spectrum is a natural and limited resource. Spectrum scarcity problem needs to be solved as early as possible. To efficiently utilize the spectrum and meet the rising demand of spectrum by wireless devices new technology called cognitive radio (CR) technology came into existence. Cognitive Radio (CR) users or secondary users (SU) access the spectrum allocated to licensed users called primary users (PUs) using dynamic spectrum access (DSA) method. The term Cognitive Radio was given by Joseph Mitola III in 1998 [2].

A cognitive radio is defined as a radio that can change its transmitter parameters based on the interaction with the environment in which it operates [1]. Transmission parameters can be carrier frequency, bandwidth, modulation scheme, etc.

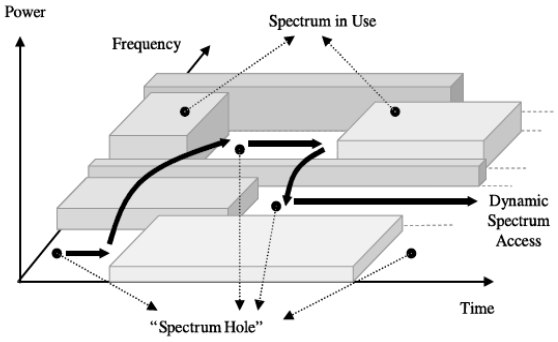


Figure 1: Spectrum holes [5]

1.1 Characteristics of Cognitive Radio

CR has two important characteristics: [3], [4]

***Cognitive capability*:** It is the ability of CR to sense and gather information from the radio environment. It finds out the spectrum holes (unused portion of the spectrum allocated to licensed users) [5]. Best spectrum holes are chosen according to the user requirement of data and quality of service needed.

Reconfigurability: It deals with adapting the CR with the changing environment. CR reconfigures its transmission parameters according to the current state of network.

Licensed Under Creative Commons Attribution CC BY

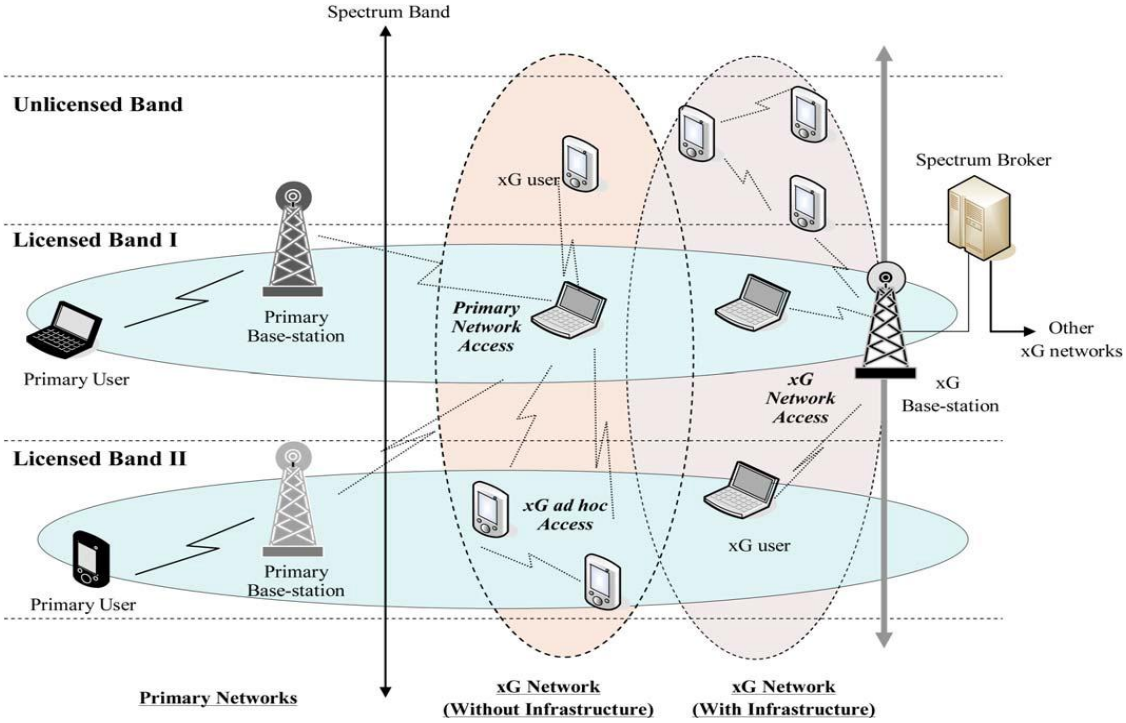


Figure 2: Cognitive radio/ Next generation network [5]

