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An Analysis on Decentralized Adaptive MAC Protocols for Cognitive Radio Networks

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***Abstract*— The scarcity of bandwidth in the radio spectrum has become more vital since the demand for more and more wireless applications has increased. Most of the spectrum bands have been allocated although many studies have shown that these bands are significantly underutilized most of the time. The problem of unavailability of spectrum and inefficiency in its utilization has been smartly addressed by the Cognitive Radio (CR) Technology which is an opportunistic network that senses the environment, observes the network changes, and then using knowledge gained from the prior interaction with the network, makes intelligent decisions by dynamically adapting their transmission characteristics. In this paper some of the decentralized adaptive MAC protocols for CR networks have been critically analyzed and a novel adaptive MAC protocol for CR networks, DNG-MAC which is decentralized and non-global in nature, has been proposed. The results show the DNG-MAC out performs other CR MAC protocols in terms of time and energy efficiency.**

Keywords- Cognitive Radio; MAC Protocols; Common Control Channel; Cooperative Communication

I. INTRODUCTION

The modern communications have become more dependent on wireless technology. Wi-Fi, Cellular phones, Bluetooth, TV broadcasts and satellite are proliferation of wireless services. The increased number of wireless applications from home appliances to satellite control has created huge demand for more radio spectrum. For every wireless application some portion of the radio spectrum need to be purchased, and the Federal Communication Commission (FCC) allocates the spectrum for fee for such services [1]. This has led to the problems like scarcity of spectrum, shortage of spectrum to use in new wireless services and lack of radio resource and wireless services to those who are more appropriate and needy. Most of the frequencies in the radio spectrum have been allocated although many studies have shown that the allocated bands are not efficiently being used [2]. Cognitive Radio Technology [3] is the solution to the shortage of spectrum and inefficiency of its utilization. Cognitive Radios are intelligent wireless devices that sense the environment, observe the network changes and then using knowledge learnt from the previous interaction with the network, make intelligent decisions to seize the opportunities to transmit. This process of scanning the spectrum (S), exchanging control information (E), agreeing upon white space (A) and transmitting data (T) on the network is repeated continuously in a cycle [4]. Figure 1 shows how a cognitive radio learns from its environment and tunes its transceivers to adapt the network changes. CR network serves as a framework in accessing the spectrum allocation dynamically and spectrum opportunity [5] deals with the usage of a free channel that is part of radio spectrum which is not currently being used by primary users (PUs). The licensed user or PU of the frequency band is the wireless application who purchases the portion of radio spectrum from FCC for fee, and those who utilize spectrum opportunistically for communication without interference to PU are called secondary users (SUs). Each cognitive device is equipped with sensors and transceivers that sense the spectrum and allow SUs to access licensed spectrum bands as long as SUs do not impose any interference to PUs.

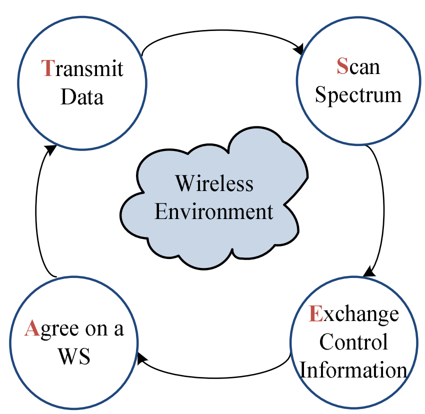

Figure 1. SEAT Cycle

PUs when not transmitting create free channels or empty spaces in the spectrum, and these empty spaces, also called white spaces, are used by SUs opportunistically. The existence of Common Control Channel (CCC) is mandatory for all CR nodes for control information exchange. Before any cognitive devices start sending and receiving data, they first have to coordinate and decide about the transmission on the CCC. The pair of SUs exchange initial information such as how to send requests, which white spaces to be used and how long will the communication last. This information could also include exchange of Request-To-Send (RTS) and Clear-To-Send (CTS) control frames in order to solve the hidden terminal problem and avoid collisions in random access protocols, mostly used by cognitive radio devices for exchange of control information. Figure 2 shows the process of formation of white spaces in the spectrum. The CCC could be static or dynamic. Under the static case, the control channel can be either specially licensed to the secondary users by FCC or use the unlicensed spectrum band (2.4GHz), and in the latter case it could be called GCCC. In the dynamic case, the control channel could be one of the most reliable and available white spaces.

