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Performance Evaluation: Cognitive Medium Access Control Protocols

Shimaa Abdzaher[1], Imane Saroit[2]

[1]Computer Science, Faculty of Computers and Information, Suez University, Suez, Egypt
[2]Information Technology, Faculty of Computers and Artificial Intelligence, Cairo University, Suez, Egypt

ABSTRACT
A comprehensive study and an accurate comparison are introduced about what are the integrated features of medium access control protocols for cognitive radio ad hoc wireless networks. This study Also provides comparison of thirty medium access control protocols designs according to the mentioned features. Finally, we evaluate the performance of two systems for medium access control protocols; common control-multi channels cognitive medium access control protocol and non-common control -multi channels cognitive medium access control protocol using Network Simulator 2. This study shows the impact of increasing the packet size on the performance metrics such as network throughput and the packet delivery ratio. Simulation results prove that common control-multi channels cognitive medium access control protocol outperforms non-common control-multi channels cognitive medium access control protocol in all aspects of performance metrics with increasing the packet size.

KEYWORDS: *Cognitive radio, cognitive radio networks, dynamic spectrum access, medium access control protocols, opportunistic spectrum access, spectrum sharing, Performance evaluation*

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INRODUCTION

The Cognitive Radio Ad Hoc Network (CRAHN), comprehensively investigated in [1] [2], is a hopeful wireless network and it is considered a suggested solution to cope with the great increase requirements on modern communications. CRAHN, also known distributed wireless network, can solve the issues of fixed policies of the spectrum regulation such as an inefficient usage of whole spectra [3]. In this review, we comprehensively concentrate on the CRAHNs based on the Opportunistic Spectrum Access Concept (OSA). In OSA, each user is called unlicensed user or Secondary User (SU). Each SU is allowed to opportunistically exploit the free licensed bands (LCs) under the following condition: the absence of the owner of the licensed band 'Primary User'(PU) [4]. In literature, features of Cognitive Medium Access Control protocols (CR-MACs) have been widely discussed and several surveys have been shown. The best of our knowledge, is [2] considered the first survey which exhaustively investigates CRAHNs. In [2], the key features and current research issues of CRAHNs are addressed and studied. In [5], the pros and the cons of several existing CR-MACs are implicitly provided on basic functions of CR-MAC. In [6], an efficient discussion has been shown where twenty-two CR-MAC protocols are compared. Nana et.al. [7] concentrate on two major perspectives related to the designs of CR-MAC protocols. The authors also reviewed the functions of Dynamic Spectrum Access (DSA) from the point of MAC protocol design. In DSA, every user can dynamically exploit the free channels. In [8], the authors introduced the important features of CRMACs by general classification and systematization for CRMAC protocols. of CR-MACs features and introduce more integrated insight of how CR-MACs can perform their functions. In section 3, a comprehensive review and detailed comparison of thirty conventional CR-MACs found in literature are given according to the proposed features. The authors in [9], provided a surveyed study of the cooperative medium access control protocol. In [10], the paper concentrated on the literature problems which affect the CRAHNs and the processing standardization efforts are mentioned. In section 2, we extend the study and analysis of CR-MACs features and introduce more integrated insight of how CR-MACs can perform their functions. In section 3, a comprehensive review and detailed comparison of thirty conventional CR-MACs found in literature are given according to the proposed features.

Integrated Features for Cognitive Medium Access Control Protocols

➢ **Number of Radios**

The efficient CR–MAC design should basically depend on the number of used radios /transceivers. The number of required radios can be divided into three types: CR–MAC based on single transceiver, CR-MAC based on only two transceivers one for exchanging control data and another one for data transmission and CR-MAC based on Multi-

Radios It is preferable that CR-MACs possess one radio rather than two or multi- radios in order to save energy consumption and reduce the cost.

➢ **Prior Knowledge of Licensed Bands**

There are two categories of PUs systems: one-way communication systems such (TV band, radio broadcasts) and two-way communications' system in which there are bidirectional communications between PU transmitter (PU Rx), PU receiver (SU Rx) used for spectrum sensing [11]. However, the CRMAC designer must determine in which PU Systems, the CRMAC can operate. A prior knowledge of the PUs systems may affect MAC designs where the number of used antennas of PUs system influences on selecting perfect transmit strategy of SUs. For example, when PU Rx and SU Rx have only single antenna, the cognitive beam-forming [12] can be used in transmit strategy. Another Example, in TV bands, many TVs Programs may be previously determined in some areas. Hence, the free spectrum information can be broadcast to SUs. Another observation provided in [13] is that the delay of all CR- MAC classes becomes higher with increasing PU packet size. When the PU signal waveform, the noise power, and the cyclic frequency of the PU signal are all known to theSU users, this may help SUs for rapidly detecting the PU signal. If no information is allowed about licensed networks, a suitable spectrum sensing schedule must be taken into consideration.

➢ **Prior Knowledge of Secondary Users Systems Around**

Based on the topology information such as one-hop neighbor information, two-hop neighbor information, whole the network topology information, SU can select the efficient broadcast mechanism for saving the energy consumption [14].