1.2 Dynamic Spectrum Access (DSA) Method

Primary users or licensed users are allocated spectrum using Fixed Spectrum Assignment policy (FSA). In FSA, a user is allocated some portion of spectrum on permanent basis or given license for some period of time. This spectrum is not in use all the time and becomes underutilized. To use the spectrum efficiently dynamic spectrum access (DSA) technique is used by CR users (also known as secondary users). In DSA, SUs use the spectrum allocated to primary users without affecting their communication. SUs access spectrum using DSA in two ways: [9]

1.2.1 Opportunistic Spectrum Access (OSA)

In OSA, SU finds the spectrum holes and uses them to transmit data to other SU Fig. 1. With cognitive capability of CR, SU can collect information about spectrum holes and will select best spectrum hole to use for data transmission. Whenever PU becomes active SU has to vacant this portion of spectrum and switch to some other spectrum hole and reconfigure its transmitter parameters accordingly. This spectrum access scheme is also known as spectrum pooling [2], [6] or spectrum overlay [7], [8].

1.2.2 Concurrent Spectrum Access (CSA)

In CSA, SUs transmit data when PU is also transmitting data and using the spectrum but the constraint is that interference by the SU to primary receiver should be below a tolerable threshold. SU and PU can transmit simultaneously. When interference to PU by SU becomes greater than threshold SU has to vacant that spectrum. It is also known as spectrum underlay [8].

2. Cognitive Radio Network Architecture

Key components of CRN are: Primary network and Cognitive Radio Network/xG Network. Fig. 2

- ***Primary Network*:** It operates only in licensed spectrum. Primary base station controls access to licensed spectrum among PUs. When PU wants to access spectrum to transmit its data its request is handled by base station. Base station allocates the best available spectrum to PU according to the requirement of PU.
- ***Cognitive Radio Network / xG Network*:** Cognitive radio network (CRN) can exist in both licensed as well as unlicensed bands. Architecture of CRN can be implemented with or without infrastructure. In CRN with infrastructure support, a central entity controls spectrum allocation and resource management. All other CR nodes follow decision taken by the central entity (base station). CRN uses the spectrum assigned to primary network using OSA (opportunistic spectrum access) or CSA (concurrent spectrum access) technique.

Spectrum broker acts as a central entity that controls spectrum sharing among different CRNs. It can be connected with different CRNs.

3. MAC Protocols for Cognitive Radio Network

SUs use the spectrum allocated to licensed users (PUs) in opportunistic manner. SUs find spectrum holes and compete for the same. To fairly allocate spectrum among SUs and utilize the spectrum in efficient manner medium access protocols are required. MAC protocols required for CRN depend on many factors such as CRN architecture, spectrum access method, number of channels used for data transmission, number of transceivers SU is equipped with, use of control channel or not, channel access is contention based or slotted, objective of MAC protocol is to globally optimize network utilization or only local optimization, etc.

Licensed Under Creative Commons Attribution CC BY

3.1 Broader classification of MAC protocols for Cognitive Radio Networks

Broadly, MAC protocols can be classified as centralized or distributed on the basis of underlying architecture of CRN. In centralized or infrastructure based CRN, medium access is controlled by a central entity such as a base station. Communication between two nodes in CRN is arbitrated by this central entity. Central node tightly holds whole network together. In distributed MAC protocols every node takes its own decision to access medium. When the size of network becomes huge it becomes difficult to implement medium access using centralized scheme and distributed protocols comes in handy. Distributed protocols are more flexible and robust. Infrastructure cost is also less in distributed protocols. Centralized protocols have an extra overhead in collecting data and processing it at a central node. Centralized or distributed protocols can be further classified.