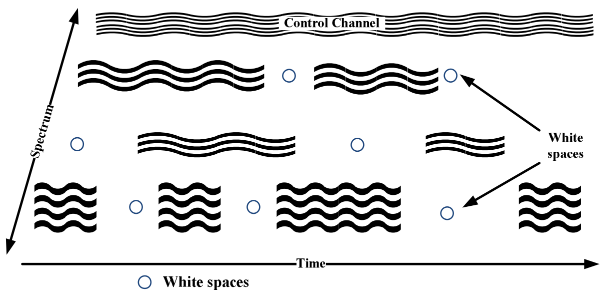

Figure 2. Spectrum Usage by PUs and formation of white spaces

II. Literature Review

Different areas of CR networks are being explored by scientists and researchers. Some of the areas are architecture, MAC protocols, scheduling policy, spectrum sensing, QoS, energy efficiency and security for CR networks. In CR networks channel availability can rapidly change, so timely coordination is the key challenge in MAC protocols to adapt the environment and quickly detect the free channels for subsequent transmission. MAC protocols for CR networks can be broadly classified as centralized and decentralized. The centralized MAC protocols use a central entity usually called a base station which is responsible for detection, coordination and communication of multiple cognitive devices in a cognitive radio network (IEEE 802.22) [6,19].

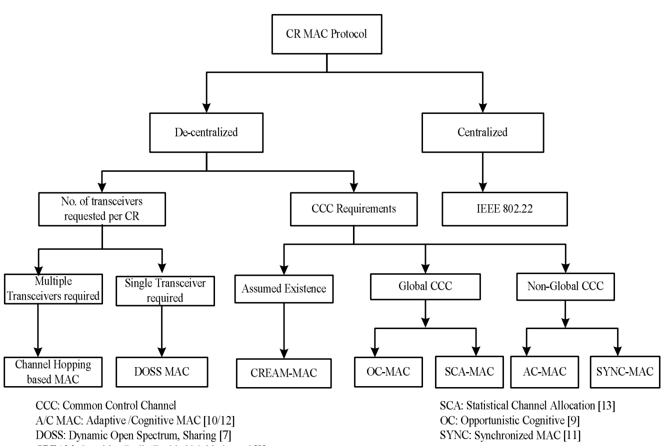

Figure 3. Classification of CR MAC Protocols

The decentralized MAC protocols consider different aspects such as the number of transceivers, channel access mechanism, spectrum sensing techniques and selection criteria for control channel. For example, the authors of [9,13] make use of GCCC for control information exchange while [10,11,12] use non-GCCC to setup initial configuration dialogue. The authors of [8] do not delve into the selection of CCC and assume that a control channel already exists (Figure 3). In the next section of this paper we critically analyze the decentralized MAC protocols of both the global CCC and non-global CCC.

III. Analysis of Decentralized Adaptive MAC Protocols for Cognitive Radio Networks

A. *Cognitive Radio-EnAbled Multichannel MAC (CREAM-MAC) Protocol*

CREAM-MAC [8] is a decentralized CR MAC protocol which assumes that a CCC has been found and agreed upon by all CR nodes in the vicinity before the CREAM-MAC starts its operation. The sender initiates four-way dialog by exchanging four types of packets namely RTS, CTS, Channel-State-Transmitter (CST) and Channel-State-Receiver (CSR). The control information dialog contains the information about the number of channels available, reliability of channel and the length of transmission. After agreeing upon all the communication rules exchanged during the handshake data is transmitted over one of the free channel common to both SUs. CREAM-MAC calculates the PU interference probability and the channel utilization by PU, and the aggregated throughput. CREAM-MAC assumes that a control channel is already available and always reliable. It is strongly believed that finding a common channel to exchange control information is the primary task of cognitive nodes. Subsequent operation could not take place if the existence of a control channel has not been addressed. So assumption of an available control channel is not a well-built justification.

