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An Efficient MAC Protocol for Improving the Network Throughput for Cognitive Radio Networks

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***Abstract*— The limitation of spectrum has become a major bottleneck of the development of next generation radio system. One of the key challenges of the emerging opportunistic cognitive radio is how to utilize unused spectrum holes efficiently without interference to incumbent system. Assuming that channel status is known, in this paper, we propose a decentralized adaptive medium access control (AMAC) protocol that has no dedicated global common control channel (CCC) and can utilize available resources efficiently. In AMAC, each cognitive radio maintains channel status table and indexes them frequently. The channel that has more probability to be stable is ranked channel one. The most reliable common channel between communicating pair is selected as a CCC. We proposed two data communication mode according to the channel condition. The simulation results show that the proposed decentralized adaptive medium access control (AMAC) protocol significantly increases cognitive radio networks (CRNs) connectivity and data throughput.**

Keywords-cognitive radio networks; MAC protocol; common control channel; cognitive MAC.

I. INTRODUCTION

Due to the fixed radio spectrum allocation system, some licensed radio spectrum resources are underutilized. On the other hand the limitation of unlicensed spectrum has become a major bottleneck for the development of next generation radio system. Measurement has shown that large portion of the licensed spectrum remains unused or underutilized. The spectrum policy task force report of the Federal Communication Commission (FCC) [1] shows that over 70% of the allocated spectrum is not in use at any given time, even in a highly dense area where the spectrum is intensive. Cognitive radio [2]-[4] came up with the idea of open spectrum that allow secondary users to utilize these underutilize spectrum bands opportunistically. Multi-hop cognitive radio is similar to multi-channel wireless multi-hop networks but the protocols used in multi-channel wireless networks cannot directly be used in multi-hop cognitive radio because communication channel availability for the secondary users depends on the primary users' occupancy on the channel.

In this paper, we present a decentralized adaptive medium access control (AMAC) protocol for cognitive radio. We consider cognitive devices that can communicate in both industrial, scientific and medical (ISM) spectrum and licensed spectrum. We further consider there are two non-cooperative types of network users- the primary users and the secondary users. Primary users are the licensed user of a frequency band. Secondary users use free spectrum opportunistically for communication which is not used by the primary users.

Most of the existing MAC protocols for cognitive radio [5]-[7], [9]-[10] need an extra dedicated global control channel called common control channel (CCC), which may be not available in some practical cost-sensitive application. Further, CCC may get saturated as the number of users increase and it is wasteful of channels. To resolve this problem, in this paper we proposed non-dedicated and non-global CCC based MAC protocol for CRNs. AMAC protocol enables the secondary users to exchange the negotiation packets (e.g. RTS/CTS (request to send / clear to send), similar to 802.11 DCF [17]) in common channels between cognitive radio (CR) pairs such that no global dedicated CCC is required. AMAC protocol is distributed in nature and it switches in to the dual mode and utilizes the data backup channel when the channel condition is poor and below the threshold value, hence maximizes the network throughput. Further, it solves the well-known traditional hidden terminal problem and multi-channel hidden terminal problem [13]-[14]. We evaluate AMAC protocol in terms of aggregate throughput.

The rest of this paper is organized as follows. Related work is reviewed in section II. The proposed decentralized adaptive medium access control (AMAC) protocol is described in section III. Simulation results and performance evaluations are discussed in section IV. Finally, conclusion and future works are given in section V.

II. RELATED WORKS

Designing an efficient MAC protocol is one of the most challenging issues in cognitive radio networks. Though a number of MAC protocols for cognitive radio networks exist in the literature, there are many areas where improvements are desirable and possible. Fig. 1. shows a classification of existing cognitive radio MAC layer protocols.

The IEEE 802.22 working group [5] is working for IEEE 802 LAN/MAN standards committee. It aims at constructing WRAN and is in the process of standardizing a MAC layer based on CR for reuse of spectrum that is allocated to TV broadcast service. IEEE 802.22 specifies that the network should operate in a point to multipoint basis. The architecture of the 802.22 MAC layer is centralized and relies on the base station.