3.2 Classification of MAC Protocols for CRN on the basis of Spectrum sharing

SUs can share spectrum allocated to primary network in two ways:

3.2.1 Opportunistic/ Overlay Spectrum Access (OSA)

In OSA, SUs sees spectrum holes (unused spectrum allocated to PU in frequency and time domain) as opportunities and transmit data only when the PU is inactive at the spectrum allocated to it. In [10], a decentralized MAC for ad hoc network is proposed without a dedicated control channel. Channels allocated to primary network are slotted. Network state at slot t tells availability of each channel. Secondary users (SUs) seek opportunities in these channels and use the channels in which primary users are not active at a slot. Every SU does not have complete knowledge of unused primary channels. Only a partial knowledge of channels availability is sufficient for SU. Each SU select a set of channels to sense and a set of channels to access on basis of sensing. Throughput of secondary user is maximized. Before transmitting in a slot SU waits for random backoff time and if slot is still found to be idle SU transmits data. After successful transmission receiver sends ACK.

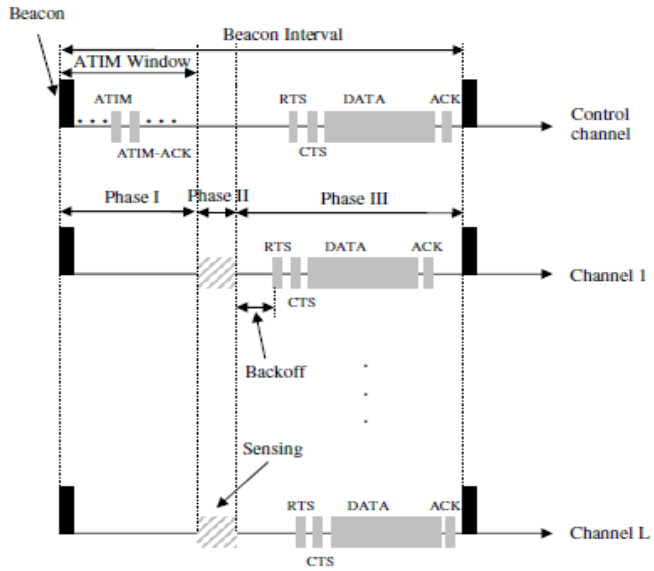


Figure 3: Timing structure of OSA-MAC protocol [11]

Protocol in [11] uses unused channels of primary users in opportunistic manner. A dedicated control channel is used to exchange control information between secondary users (SU). Time is divided into beacon intervals each divided into three phases: channel selection, sensing and data transmission. In first phase sender selects a channel and send ATIM (ad hoc traffic indication message) to intended receiver on control channel. If receiver agrees on selected channel it reply with ATIM-ACK. During phase two selected channel is sensed to ensure that only idle channel will be used for transmission. When more than one SU chooses same channel in first phase those SU will contend in phase three using RTS/CTS/DATA/ACK four way handshake of IEEE 802.11 CSMA/CA protocol. To minimize collision with primary users send only one packet is transmitted from winning SU on each channel in phase three.

3.2.2 Concurrent/ Underlay Spectrum Access (CSA)

In CSA, both the PU and SU use spectrum simultaneously but maintains the interference to each other below a tolerable threshold limit. If interference to PUs becomes larger than this limit, SU will stop using this spectrum portion.

In [12] CRN (cognitive radio network) is composed of a base station and multiple CRN nodes. By using the rate-distance nature of wireless communication of primary system (PS) it is possible to simultaneously transmit data by mobile station (MS) of PS and CR. Primary system also contains base station and a number of PSs. MS of PS are given priority in using channel. CR node senses medium for longer duration than MS and hence MS will get more chance to use spectrum. Signal to Noise and Interference Ratio (SINR) is used to take decision whether channel can be used for transmission by CR. RTS/CTS packets are used to decide on transmission parameters and for contention. After successful contention data is transmitted. To keep interference minimum CR is allowed to transmit only one packet after each successful contention.