➢ **Single/parallel rendezvous**

In CRAHNs, when two SUs need to establish a link and initialize communications, they need to find each other first. This process is basically known as rendezvous or neighbor discovery [15]. A rendezvous is basically a meeting at an appointed time and place [16]. Since a channel only presents an opportunity to the SU pair if it is available at both the transmitter and the receiver, spectrum opportunities need to be identified jointly by both the SU transceiver and the SU receiver. This is known as spectrum Opportunity identification (rendezvous) problem in [59]. In literature, there are a single rendezvous common channel (SRCC) and parallel rendezvous common channel (PRCC) schemes for exchanging control information.

- In SRCC protocols, the exchange of control information happens on only one channel at any time.
- In PRCC schemes, also known as multiple rendezvous in [17], utilize available channels in parallel such that multiple SUs can exchange control information at the same time, using all free channels [18]. Each SU knows the hopping pattern of the other SUs which easily makes control exchange potential by following the intended SU receiver's hopping pattern. PRCC highly distributes both control and data exchanges across the LCs by using random way.

➢ **Efficient sensing Schedule**

Sensing techniques are divided into two categories: cooperative-based technique(C-based) and self -based technique(S-based). In c-based sensing techniques, all SUs cooperate for constructing the sensing results table by exchange their sensing information about free channels. In s-based sensing technique, each SU should collect the sensing results and construct the sensing result table by itself. This table contains the free channels.

➢ **Control channel in licensed band or unlicensed band**

Common control channels (CCC) may be in licensed band, in unlicensed bans, or construct in both. CR-MACs designs should clarify in which bands will operate.

➢ **Spectrum Allocation method for free channels**

In which SUs should make a wise decision for selecting the best available channels (the best opportunity) with efficient transmission parameters [19]. After successful sensing mechanism, all available free channel should be determined in list. Then, each SU can select the best free opportunity from the list. The accuracy of spectrum allocation process has typically important effects on both the network throughput and the overall spectrum utilization [20]. CR-MAC must decide which channel or set of channels to use among the potentially large pool of spectrum available for opportunistic use.

➢ **Spectrum Access Techniques**

In literature, the access to the spectrum is usually occurred through" sense-before-transmit" concept, i.e., a channel is sensed before any transmission and another one is searched if the PU is active on this channel. There are three conventional spectrum access schemes; contentions-based, time slotted and hybrid) [21]:

- Random access scheme is generally based on the collision multiple accesses with collision avoidance (CSMA/CA) concept and No time synchronization is needed. Each secondary user scans the spectrum band to detect when there is no transmission from the rest of SUs and from the PU side. Then, SU transmits after a back off duration to prevent collision among other secondary users. These Schemes also need to spend more time in exchanging control information massage [22]. Hence, the method may waste opportunities.
- Time-slotted also known Time Division Multiple Access (TDMA) Scheme, requires general synchronization among all secondary users, where time is slotted into slots for both the control messages and the data transmission.
- Hybrid scheme uses a partially slotted portions, in which the control information messages generally occur over synchronized time slots. Then, the data transmission may have random access methods without time synchronization. Another form of hybrid CRMAC protocol is in which the for control and data transmission may have predefined constituting a super frame. Each super frame is common to all SUs in the network. Within each control or data duration, the access to the available channel may be completely random. Hybrid CR-MAC protocols and time slotted CRMAC protocols require synchronization among the SUs in the CRAHNs which is a challenge without using a centralized unit.

➢ **Secondary user Adaption with Primary User sudden Appearance**

CR-MAC protocols for such CRAHNs must overcome the sudden presence of the PUs in available channels. They must be sensitive to the presence or absence of PUs in particular bands because the SUs must vacate any band soon after a PU starts transmission in it [23]. In existing literature, there are three strategies to show how the SU copes with the sudden appearance of the PU as shown in Figure 1. In the following subsections, three strategies are discussed.

1. NO Buffer and No Switch strategy

Each SU should vacate operational channel due to the sudden appearance of the PU in this channel and the transmission is lost. This leads to high depletion of all network performance.

2. Buffer strategy

The SU buffers its transmission in case of the PU appearance until the PU ends its transmission. Then, it resumes its transmission at the same channel. A buffered connection time expires after specific time. The SU may not be able to re-establish its transmission due to the PU which is still in this channel also results to high delay [24,25]. The SUs connection is discarded.

3. Switch Strategy

When PU suddenly appears on the operational channel used by SU, the SU should rapidly vacate thischannel, select and switch to new available channel [26-32].