Channel-hopping based cognitive MAC protocol [6] is a single transceiver based MAC protocol for cognitive

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radio networks. In this protocol each secondary user generates its own channel-hopping pattern with the unique sequence generating seed. A secondary user follows its own channel-hopping pattern when it doesn't have packets to send, while it follows its intended receiver's channel-hopping pattern if it wants to send packets to the intended receiver. This protocol neither needs dedicated control channel nor centralized controllers. Dynamic Open Spectrum Sharing (DOSS) MAC protocol [7] requires multiple radio transceivers (at least three sets). It provides a scalable real-time efficient spectrum allocation solution. DOSS incorporates three bands called the control band, the data band and the busy-tone band [8] for channel negotiation, for sending data and for raising the busy-tone signal to solve the hidden and exposed terminal problems respectively. Distributed cognitive radio MAC (DCR-MAC) protocol [9] incorporates incumbent system reporting and channel-status table maintenance mechanism to utilize spectrum holes effectively and avoid possible interference to incumbent devices. DCR-MAC reduces sensing overhead and data channel access delays by utilizing overhearing.

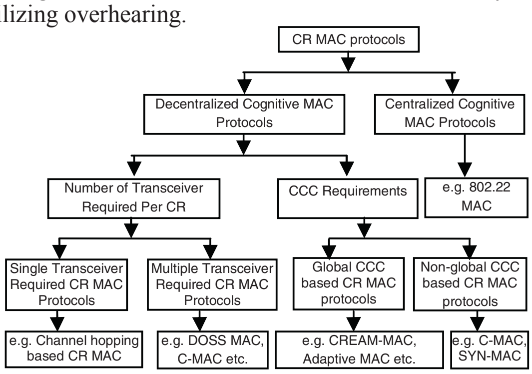

Figure 1. Classification of MAC protocols for cognitive radio networks.

C-MAC [10] is based on the MMAC protocol. A rendezvous channel (RC) is proposed in this protocol that acts as a common control channel but is not dedicated to controlling information exchanges. Each channel has its own super-frame structure, and one of the sub-channels is selected to serve as the RC while the other channels periodically switch to the RC to perform synchronizations and to exchange control information. This protocol mitigates access delay and channel resource waste in MMAC. It does not differentiate the primary users and secondary users. Cognitive Radio-EnAbled Multi-channel MAC (CREAM-MAC) protocol [15] is a single transceiver and a common control channel based protocol. It uses contention mechanism similar to 802.11 DCF [17] and it has a four way handshaking to solve the traditional and multi-channel hidden terminal problems. Dynamic channel assignment (DCA) MAC protocol [11] employs a default control channel while other channels may be used for data transmission. It assumes that each cognitive radio is equipped with two transceivers in which one constantly monitors the common channel, allowing it to avoid the multichannel hidden terminal problem. The other transceiver locates on the data channel. RTS/CTS packets are exchanged in the control channel and serve to negotiate a data channel for Data/ACK transmission. Any node wishing to begin a transmission must ensure that the channel it wants to use is idle. If no channel is available, a node wishing to transfer packets must wait for an idle channel through observation of the common control channel and wait for a random back-off time to access the channel again.

Non-dedicated and non-global CCC based cognitive MAC protocols have been proposed in the literature. Those protocols do not need global and dedicated CCC. In some approaches CCC is selected by negotiating two radio nodes and the CCC is only common between those pair. That CCC is not dedicated for entire network lifetime and need to reselect another CCC after maximum toleration time of the primary user. Channel-hopping based cognitive MAC [6], synchronized MAC protocol for multi-hop cognitive radio networks (SYN-MAC) [16] etc. are few examples of non-dedicated and non-global CCC based MAC protocols.

Most of the existing MAC protocols for cognitive radio networks are based on global CCC. As we mentioned in section I, global CCC may saturate, and can be a victim of DoS attack [12]. Further, allocating one channel just for control packet exchange is wastage of resource for channels constrain (802.11b kind of networks where there are only 3 channels) networks. Our proposed protocol does not require any dedicated global CCC, as in Channel-hopping based cognitive MAC [6] and synchronized MAC protocol for multi-hop cognitive radio networks (SYN-MAC) [16]; hence, it is free from the above mentioned threats. Furthermore, it considers several aspects to index the available channel lists and negotiate for the best channel, e.g. available bandwidth, rate adaptation, channel condition and channel reliability, dual channel usability etc., for improving the network reliability and to improve the network throughput.

III. OUR PROPOSED PROTOCOL DESCRIPTION

We assume that there is a set of channels N={C1, C2, C3…… C_n}. After sensing the licensed spectrum for a period of time, each secondary user has the information of the channel state in these spectrum bands. Then, the secondary user can opportunistically access the vacant channels which are not occupied by the primary users. The availability of primary channel i for the secondary users (A_i) can be calculated as:

$$A_{C_i} = B_i(1-U_i) \tag{1}$$

Where, B_i is the capacity of a primary channel i and U_i is the average utilization of the C_i. *For the first time the* channels are sensed blindly. Because of hardware constrain of CR device, the number of channels a CR device can sense are limited. Therefore, to utilize all the sensed channels fully we use the estimated available bandwidth (AB) (we discuss about it in the following sub section) to select the channels those use less frequently by the primary users.