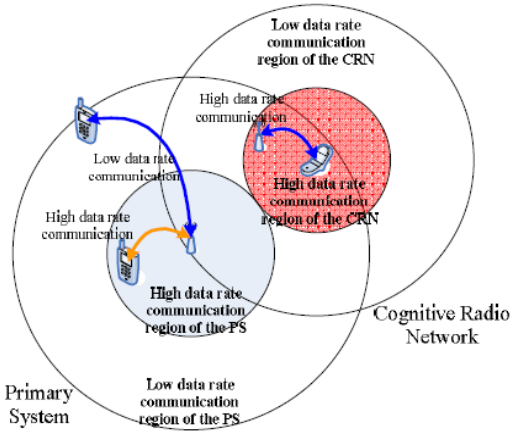


Figure 4: PS and CRN coexists together [12]

3.3 Classification of MAC Protocols for CRN on the basis of number of channels used by SU for data transmission

Data of SU can be transmitted on a single channel or multiple channels simultaneously and MAC protocols can be classified accordingly.

Licensed Under Creative Commons Attribution CC BY

3.3.1 Single Channel MAC

A single channel is used to transmit data out of available channels. Data transmission on a single channel results in slow data transfer, higher interference to PU and low utilization of spectrum as compared to multiple channel protocols. In multi-channel MAC protocols whenever PU returns lesser number of SUs will be affected.

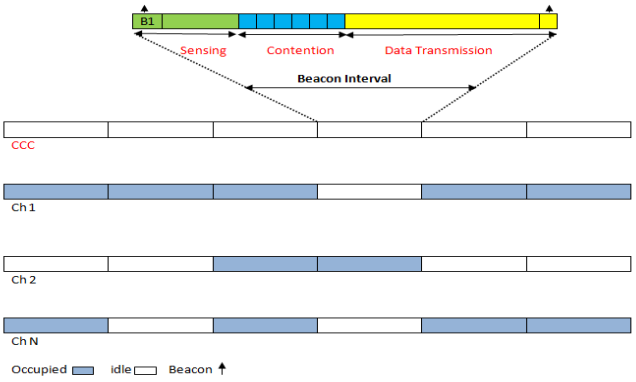


Figure 5: Timing structure model [13]

The protocol in [13] uses two transceivers: one for listening to control channel information and other for sensing and transmission of data. No common control channel (CCC) is used. SU use dedicated band owned by them as CCC. Time is divided into beacon which is further divided into three phases: sensing, contention and data transmission. Cooperative sensing is used. Each SU exchange sensing information of which primary user (PU) channel is idle with other SUs sensing information. During contention phase SU contend to reserve a channel. When a channel is reserved for sender-receiver pair neighbour nodes set network allocation vector (NAV) for channel. After successful transmission ACK is sent by receiver.

3.3.2 Multi-channel MAC

Data from SU is transmitted on multiple channels concurrently. Multi-channel MAC protocols increases efficiency of network and results in better utilization of bandwidth. Multi-channel protocols can be further divided on the basis of control channel used.

If a single dedicated control channel is used, MAC protocol will be single rendezvous and if no permanent control channel is available protocol will be parallel rendezvous.

This [14] protocol uses multiple channels to transmit data at a time. Each CR user is equipped with single transceiver. A dedicated control channel is used to transmit control messages. Proposed protocol uses TDMA scheme. Time is divided into frames. Frame is further divided into: sensing window, ad-hoc traffic indication messages (ATIM) window

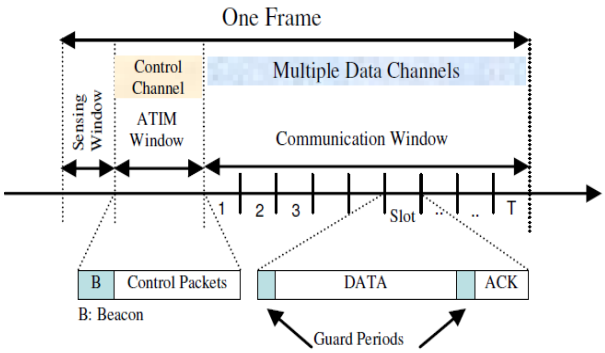


Figure 6: Structure of CR-MAC protocol [14]

and communication window. ATIM window is divided into beacon and control window. Sensing is done to avoid collision with primary users. ATIM window is contention based and is used for contention and exchange of control messages on control channel. Communication window is time slotted. If during contention sender-receiver pair successfully negotiates to reserve a slot that slot is used to transmit data. All neighbour nodes of intended receiver remain silent during transmission. Beaconing helps a node to find out list of available channels within two hop neighbour and transmission schedule of communication schedule of one hop neighbour.