B. *Opportunistic Cognitive MAC (OC-MAC) Protocol*

OC-MAC protocol [9] is a decentralized and connection-oriented MAC protocol over CR network. OC-MAC is different from the CREAM-MAC by co-existing with wireless local area networks (WLAN). OC-MAC uses a dedicated channel for control information, on which CR nodes compete with one another for data channel reservation. Like WLAN IEEE802.11, CR nodes apply DCF (Distributed Coordination Function) mechanism [15], and the status of each channel is recorded with the execution of DCF. OC-MAC uses the typical exchange of RTS/CTS followed by Control-Channel-Request-to-Send (CRTS) and ACK. The protocol evaluates the throughput with and without the PU traffic. OC-MAC is a decentralized non-global CR MAC protocol that exchanges the information obtained from the spectrum sensors at PHY layer over the CCC. The statistics of each channel is maintained in the Channel-State-Table (CST) which every secondary user updates after each scan. OC-MAC maximizes the throughput of the network by exchanging the statistics amongst each secondary communicator in the cognitive radio network. It avoids collisions by using these statistics. However, there are some vital design flaws in OC-MAC which make it in-appropriate for CR nodes. First of all, the operation of OC-MAC is started with the assumption of existence of control channel which will be used for exchange of RTS/CTS/CRTS and ACK, and no justification of this assumption is provided. Secondly, CR nodes in OC-MAC predict the length of a spectrum hole, we strongly criticize this because a CR network is an opportunistic network and it is very hard to find the exact period during which PU will not be utilizing the spectrum so that the time length of spectrum hole could be calculated. Lastly, the protocol claims to be co-existent with WLAN, however, the justification for this theory is neither clearly presented in the paper nor we believe that CR nodes need to coexist with WLAN because WLAN uses the ISM band (e.g., 2.4GHz) which is already freely available to any user. There is no need to seize the opportunity to transmit in the ISM band, and nodes only need to contend for the ISM band.

C. Statistical Channel Allocation MAC (SCA-MAC) Protocol

SCA-MAC protocol [11] intelligently senses the spectrum and dynamically accesses the unused or underutilized spectrum with the minimum or no interference to PUs. Two basic control parameters are *operating range* and *channel aggregation* for SCA-MAC. This protocol also uses CSMA/CA [14,15] mechanism to achieve a higher spectrum utilization. To avoid interference to primary users SCA-MAC evaluates its impact in real time by predicting the successful rate of each transmission. Spectrum sensing is performed continuously and rapidly. SCA-MAC uses the cyclostationery feature detection [16,17] for the continuous and rapid spectrum sensing. After exchange of Control Channel Request to Send (CRTS) and Control Channel Clear to Send (CCTS) frames on GCCC, both sender and receiver tune their transceivers to the agreed data channel. This protocol can speed up transmission by using more than one channel for data transmission and can wait for some time for a channel with a higher bandwidth to become available. SCA-MAC is a global decentralized CR protocol which performs the 2-way handshake by sending CRTS and CCTS frames which contain the information of the best opportunity. SCA-MAC emphasizes on the data transmission, and ignores the pre-transmission overheads. Obviously, more number of frames exchanged as control information will not only add delay in QoS aware data but will also contribute towards inefficient energy consumption as nodes will have to wait longer before the actual transmission starts.

D. Adaptive MAC (A-MAC)Protocol

A-MAC protocol [12] is a decentralized MAC protocol for CR networks, which is distributed in nature and does not require any GCCC and can utilize backup data channel when higher throughput is required. The protocol considers different aspects such as bandwidth, channel reliability, channel condition and rate adaption to perform channel indexing, create FCL and find the best channel. Indexed channel listing (ICL) is done according to the available bandwidth. The higher is the bandwidth of a channel, the higher will be the statistics of the channel. The other parameters that A-MAC uses to build a channel rank are SNR (signal-to-noise ratio), queue length, frame error rate and past history. The protocol starts its operation by sending the ICL in the RTS frame, and the receiver replies with its own ICL. Both the communication partners switch to the agreed data channel after exchanging channel reservation control packet which confirms the white space to be used as data channel.