A. Channel Indexing

Entirely sensed channels are indexed at least once in a T_{max} time. T_{max} time is the maximum tolerable time for the primary users. Indexing is done according to the AB (equation 3). A channel that has higher bandwidth is ranked as a number one (channel C1) and a channel that has a least AB is ranked as number n (channel C_n). To determine the reliability of a channel, AB can be combined with calculation of SNR (signal-to-noise ratio), queue length, frame error rate, past history of the channel etc. However, we keep this for our future work. Hence, C1 is considered as the most reliable channel. Among the channels in N, the reliable superiority is from left to right. For example, in channel set {C1, C2, C3, ……. C_n}, C1 is the most reliable available channel and C_n is the least reliable channel for T_{max} time.

B. *Negotiation for non-dedicated (non-global) common control channel*

When CR device (we use the term node from now onward) R_1 has to send data to node R_2, node R_1 sends RTS with indexed channel list (ICL). After receiving RTS with ICL, R_2 checks the common channels between them and makes an indexed common channel list (ICCL) and sends back to node R_1. The neighbor nodes within the communication range also update their neighbors' ICL when they overhear RTS from node R_1. However, overhearing nodes do not update ICCL list, because ICCL list is the common channel list between two nodes (R_1 and R_2).

C. *Selection of non-dedicated (non-global) CCC between communicating pairs*

We use the most reliable common channel between communicating pair as a non-dedicated (non-global) CCC (NCCC) between the communicating pair (CCP). NCCC for R_i and R_{i+1} is selected as:

$$NCCC(R_i, R_{i+1}) = \left\{ \underset{C_i \in N}{Max}\, f_i\left(ICR_i^t\right) | \, R_i \cap R_{i+1} \right\} \tag{2}$$

Where, $f_i\left(ICR_i^t\right)$ is an indexed channel ranking function (ICR) for node R_i at time t and can be calculated as $ICR = \underset{AB}{Max}\{R_1C_i + R_2C_i \,|, R_1C_i \cap R_2C_i\}_{i=1,2,\ldots,n}$. Node Ri+1 is the node which receives request to select NCCC from node Ri.

D. *Negotiation for the data channel*

When node R_1 receives RTS along with ICCL, node R_1 selects C2 as a data channel (C_d) and sends channel reservation control packet (CRCP) in NCCC to CCP. It also selects C3 as a data backup channel (C_{db}) that is used for dual channel utilization (we will discuss about it later). Overhearing nodes update their channel list for R_1 and assume that, that particular channel is reserved for at least WT time and do not sense that channel for WT time (instead of that, they sense other channels). WT time is given in Fig. 2, and is similar to the Network Allocation Vector (NAV) in 802.11 DCF [17]. Receiving CRCP from node R_1, node R_2 sends confirmation of channel reservation control packet (CCMP). This four ways handshaking ensures the channel availability and reservation for NCCC, C_d and C_{db}.

E. *Data communication*

After successful reservation of channel, node R_1 sends data frame in C_d according to the channel condition. Two types of channel conditions are: (i) robust channel condition and (ii) deprived channel condition. In case of robust channel condition, R_1 use the dual channel (probably multi-channel in future) utilization scheme.

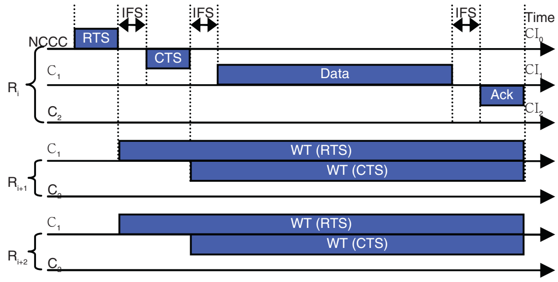

Figure 2. Proposed decentralized adaptive medium access control (AMAC) protocol and WT.