➢ **Energy Consumption Efficiency**

The battery consumption is generally one of the basic design issues in ad hoc networks If Cognitive Radio technology is applied on the Ad hoc devices like laptop, smart phones, and wireless sensors networks, it will cause battery consumption issue [33] and [34] due to spectrum sensing requirements, coexistence and mobility processes. The battery consumption is one of the major issues in ad hoc/mobile devices. Hence, developing efficient CR-MAC design with energy saving mechanism for CRAHNs is now today's need. CRMAC design should take into consideration the efficient usage of energy consumption in order to typically accommodate less power consumption, high transmission rate and high throughput [35]. Therefore, one of the most important targets in CR- MAC protocol design is how to efficiently use available channels and limited power budget in order to increase the whole network throughput.

➢ **Quality of Service Provisioning**

CRAHNs should meet the quality of service requirements.

➢ **Bootstrapping**

It means that how the new secondary user (SU fir) joints the CRAHNs. Bootstrapping is the process during which a new SU wants to starts or joins CRAHN and decides which PU channels are suited to opportunistic spectrum communication. Each SU senses those channels. Next to finding the free channels, each SU should inform its set of free channels to other SUs in the network [13]. In perspective of Q. o. S, A bootstrapping delay is also very important factor [37].

➢ **Fairness issue**

The solution to achieve the fairness requirement among SUs in CRAHNS, is that CR- MAC design incorporate the enhanced version of bake-off scheme of IEEE802.11. CRMAC design should grantee how to achieve the fairness among all the secondary users in the CRAHNs.

Comparison of Twenty Cognitive Medium Access Control Protocols

Thirty CR-MACs are studied and analyzed based on the previous properties in tables [I-IV].

Simulation Scenario

➢ **Simulation Tools**

Enhancement version of network simulator (NS2) is proposed to be efficient for the proposed simulation stages. The proposed simulation model is set by using a combination of (NS2-CRAHN) [60] an extension of NS2 and the simulation framework for cognitive radio network (CogNS) [61]. Then, the performance of the multi channels cognitive medium access control protocol (CM-CMAC) and the performance of the multi channels Cognitive medium access control protocol (Non-CM-CMAC) protocol for the proposed CRAHN are tested, and analyzed. Finally, the results are compared and evaluated.

➢ **Simulation Model**

In simulated CRAHN, twenty-six SUs are participated used ten licensed channels. The used propagation model of SU is Two-ray ground model. The used routing protocol is the dynamic source routing protocol. Each simulation is executed 11 times and results are averaged. The simulation run time for each simulation is 100s. The number of PUs is 10.

➢ **Simulation Results**

Simulation results introduces that CM-CMAC protocol outperforms the non-CM-CMAC protocol in all aspects of performance metrics with increasing the packet size. In next Parts, we typically illustrate the impact of increasing the packet size on the CRAHN's performance metrics such as average throughput and packet delivery ratio.

- **The impact of increasing the packet size on the average throughput**

"Fig. 1," displays the impact of increasing the packet size on the network throughput. It is noticed that the average throughput of the simulated system using the CM-CMAC protocol is better than it using Non-CM-CMAC protocol.

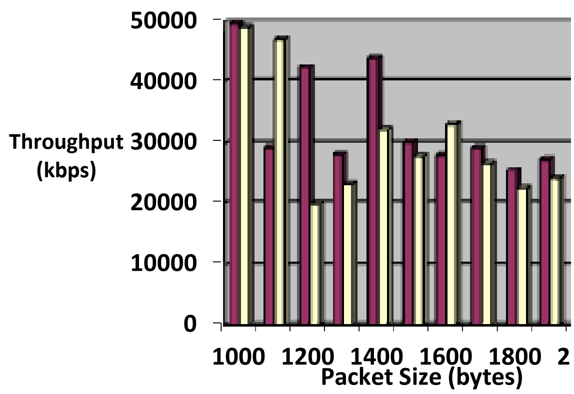

Fig.1. the impact of increasing the packet size on network throughput for both protocols

- **The impact of increasing the packet size on the packet delivery ratio**

"Fig. 2," shows the impact of increasing the packet size on the packet delivery ratio. It is noticed that the packet delivery ratio of the simulated scenario using the CM-CMAC protocol is better than it using Non-CM-CMACs-protocol.

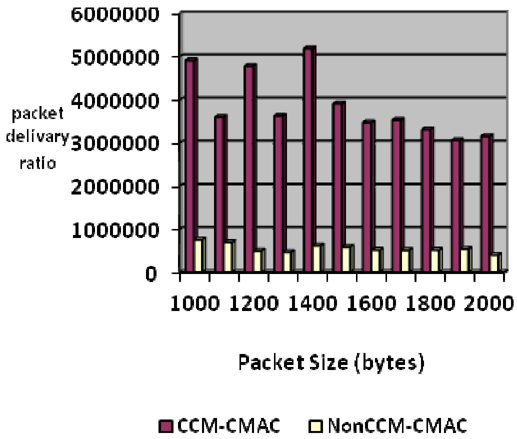

Fig.2. the impact of increasing the packet size on packet delivery ratio for both protocols

Conclusion

The integrated features of CR-MAC protocols for CRAHNS are introduced. A comparison of Thirty CR-MAC protocols designs is provided according to the mentioned proprieties. The impact of increasing the packet size affects the performance of whole CRAHNs. Simulation results prove that common control-multi channels C- MAC outperforms non-common control-multi channels C-MAC in every aspect of the performance metrics with increasing the packet size.