In [15] each SU (secondary user) is equipped with single transceiver. There are G channels each of which are time slotted and every channel has different data rate. SU opportunistically access spectrum when PU (primary user) is idle. Proposed protocol is channel hopping based parallel rendezvous MAC protocol. It does not require common control channel to exchange control information. Nodes jump to different channels based on their own sequence to exchange control messages. Every Su has fixed hopping sequence calculated on basis of MAC address. To exchange control information with intended receiver, sender need to know hopping sequence of receiver. Hopping sequences are broadcasted using beacon messages. In the beginning of each slot some portion is used to sense if channel is idle. If no PU activity is found on that channel SU can use that channel to transmit data.

3.4 Classification of MAC Protocols for CRN on the basis of Channel Access Method

When multiple CR users want to access the channel they can be allowed to access the spectrum in random, time-slotted or hybrid manner. In random access scheme, CR users contend to win the channel among multiple CR users. CR user who wins the contention will get access to the channel. For contention, CSMA/CA protocol can be used. In slotted protocols, channel is divided into slots of equal size and every CR user is assigned a slot and it can transmit in that particular slot only. In hybrid protocols channel is time-slotted and CR users contend for a slot and the CR user winning the slot will transmit data in that slot. Time slotted protocols require network wide synchronization but random access protocols do not require time synchronization.

Licensed Under Creative Commons Attribution CC BY

Proposed protocol in [16] is a random access channel MAC and can be implemented with or without control channel. If control channel is used it uses a third transceiver which remains tuned to this control channel. If no control channel is used broadcast messages are transmitted on HCh of receiver. This protocol is full duplex and uses two transceivers: one as a transmitter and other as receiver. Out of available channels for communication a node will select a channel as its home channel (Hch). Receiver will be tuned to HCh. A node that wants to send data to some other node will tune its transmitter to receiver node's HCh. Sender node uses CSMA/CA scheme of IEEE 802.11 DCF mode to transmit data. Transmission from multiple nodes is distributed on multiple channels.

Proposed protocol in [17] is time-slotted. Each channel is divided into superframes. Superframes are further divided into two parts: BP (beacon period) and DTP (data transfer period). BP of different channels does not overlap in time. One of the channels is RC (rendezvous channel or control channel). Periodic tuning to BP provides synchronization and neighbourhood information. Every user can broadcast its channel requirement and neighbourhood information on RC channel. BP is used to reserve a channel and after reservation data transmission takes place in DTP portion of superframe.

3.5 Classification of MAC Protocols for CRN on basis of Local or Global optimization of network resources

3.5.1 Local Optimization

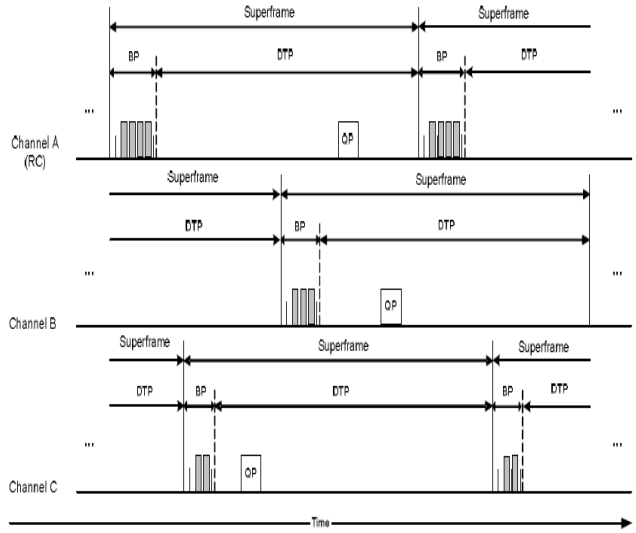


Figure 7: Superframe structure in C-MAC [17]