F. *Dual channel utilization scheme*

Whenever a node finds AB of C_d is less than certain predefined value, it decreases the flow rate until it reaches predefined threshold value. Once it exceeds the threshold, then it stops decreasing the flow rate and sends concurrently frames in the both C_d and C_{db}. If frame error occurs in C_d, node R_2 recovers those frames from C_{db}. To know the channel condition we estimate the available bandwidth of C_d as follows. Let D_r be the negotiated data rate between node R_1 and node R_2. Suppose, furthermore, that $AB(R_1, R_2)$ is available bandwidth of the C_d from node R_1 to node R_2 and I_r is the rate at which the channel is idle.

$$AB(R_1, R_2) = D_r \times I_r \tag{3}$$

And,

$$I_r = 1 - \frac{T_{Ri}}{T} - \frac{T_p}{T} \tag{4}$$

Where, T_{Ri} is the total busy time of channel C_d by R_1, T_p is the total time channel occupied by primary users and T is the total elapsed time. More specifically, to calculate T_{Ri}, we calculate the total transaction (T_{total}) time of node R_1.

$$T_{total} = T_{snd}(R_1, R_2) + T_{rcv}(R_2, R_1) \tag{5}$$

Where, $T_{snd}(R_1, R_2)$ is the sending time from node R_1 to R_2 and $T_{rcv}(R_2, R_1)$ is the receiving time from node R_2 to R_1. In fact, the total busy time of the C_d is the total transaction time of node R_1 and transaction time of other neighbor nodes.

$$T_{Ri} = T_{total} + WT \tag{6}$$

WT, as shown in Fig. 2, is the time similar to NAV in 802.11 DCF [17] and is occupied by neighbor of R_1 or the time occupied C_d by other nodes.

Fig. 2 shows the proposed AMAC protocol. The scanned and indexed channels of node R_i are CI_0, CI_1 and CI_2. Where, CI_0 is used as a control channel after negotiation with immediate receiving neighbor node. Node R_{i+1} and node R_{i+2} are the neighbor nodes. As channel C_1 is reserved by node R_1, other nodes (node R_{i+1} and node R_{i+2}) cannot use C_1 for at least WT(RTS) time. The node R_{i+1} and node R_{i+2} can use only channel C2. However, node R_{i+1} and node R_{i+2} can still use NCCC while R_i is communicating with the receiver in data channel (C_i).

G. *Channel switching*

Once a node starts sending data frames, it sends for T_{max} time. Before expiring T_{max} time, communicating pair (node R_1 and node R_2) negotiate for next channel and switch to updated NCCC of new ICCL. Entire channel negotiation and reservation process for new channels are done as described in above sections. Nodes can switch channels also before expiring T_{max} time if primary appears in the communicating channel/s.

H. Multi-channel hidden node problem

Although, CTS/RTS solves the traditional hidden node problem, it cannot solve multi-channel hidden node problem in cognitive radio networks. While reading data in data channel, radio node may not hear ongoing communication in NCCC. It may cause collision whenever it tries to access in control channel. This problem is called multi-channel hidden node problem.

To solve this problem, in AMAC protocol, once node communicates in any channel C_i, it does not communicate again at least for T_{max} time.

IV. PERFORMANCE EVALUATION

We simulated AMAC protocol using ns-2. We selected CREAM-MAC [15] as a representative global CCC based MAC protocol and we compared AMAC with CREAM-MAC. In Fig. 3, we evaluated the number of connectivity as the number of nodes is increased. Fig. 3 shows, as the number of channels (except NCCC/CCC) increases, the percentage of connectivity increases in both CMAC and AMAC but in AMAC's connective is significantly high. The reason of high connectivity in AMAC is it can communicate even without global CCC.

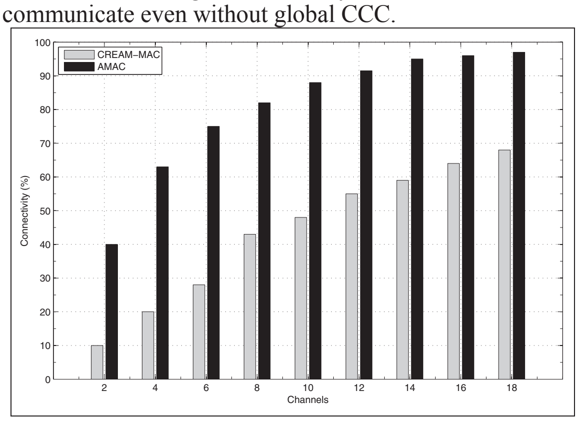

Figure 3. Connectivity vs. number of channels.

Fig. 4 shows the effect of channel conditions in aggregated throughput. The aggregated throughput in the Fig. 4 is the average of 50 simulations. Regardless of channel condition, AMAC has significantly higher throughput than CREAM-MAC. There are two main reasons of higher throughput in AMAC. (a) higher connectivity and (b) AMAC has a dual channel utilization scheme. Even in a poor channel condition it can perform well.