TABLE I TABLE STYLES

properties	Protocols				
Table Head	**SWITCH [20]**	**Wang et.al [30]**	**CREAM-MAC [27]**	**A-MAC [38]**	**EECR-MAC [39]**
No. of Radio	2	-	Multi	2	1
Radio Interface Prior knowledge of LCs	SDR No	Not discussed No	Multi Sensors + SDR No	GNU Radio + Wi-Fi No	Not discussed No
period knowledge of networks around	No	No	No	No	No
Single/parallel rendezvous SR/PR	SR	PR	SR	SR	SR
Efficient sensing Schedule	c-based	C-based	C-based	C-based	C-based
Control Channel in Licensed Channel LC/ Unlicensed	UC	UC	UC	UC	UC
Channel UC Control Information Exchange	CCC	CCC	CCC	CCC	CCC
Spectrum Allocation method for free channel Spectrum Access Techniques	Not discussed Random	Smart Ch. selection Random Access	Use aggregation method Random Access	Not discussed Hybrid	CDA method Time - slotted
Adaption of Primary User sudden Appearance	Access Switch With	Switch	Stop	Stop	Stop
Energy Consumption	BC Not	Not discussed	Not discussed	Not discussed	Yes
Quality of. Service Provisioning	discussed Not	Not discussed	Not discussed	Yes	Not discussed
Bootstrapping	discussed Not	Not discussed	Not discussed	Yes	Not discussed
Fairness issues	discussed Yes	No	Yes	No	Yes
Inefficient Spectrum Utilization	Try to solved	Not Solved	Not Solved	Not Solved	Try To solved

TABLE II A Comprehensive Analysis of Conventional Cognitive Radio Medium Access Control Protocols

Properties	Protocols				
	DDH-MAC [40]	OSABR [16]	MCRN [41]	ACAP-MAC [42]	SAMAR-MAC [43]
No. of Radio	2	1	2	1	1
Radio Interface	Half-duplex	DSR	-	-	-
Prior knowledge of licensed band	No	No	No	Yes	No
period knowledge of networks around	No	No	No	No	No
Single/parallel rendezvous SR/PR	PR	SR	SR	SR	SR
Efficient sensing Schedule	C-based	C-based	C-based	C-based	C-based
Control Channel in Licensed Channel LC/ Unlicensed Channel UC	UC+LC	UC +LC	LC	LC	LC
Control Information Exchange	CCC	No CCC	CCC	CCC	CCC
Spectrum Allocation	Not	Not	discussed	discussed	discussed
method for free channel	discussed	discussed			
Spectrum Access Techniques	Hybrid	Random Access	Random Access	Hybrid	Hybrid
Adaption of Primary User sudden Appearance	Stop	Switch	Stop	Stop	Switch
Energy Consumption	Try To solved	Not discussed	Not discussed	Not discussed	Not discussed
Quality of. Service Provisioning	Try To solved	Not discussed	Not discussed	Not discussed	Yes
Bootstrapping	Yes	Not discussed	Not discussed	No	Not discussed
Fairness issues	Yes	Yes	Yes	Yes	Yes

TABLE III A Comprehensive Analysis of Conventional Cognitive Radio Medium Access Control Protocols

Proprieties	Protocols				
	DSATMAC [44]	DOSS [45]	Mehanna et.al [46]	ECRQ MAC [47]	C-MAC [48]
No. of Radio	1	Multi	1	1	1
Radio Interface	Not discussed	Not discuss	Not discussed	Half-duplex	Half duplex
Prior knowledge of licensed band	No	No	No	No	No
period knowledge of networks around	No	No	No	No	No
Single/parallel rendezvous SR/PR	SR	SR	SR	PR	PR
Efficient sensing Schedule	Self-based	C-based	Self -based	C-based	C-based
Control Channel in Licensed Channel LC/ Unlicensed Channel UC	LC	LC	LC	UC	LC
Control Information Exchange	No CCC	No CCC	No CCC	No CCC	No CCC
Spectrum Allocation method for free channel	Not discussed	Not discussed	Ch. with the lowest statistics of primary traffic	Ch. with best quality	Ch. with the Lowest load Of SUs
Spectrum Access Techniques	Hybrid	Random Access	Time slotted	Time slotted	Time slotted
Adaption of Primary User sudden Appearance	Switch	Stop	Stop	Switch	Stop
Energy Consumption Efficiency	Yes	Not discussed	Not discussed	Try To solved	Not discussed
Quality of. Service Provisioning	Yes	Not discussed	Not discussed	Yes	Yes
Bootstrapping	Yes	Yes	Not discussed	Yes	Yes
Fairness issues	Yes	Yes	No	No	No
Hidden Incumbent Device Problem	Not discussed	Not discussed	Not discussed	Solved	Try to solved