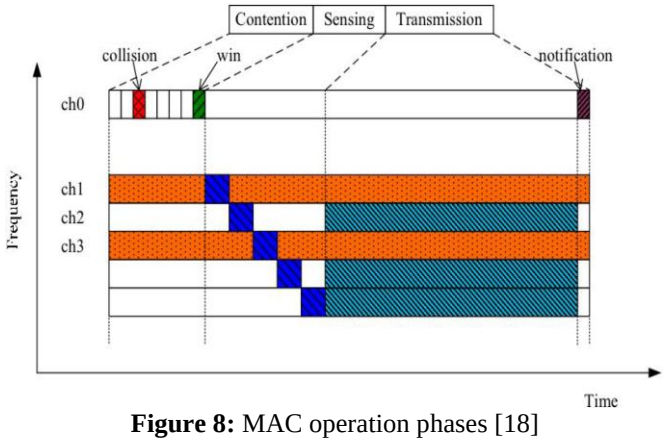


Figure 8: MAC operation phases [18]

Nodes in CRN can work towards their own optimization of bandwidth usage and falls in category of local optimization.
In [18] proposed protocol belongs to the category of local optimization. All nodes want to optimize their own communication. A global common control channel (CCC) is used to transmit control messages. Three types of packets are exchanged on CCC: C-RTS/C-CTS, S-RTS/S-CTS and T-RTS/T-CTS. Time frame is divided into three phases: contention, sensing and transmission. HC-MAC uses media access scheme similar to IEEE 802.11 DCF during contention. In contention phase sender node sends C-RTS to intended receiver. If receiver replies with C-CTS sender receiver pair wins contention for reservation and spectrum sensing. During C-RTS/C-CTS exchange, other nodes will stop sensing and transmission. Sensing phase can have one or more slots. Sensing and negotiation is done on each slot for some channel. Sender sends S-RTS informing receiver if this channel is available or not. If receiver agrees with sender it will reply with S-CTS. A sensing continuing or stopping decision is made on each at sensing slot. In transmission phase, set of channels on which both sender and receiver agreed in phase two will be used to transmit data. Transmission includes multiple data and ACK packets. After all data packets are successfully transmitted sender sends T-RTS and receiver replies with T-CTS. It will end the deferring session for neighbouring nodes and marks beginning of next round of contention.

The protocol in [19] also belongs to local optimization in which pair of node contends to optimize their transmission. Two transceivers are used. Control transceiver is used to obtain information of idle channels and for contention purpose with other secondary users (SU). SDR transceiver is used to sense channels and transmit or receive data. Time is divided into slots. Control channel's slot is divided into two phases: report and negotiation phase. Each phase is divided into N mini slots. Each mini slot corresponds to one of N licensed channels. Each SU randomly selects some channel to sense using SDR transceiver and report its state (idle or busy) using control transceiver in respective channel's mini slot of report phase. In negotiation phase SUs exchange RTS-CTS messages packets over control channel to win contention. SU who won contention in last slot will transmit data on all the idle channels in current time slot.

3.5.2 Global Optimization

If the nodes work in coordination in order to optimize the performance of whole network it is called global network optimization. Global optimization protocols are more difficult to implement and scale than local ones. These require extra infrastructure and powerful systems which increases the cost. The protocol [20] belongs to network wide optimization of spectrum usage. It uses a localized version of the island Genetic Algorithm (LiGA). Every node stores information of nearby nodes and not of the nodes of whole network. Every node works on a part of problem and cooperates with other nodes to provide network wide solution. Exchange controller is used to exchange spectrum information. The island Genetic Algorithm Controller monitor network performance, triggers nodes LiGA processes, collects network topology and spectrum information. LiGA tries to find best link-channel mapping. When some node wants to communicate with some other

Licensed Under Creative Commons Attribution CC BY

node it will search configuration database for respective link-channel mapping. If it finds corresponding entry in database and channel is unused at that moment sender node can use it to transmit data. Otherwise a rendezvous protocol is used to communicate with destination.