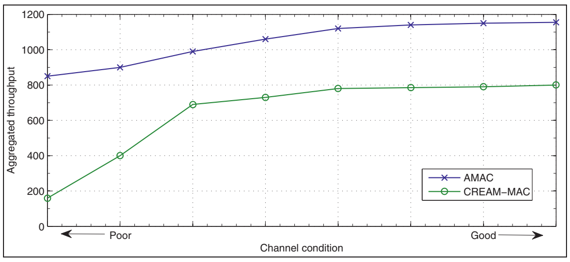

Figure 4. Effect of channel condition in throughput.

V. CONCLUSION AND FURTHER WORK

We presented a new decentralized adaptive medium access control (AMAC) protocol to maximize network throughput. Our approach has many advantages compare to the existing MAC protocols for cognitive radio. In AMAC, communication is possible even if there is no dedicated common control channel available. The aggregated throughput is higher even in poor channel condition. AMAC protocol not only solves the traditional hidden terminal problem but it also solves the multi-channel hidden terminal problem. In the future we will observe long term behavior of primary channels and analyze the channel behaviors in terms of channel utilization. The channel indexing mechanism, applying all the possible factors including neural networks and comparison of various aspect of AMAC with the existing CCC based protocols and non-global CCC based protocols are the future works.

REFERENCES

[1] FCC, "Spectrum policy task force report," No. 02-155, November 2002.

[2] J. Mitola III and Jr. G. Q. Maguire, "Cognitive radios: Making software radios more personal," IEEE Personal Communications, vol. 6, no. 4, Aug. 1999.

[3] J. Mitola, "Cognitive radio: An integrated agent architecture for software defined radio," PhD Dissertation, Royal Inst. Technol. (KTH), Stockholm, Sweden, 2000.

[4] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," in IEEE JSAC, vol. 23, no. 2, Feb. 2005.

[5] IEEE 802.22 draft standard, "IEEE P802.22TM/D0.1 draft standard for wireless regional area networks," http://www.ieee802.org/22/, doc. no. 22-06-0068-00-0000, May 2006.

[6] H. Su, and X. Zhang, "Channel-hopping based single transceiver MAC for cognitive radio networks," 42nd Annual Conference on Information Sciences and Systems, 2008. CISS 2008, 19-21 March 2008, pp 197-202.

[7] L. Ma, X. Han, and C-C. Shen, "Dynamic open spectrum sharing MAC protocol for wireless ad hoc networks," In Proceedings of IEEE International symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN'05), pp. 203–213, 2005.

[8] J. Deng, and Z.J. Haas, "Dual busy tone multiple access (DBTMA)- A new medium access control for packet radio networks," In Proceedings of IEEE ICUPC'98, pp. 975–985, 1998.

[9] S-J. Yoo, H. Nan, and T-I. Hyon, "DCR-MAC: Distributed cognitive radio MAC protocol for wireless ad-hoc networks," Wireless Communications and Mobile Computing, Vol. 9, Issue 5, March, 2008, pp. 631 - 653

[10] C. Corderio and K. Challapali, "C-MAC: a cognitive MAC protocol for multichannel wireless networks," in Proceedings of IEEE Symposium on New Frontiers in Dynamic Spectrum Access networks, April 2007.

[11] S-L. Wu, C-Y. Lin, Y-C. Tseng, and J-P. Sheu, "A new multi-channel MAC protocol with on-demand channel assignment for multihop mobile ad hoc networks," In Proceedings of IEEE International Symposium on Parallel Architectures, Algorithms and Networks (I-SPAN'00), pp. 232–237, 2000.

[12] K. Bian and J. M. Park, "MAC-layer misbehaviors in multi-hop cognitive radio networks," 2006 US - Korea Conference on Science, Technology, and Entrepreneurship (UKC2006), Aug. 2006.

[13] J. So, and N. Vaidya, "Multi-channel MAC for ad hoc networks: handling multi-channel hidden terminals using a single transceiver," MobiHoc'04, pp. 222–233, 2004.

[14] H. Nan, T-I. Hyon, and S-J. Yoo, "Distributed coordinated spectrum sharing MAC protocol for cognitive radio," IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, pp. 240–249, April 2007.

[15] H. Su and X. Zhang, "CREAM-MAC: An efficient cognitive radio-enabled multi-channel MAC protocol for wireless networks," International Symposium on a World of Wireless, Mobile and Multimedia Networks, WoWMoM '08, 23-26 June 2008, pp.1-8.

[16] Y.R. Kondareddy and P. Agrawal, "Synchronized MAC protocol for multi-hop cognitive radio networks," IEEE International Conference on Communications, ICC '08, 19-23 May 2008, pp. 3198-3202.

[17] IEEE Standard "Wireless LAN medium access control (MAC) and physical layer (PHY) specification," in IEEE standard 802.11-1997, 1997.