TABLE IV A Comprehensive Analysis of Conventional Cognitive Radio Medium Access Control Protocols

Proprieties	Protocols				
	Su et.al [49]	Zhao et.al [50]	SYN-MAC [51]	DRA-MAC [17]	EDA-MAC [22]
No. of Radio	1	Multi	2	1	1
Radio Interface	SDR	Not discussed	Not discussed	SDR	Half-duplex
Prior knowledge of li censed band	No	Yes	No	Yes	No
period knowledge of networks around	No	No	No	No	No
Single/parallel rendezvous SR/PR	PR	PR	SR	SR	PR
Efficient sensing Schedule	c-based	C-based	c-based	C-based	C-based
Control Channel in Licensed Channel LC/Unlicensed Channel UC	LC	LC	LC	LC	LC
Control Information Exchange	No CCC	No CCC	No CCC	No CCC	No CCC
Spectrum Allocation method for free channel	Not discussed	Not discussed	Not discussed	The Ch. With the highest data rate	Ch. With lowest load
Spectrum Access Techniques	Hybrid	Hybrid	Time slotted	Hybrid	Time slotted
Adaption of Primary User sudden Appearance	Buffer	Stop	Stop	Buffer	Stop
Energy Consumption Efficiency	Not discussed	Not discussed	Not discussed	Not discussed	Yes
Quality of. Service Provisioning	Not discussed	Not discussed	Not discussed	Not discussed	Not discussed
Bootstrapping	Yes	Not discussed	Yes	Yes	Yes
Fairness issues	No	Yes	Yes	Yes	No

TABLE V A Comprehensive Analysis of Conventional Cognitive Radio Medium Access Control Protocols

Proprieties	Protocols				
	DH-MAC [54]	DOFDM [52]	CA-MAC [53]	SHCH MAC [37]	RODMAC [23]
No. of Radio	1	1	2	1	1
Radio Interface	SDR	DOFDM+DSR	Not discussed	Half duplex	Half duplex
Prior knowledge of licensed band	No	No	No	No	No
period knowledge of networks around	No	No	No	No	No
Single/parallel rendezvous SR/PR	PR	SR	PR	PR	PR
Efficient sensing Schedule	C-based	C-based	C-based	C-based	C-based
Control Channel in Licensed Channel LC/ Unlicensed Channel UC	LC	LC	LC	LC	LC
Control Information Exchange	No CCC	No CCC	No CCC	No CCC	No CCC
Spectrum Allocation method for free channel	Dynamic Hop sequence method	Not discussed	Ch. with the least common among SUs	Not discussed	Not discussed
Spectrum Access Techniques	Hybrid	Time slotted	Random Access	Hybrid	Random Access
Adaption of Primary User sudden Appearance	Switch	Stop	Stop	Stop	Switch
Energy Consumption Efficiency	Not discussed	Not discussed	Not discussed	solved	Not discussed
Quality of. Service Provisioning	Not discussed	Not discussed	Not discussed	Not discussed	Yes
Bootstrapping	Yes	Yes	No	Yes	Yes
Fairness issues	Not discussed	Yes	Yes	Yes	Yes

TABLE VI A Comprehensive Analysis of Conventional Cognitive Radio Medium Access Control Protocols

Proprieties	Protocols				
	Cog MAC [55]	Cog MAC+ [59]	C2R MAC [56]	J. Ahn et.al [57]	SPMAC [58]
No. of Radio	1	1	1	1	1
Radio Interface	Half duplex	DSR	-	DSR	USRP
Prior knowledge of licensed band	No	No	No	No	No
period knowledge of networks around	No	No	No	No	Yes
Single/parallel rendezvous SR/PR	PR	PR	SR	PR	SR
Efficient sensing Schedule	c-based	C-based	C-based	C-based	C-based
Control Channel in Licensed Channel LC/ Unlicensed Channel UC	LC	LC	LC	LC	LC
Control Information Exchange	No CCC	No CCC	No CCC	No CCC	No CCC
Spectrum Allocation method for free channel	Not discussed	Not discussed	Not discussed	Not discussed	Not discussed
Spectrum Access Techniques	Random Access	Random Access	Time slotted	Time slotted	Time slotted
Adaption of Primary User sudden Appearance	Buffer	Buffer	Stop	Stop	Stop
Energy Consumption Efficiency	Not discussed	Yes	Not discussed	Yes	Not discussed
Quality of. Service Provisioning	Not discussed	Not discussed	Not discussed	Not discussed	Not discussed
Bootstrapping	Yes	Yes	Not discuss	Yes	Not discussed
Fairness issues	Yes	Yes	Yes	Yes	Not discussed

References

[1] Y. C. liang, C. Chen, G. Z. Li, and P. Mahonen, "Cognitive radio networking and communications: An overview," IEEE Trans. Veh. Technol., vol. 60, no. 7, pp. 3386–3407, 2011.

[2] I. F. Akyildiz, W. Y. Lee, and K. R. Chowdhury, "CRAHNs: Cognitive Radio Ad Hoc Networks," Ad Hoc Network, vol. 7, no. 5, pp. 810–836, 2009.