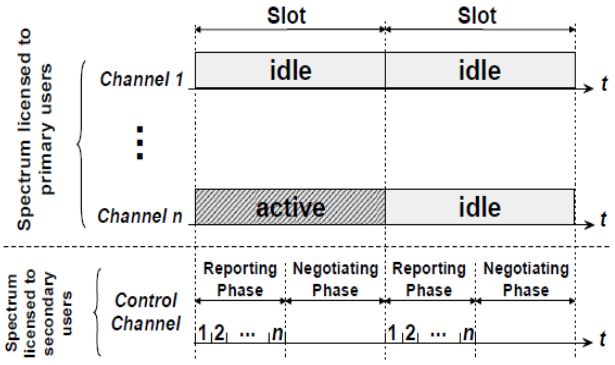


Figure 9: Structure of MAC protocol proposed in [19]

In [21], a single primary user shares its spectrum with multiple secondary users (SU). The spectrum sharing problem is formulated as oligopoly market in which few firms compete for the amount of commodity supplied to maximize profit. Similarly SUs compete for spectrum and cost is also specified using price function. Cournot game is used to analyze situation and Nash equilibrium is used as solution of problem to maximize profit of all SUs. In static cournot game model every SU know strategy (spectrum size) and payoffs (profit) of other SUs and will make its strategy accordingly. But it is not possible to have strategy information of every SU. Therefore dynamic model is used in which SU's strategy depends only on pricing information of PU. Using Nash equilibrium we can find optimal spectrum size allocated to SUs.

4. Comparison of various MAC protocols for Cognitive Radio Network

MAC protocols for CR can be compared on many factors such as architecture of CRN (ad hoc or infrastructure), channel access method, spectrum sharing technique, number of transceivers used by SU, control channel is used or not, etc. Comparison of protocols summarized in section 3 is given in Table 1.

5. Conclusions

Due to inefficiency in fixed spectrum allocation policy and underutilization of allocated spectrum, scarcity problem of spectrum is going to be a huge problem. Cognitive radio technology can use this underutilized spectrum and meet the increasing demand of spectrum by wireless devices. Cognitive radio network will also increase overall network utilization of spectrum. A brief overview of Cognitive radio network is given. To access the spectrum secondary users need MAC protocol which can protect primary user transmission and fairly allocate unused spectrum among multiple SUs. Different categories of MAC protocols are summarized to provide good understanding of same for CRN. Comparison of various MAC protocols for CRN is also provided.

Table 1: Distinguishing Characteristics of various MAC protocols for Cognitive Radio Network

Protocol	*CRN architecture*	*Spectrum sharing*	*Channel access*	*Uses control channel*	*No. of transceivers*
POMDP[10]	Ad hoc	OSA	Hybrid	No	1
OSA-MAC[11]	Ad hoc	OSA	Time-slotted	Yes	1
CSMA-MAC[12]	Infrastructure	CSA	Random	No	1
OTT-MAC[13]	Ad hoc	OSA	Hybrid	Yes	2
Cr-MAC[14]	Ad hoc	OSA	Hybrid	Yes	1
FDM- MAC [16]	Ad hoc	OSA	Random	May/may not	Multiple
C-MAC [17]	Ad hoc	OSA	Time-slotted	No	Multiple
HC-MAC[18]	Ad hoc	OSA	Random	Yes	1
Opportunistic-MAC [19]	Ad hoc	OSA	Hybrid	Yes	2

References

[1] FCC, ET Docket No 03-222," Notice of Proposed Rule Making and Order," Dec. 2003.
[2] J. Mitola and G.Q. Maguire, "Cognitive radio: Making software radios more personal," IEEE Personal Communications, vol. 6, no. 4, pp. 13-18, Aug. 1999.
[3] FCC, ET Docket No 02-135, "Spectrum Policy Task Force Report", Nov. 2002.
[4] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," IEEE Journal of Selected Areas in Communications, vol. 23, no. 2, pp. 201–220, Feb. 2005.
[5] I. F. Akyildiz, W. Y. Lee, M. C. Vuran and S. Mohanty, "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey," Computer Networks, vol. 50, no. 13, pp. 2127–2159, Sept. 2006.
[6] J. Mitola, "Cognitive radio—An integrated agent architecture for software-defined radio," Ph.D. dissertation, Roy. Inst. Technol., Stockholm, Sweden, May, 2000.
[7] W. Lehr and J. Crowcroft, "Managing shared access to a spectrum commons," in Proc. IEEE 1st International Symposium on DySPAN, Baltimore, MD, pp. 420–444, Nov. 2005.
[8] Q. Zhao and B.M. Sadler, "A survey of dynamic spectrum access," IEEE Signal Process. Mag., vol. 24, no. 3, pp. 79–89, May 2007.
[9] Y.C. Liang, K.C. Chen, G.Y. Li, P. Mähönen, "Cognitive Radio Networking and Communications: An Overview," IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, vol. 60, no. 7, Sept. 2011.