[3] R. Kaur, A. S. Buttar, and J. Anand, "Methods of Hybrid Cognitive Radio Network: A Survey," in Second International Conference on Elec- tronics, Communication and Aerospace Technology (ICECA). IEEE, 2018, pp. 1285–1289.

[4] S. abdzaher, M. Abdrabou, A. Al-shami, and I. Saroit, "Performance Evaluation of Medium Access Control Protocols for Cognitive Radio Ad Hoc Networks," in 2019 International Conference on Innovative Trends in Computer Engineering (ITCE). IEEE, 2019, pp. 76–79.

[5] C. Cormio and K. R. Chowdhury, "A survey MAC Protocol for Cognitive Radio Networks," Ad Hoc Network, vol. 7, no. 7, pp. 1315–1329, 2009.

[6] A. De Domenico, E. C. Strinati, and M. G. D. Benedetto, "A survey on MAC strategies for cognitive radio networks," IEEE Commun. Surveys, Tutorials, vol. 14, no. 1, pp. 21–44, 2012.

[7] A. Ali, W. Huiqiang, L. Hongwu, and X. Chen, "A survey of mac protocols design strategies and techniques wireless ad hoc networks," Journal of Commun., vol. 9, no. 1, pp. 30–38, 2014.

[8] L. Gavrilovska, D. Denkovski, V. Rakovic, and M. Angjelichinoski, "Medium Access Control Protocols in Cognitive Radio Networks: Overview and General Classification," IEEE Commun. Surveys Tutorials, vol. 16, no. 4, pp. 2092–2124, 2014.

[9] M. Sami, N. K. Noordin, M. Kazazian, F. Hashim, and S. Subramaniam, "A Survey and Taxonomy on Medium Access Control Strategies for Cooperative Communication in Wireless Networks: Research Issues and Challenges," IEEE Commun. Surveys Tutorials, vol. 18, no. 4, pp. 2493– 2521, 2016.

[10] P. Ren, Y. Wang, and J. Q. Du, "A survey on dynamic spectrum access protocols for distributed cognitive wireless networks," J. Wirel. Commun. Netw., vol. 60, pp. 1–21, 2012.

[11] J. Mitola, "Cognitive Radio Architecture Evolution," IEEE Journals Magazine, vol. 97, no. 4, pp. 626–641, 2009.

[12] R. Zhang and Y. Liang, "Exploiting multi-antennas for opportunistic spectrum sharing in cognitive radio networks," IEEE J. Sel. Topics Signal Process. (STSP), vol. 2, no. 1, pp. 88–102, 200888.

[13] B. Li, Q. Qu, Z. Yan, and M. Yang, "Survey on OFDMA based MAC protocols for the next generation WLAN," in IEEE Wirel. Commun. Netw. Conf. (WCNCW), 2015, pp. 2493–2521.

[14] CH. Min Chao, D. JyiHuang, and Y. RuPeng, "Energy efficient broadcast in multi-hop cognitive radio networks," J. Computer Commun, vol. 72, pp. 1–11, 2015.

[15] B. Li, Q. Qu, Z. Yan, and M. Yang, "Survey on OFDMA based MAC protocols for the next generation WLAN," in IEEE Wirel. Commun. Netw. Conf. (WCNCW). IEEE, 2015, pp. 2493–2521.

[16] H. Al-Mahdi, M. Wahed, and S.A. El-Aziz, "Design and

Analysis of an OSA BR MAC Protocol for Cognitive Radio Ad Hoc Networks," International Journal Commun. Netw. Sys. Sciences, vol. 7, no. 7, 2014.

[17] L. Jiao and F. Y. Li, "A single Radio Based Channel Data rate aware parallel Rendezvous MAC protocol for Cognitive Radio Networks," in 34th Conf. on Local Computer Netw. (LCN). IEEE, 2009, pp. 392–399.

[18] F.F. Qureshi, "Energy Efficient Cognitive Radio MAC Protocol for Ad hoc Networks," in Wirel. Telecommun. Sympos. (WTS), ser. 5, vol. 1, 2012.

[19] J. Marinho and E. Monteiro, "Cognitive radio: survey on communication protocols, spectrum decision issues, and future research directions," J. Wirele Netw., vol. 18, no. 2, pp. 147–164, 2012.

[20] M.A. Kalil, A. Puschmann, and A. Mitschele-Thiel, "SWITCH: A Multi- channel MAC Protocol for Cognitive Radio Ad Hoc Networks," in Vehicular Technology Conf. (VTC), 2012, pp. 1–5.

[21] l. f. Akyildiz, W. Y. Lee, and K.R. Chowdhury, "Spectrum Management in Cognitive Radio Ad Hoc Networks," IEEE Netw., vol. 23, no. 4, pp. 6–12, 2009.

[22] C.S. Hus, Y.S. Chen, and C. E. He, "An Efficient Dynamic Adjusting MAC Protocol for Multi-channel Cognitive Wireless Networks," in IEEE international conf. wirel. Commun. Network information Security (WCNISC), 2010, pp. 556–560.

[23] E. Nanda, U. Joshi, V. Ribeiro, and H. Saran, "RODMAC: A Robust and Distributed MAC protocol for efficient use of white spaces," in IEEE, International Conf. Commun. Sys. Netw., 2013, pp. 1–10.

[24] J. PARK, P. Pawelczak, and D. Cabric, "To Buffer or to Switch: Design of multi-channel MAC for OSA Ad Hoc Networks," in IEEE, DYSPAN. IEEE, 2010, pp. 1–10.

[25] H. Al-Mahdi and M. A. Kalil, "A Dynamic Hop-Aware Buffer Man- agement Scheme for Multi-hop Ad Hoc Networks," IEEE Commun. Lett. (COMML), vol. 6, no. 1, pp. 22–25, 2017.

[26] J. Ansari, X. Zhang, A. Achtzehn, M. Petrova, and P. Mahonen, "A Flex- ible MAC Development Framework for Cognitive Radio Systems," in WCNC. IEEE, 2011, pp. 156–161.

[27] X. Zhang and H. Su, "CREAM-MAC: Cognitive Radio-Enabled Multi- Channel MAC Protocol Over Dynamic Spectrum Access Networks," IEEE J. Sel. Topics Signal Process. (STSP), vol. 5, no. 1, pp. 110–123, 2011.

[28] M. A. Kalil, H. Al-Mahdi, and A. Mitschele Thiel, "Spectrum Hand off Reduction for Cognitive Radio Ad Hoc Networks," in 7th Interna. Sympos. Wirel. Commun. Sys. (ISWCS). IEEE, 2010, pp. 1036–1040.

[29] M. A. Kalil, H. Al-Mahdi, and A. Mitschele-Thiel, "Analysis of oppor- tunistic spectrum access in cognitive ad hoc networks," in the 16th International Conf. on Analytical and Stochastic Modelling Tech. App.(ASMTA 2009), 2009. IEEE, pp. 9–12.

[30] S. Y. Wang, Y. M. Huang, L. Lau, and C. C. lin, "Enhanced MAC Protocol for Cognitive Radios over IEEE 802.11 Networks," in IEEE Wireless Network Conf. (WCNC), 2011, pp. 37–42.

[31] H. Al-Mahdi and M. A. Kalil, "Dynamic Hop-Aware Buffer Management Scheme for Multi-hop Ad Hoc Networks," Wirel. Communn. Let vol. 6, no. 3, pp. 358–361, 2017.

[32] P. Ren, Y. Wang, and Q. Du, "CAD-MAC: A Channel Aggregation Diver- sity Based MAC Protocol for Spectrum and Energy Efficient Cognitive Ad Hoc Networks," IEEE J. Sel. Areas Commun. (SAC), vol. 32, no. 2, pp. 237–250, 2013.

[33] V. A. Badruddoza, "On the Energy Efficiency of Cognitive Radios- A Study of the Ad Hoc Wireless LAN Scenario," in Green Comput. Conf. Workshops, (IGCC),2011.

[34] L.Gavrilovska, Denkovski, V. Rakovic, and M. Angjelichinoski, "Medium Access Control Protocols in Cognitive Radio Networks: Overview and General Classification," IEEE Commun. Surveys Tutorials, vol. 16, no. 4, pp. 2092–2124, 2014.

[35] M. T. Zia, F.F. Qureshi, and S. S. Shah, "Energy Efficient Cognitive Radio MAC Protocols for Ad hoc Network: A Survey," in 15th International Conf. on Computer Modelling and Sim. (UKSim), IEEE, 2013, pp. 140– 143.

[36] A. Hsu, D. Weiy, and C. Kuo, "A Cognitive MAC Protocol Using Statistical Channel Allocation for Wireless Ad-hoc Networks," in Wirel. Commun. Netw. Conf. (WCNC). IEEE, 2007, pp. 105–110.

[37] Y. Lee and D. Kim, "Slow hopping based cooperative sensing MAC protocol for cognitive radio networks," ELSIEVIR, J, Computer Netw., vol. 62, pp. 12–28, 2014.

[38] K. Huang, X. Jing, and D. Raychaudhuri, "MAC Protocol Adaptation in Cognitive Radio Networks: An Experimental Study," in 18th Interna- tional Conf. Computer Communication Network (ICCCN), 2009, and others, Ed., pp. 1–6.

[39] P. Ren, Y. Wang, and Q. Du, "A Channel- Aggregation Diversity Based MAC Protocol for Spectrum and Energy Efficient Cognitive Ad Hoc Networks," IEEE J. Sel. Areas Commun. (SAC), vol. 32, no. 2, pp. 237–250, 2013.

[40] M.A. Shah, G.A. Safdar, and C. Maple, "DDH-MAC: A Novel Dynamic De-Centralized Hybrid MAC Protocol for Cognitive Radio Networks," in 10 th international ROEduNet Conf., 2011, pp. 1–6.