Licensed Under Creative Commons Attribution CC BY

[10] Q. Zhao, L. Tong, A. Swami and Y. Chen, "Decentralized Cognitive MAC for Opportunistic Spectrum Access in Ad Hoc Networks: A POMDP Framework," IEEE, vol. 25, no. 3, pp. 589-600, Apr. 2007.
[11] L. Le and E. Hossain, "A MAC protocol for Opportunistic Spectrum Access in Cognitive Radio Networks," in Proc. IEEE WCNC, Las Vegas, NV, pp. 1426–1430, Mar. 2008.
[12] S.Y. Lien, C.C. Tseng and K.C. Chen, "Carrier Sensing based Multiple Access Protocols for Cognitive Radio Networks," in proc. IEEE International Conference on Communications, pp. 3208-3214, May 2008.
[13] M. Chowdhury and Asaduzzaman, "An Opportunistic Two Transceiver Based MAC Protocol for Cognitive Radio Networks," International Journal of Multimedia and Ubiquitous Engineering, vol. 9, no. 12, pp. 49-60, 2014.
[14] S.M. Kamruzzaman, "CR-MAC: A Multichannel Mac Protocol for Cognitive Radio Ad Hoc Networks," International Journal of Computer Networks & Communications, vol.2, no.5, pp. 1-14, Sept. 2010.
[15] L. Jiao and F.Y. Li, "A Single Radio Based Channel Datarate-aware Parallel Rendezvous MAC Protocol for Cognitive Radio Networks," in Proc. 34th Conference on Local Computer Networks, IEEE, pp. 392–399, Oct. 2009.
[16] N. Choi, M. Patel and S. Venkatesan, "A Full Duplex Multi-channel MAC protocol for Multi-hop Cognitive Radio Networks," in Proc. 1st International Conference on CROWNCOM, IEEE, Mykonos Island, Greece, pp. 1–5, June 2006.
[17] C. Cordeiro and K. Challapali, "C-MAC: A Cognitive MAC Protocol for Multi-Channel Wireless Networks," in Proc. Dynamic Spectrum and Access Networks, IEEE, pp. 147-157, Apr. 2007.
[18] J. Jia, Q. Zhang, and X. Shen, "HC-MAC: A Hardware-Constrained Cognitive MAC for Efficient Spectrum Management," IEEE, vol. 26, no. 1, pp. 106–117, Jan. 2008.
[19] H. Su and X. Zhang, "Cross-Layer based Opportunistic MAC Protocols for QoS Provisionings over Cognitive Radio Wireless Networks," IEEE, vol. 26, no. 1, pp. 118–129, Jan. 2008.
[20] M.Y. Elnainay, F. Ge, Y. Wang, A.E. Hilal, Y. Shi, A. B. Mackenzie, and C.W. Bostian, "Channel Allocation for Dynamic Spectrum Access Cognitive Networks Using Localized Island Genetic Algorithm," in Proc. 5th International Conference on Testbeds and Research Infrastructures for the Development of Networks & Communities and Workshops, IEEE, pp. 1-3, Apr. 2009.
[21] D. Niyato and E. Hossain, "A Game-Theoretic Approach to Competitive Spectrum Sharing in Cognitive Radio Networks," in Proc. Wireless Communications and Networking Conference, IEEE, pp. 16-20, Mar. 2007.

Licensed Under Creative Commons Attribution CC BY