[41] W. Alhakami, A. Mansour, and G.A. Safdar, "Performance analysis of a novel decentralized MAC protocol for cognitive radio networks," in IEEE Asia Pacific Conf. on Wireless and Mobile (APWiMob), 2016, pp. 85–91.

[42] M. Anany and S.G. Sayed, "Opportunistic multi-channel MAC protocol for cognitive radio networks," in IEEE Canadian Conf. Electrical and Computer Engineering (CCECE), 2016, pp. 1–6.

[43] R. B. Battula, A.R. Avuthu, and S. N. Venkata, "SAMAR — Spectrum Aware token MAC for Cognitive Radio

Networks," in IEEE 31st International Conf. Advanced Information Netw. App. (AINA), 2017, pp. 686–691.

[44] R. K. Shakya, S. Agarwal, Y. N. Singh, N.K. Verma, and M. Roy, "DSAT- MAC: Dynamic Slot Allocation based TDMA MAC protocol for Cognitive Radio Networks," J. Computer Science Network Internet Architecture, pp. 1–6, 2013.

[45] L. Ma, X. Han, and C. C. Shen, "Dynamic open spectrum sharing MAC protocol for wireless ad hoc networks," in In New Frontiers in Dynamic Spectrum Access Networks, 1th DySPAN. IEEE, 2005, pp. 203–213.

[46] O. Mehanna, A. Sultan, and H. ElGamal, "Blind Cognitive MAC Proto- cols," in ICC. IEEE, 2005, pp. 1–5.

[47] M. AbdullahAl-Wadud, "An Energy Efficient MAC Protocol for Q o S Provisioning in Cognitive Radio Ad hoc Networks," J. Radio Engin., vol. 9, no. 4, pp. 567–578, 2010.

[48] C. Cordeiro and K. Challapali, "C-mac: A cognitive mac protocol for multi-channel wireless networks," in In New Frontiers in Dynamic Spectrum Access Networks (DySPAN). IEEE, 2007, pp. 147–157.

[49] H. S and X. Zhang, "Channel-Hopping Based Single Transceiver MAC for Cognitive Radio Networks," in 42nd Annual Conf. Info. Sciences Sys. (CISS), 2008.

[50] Q. Zhao, L. Tong, A. Swami, and Y. Chen, "Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: a POMDP framework," IEEE J. Sel. Areas Commun. (SAC), vol. 25, no. 3, pp. 589–600, 2007.

[51] Y. R. Kondareddy and P. Agrawal, "Synchronized MAC Protocol for Multi-hop Cognitive Radio Networks," in ICC -3202(2008)., 2008, pp. 3198–3202.

[52] M. Lee and T-J. Lee, "Multi-channel MAC Protocols with Dis- contiguous-OFDM for Cognitive Radio Networks," in International conf. Informatic Engin. Information Science (ICIEIS). Springer, 2011, pp. 594–603.

[53] S.K. Timalsina, S. Moh, L. Chung, and M. Kang, "A concurrent access MAC Protocol for cognitive radio ad hoc networks without common control channel," EURASIP J. on Advances in signal processing, pp. 1–13, 2013.

[54] C.F. Shih, T.Y. Wu, and W. Liao, "DH-MAC: A Dynamic Channel Hopping MAC Protocol for Cognitive Radio Networks," in ICC. IEEE, 2010, pp. 1–5.

[55] J. Ansari, X. Zhang, and P. Mahonen, "A Decentralized MAC Access in Cognitive Wireless Networks," J. Computer Commun., vol. 36, no. 13, pp. 1399–1410, 2013.

[56] M. Luıs, R. Oliveira, R. Dinis, and L. Bernardo, "A Novel Reservation-Based MAC Scheme for Distributed Cognitive Radio Networks," IEEE Trans. Veh. Technol., vol. 66, no. 5, pp. 4327–4340, 2017.

[57] J. Ahn, K. Kwon, M. J. Hoh, and D. Kim, "Time synchronization for SHCS-MAC based multi-hop cognitive radio networks," in IEEE Annual Consumer Commun. Netw. Conf. (CCNC),1018-1019,2017. IEEE, 2017, pp. 1018–1019.

[58] J. Kim, S. Ko, H. Cha, and S. Kim, "Sense-and-predict: Opportunistic MAC based on spatial interference correlation for cognitive radio networks," in IEEE (DySPAN). IEEE, 2017, pp. 1–10.

[59] P. Wang, M. Petrova, J. Ansari, and P. Mahonen, "Cog-MAC+: A decen- tralized MAC protocol for opportunistic spectrum access in cognitive wireless networks," J. Computer Commun., vol. 79, pp. 22–36, 2016.

[60] M. Di Felice, K. Chowdhury, W. Kim, A. Kassler, L. Bononi, End-to-end protocols for cognitive radio ad hoc networks: an evaluation study, J. performance evaluation (2011), 859-875.

[61] http://cogns.net/. Last access August 2018.