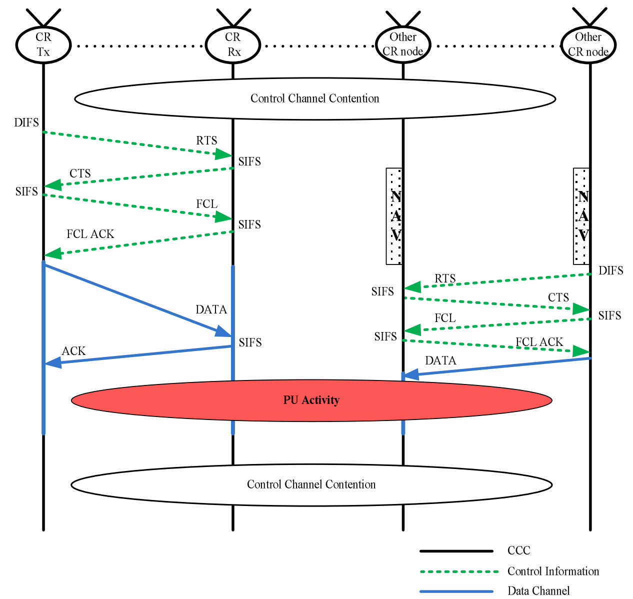

Figure 4. Generic Behavior of CR MAC Protocol

A-MAC is different from the previously discussed protocols as it makes use of non-GCCC. However the methodology used by CR nodes in the vicinity to converge on a non-GCCC is clearly missing. It is very important for nodes in the CR network to be well aware about the control channel because no subsequent transmission could occur without first finding the control channel. Also more control frames and a heavier size of each control frame cause a higher pre-transmission time. Consequently CR nodes will strive lot to seize the rare opportunity to utilize the white spaces before a PU activity is sensed.

IV. FEATURES OF CR MAC PROTOCOLS

Different CR MAC protocols have been critically reviewed in the previous section. The protocols discussed so far share some common features like selection criteria for control channel and the access mechanism, etc. while other features are unique. Many of these protocols make use of multiple frames for control information exchange (Figure 4) before transmitting data. If certain PU activity is sensed on the data channel, SUs switch on to CCC for re-negotiation. The generic behavior of these protocols is presented in

Figure 4. These features of the adaptive MAC protocols have been summarized in Table 1 below.

TABLE I. FEATURES OF THE ADAPTIVE MAC PROTCOLS

Features	CREAM-MAC	OC-MAC	SCA-MAC	A-MAC
Spectrum Sensing [18]	Energy Detection	Not discussed	Cyclo-stationery	Not discussed
Acknowledgement after transmission		✓	✓	
Avoidance of hidden terminal	✓			
Control Channel	GCCC	Non-GCCC	GCCC	Non-GCCC
Best Channel Criteria	arbitrary	arbitrary	arbitrary	BW
Use of CSMA/CA	✓	✓	✓	✓
Multi-Channel MAC [22]	✓	✓	✓	✓
Physical Layer Parameters [20]	DSSS	Not discussed	Not discussed	DSSS
Use of backup data channel			✓	✓

Some of the salient features of each adaptive MAC protocol have been provided. In the next section we propose a novel MAC protocol for cognitive radio networks.

V. DESIGN AND SIMULATION OF A NOVEL CR MAC PROTOCOL

A. A Novel CR MAC Protocol

After analyzing different decentralized MAC protocols, we see that most of CR MAC protocols cannot initiate the communication until a startup dialog or handshake, which can only be done on the control channel, is performed. The above discussed protocols avoid collision by CSMA/CA on the common control channel. However, having a dedicated control channel could be wasteful of resource. Also when one pair of SU have occupied the common control channel, all the other SUs who are the candidates for the CCC set their network allocation vector (NAV) and wait for the CCC to become idle. Some of the other problems could be: a) there is always a First-Come First-Get mechanism to access the common control channel, so the needy may suffer for long; b) the computational cost of back off algorithm gets too high when the common control channel gets saturated; c) the secondary communication pair which did not end up communication due to PU's arrival must start the process of renegotiation on the control channel.

Considering the drawbacks of GCCC, we propose a novel decentralized non-global MAC called DNG-MAC protocol which is based on the fair allocation of control channel to all candidate SUs using the Time Division Multiplexing (TDMA) mechanism. The first CR node in the DNG-MAC initiates the operation of the protocol by selecting one of the best channels as the common control channel. The selection criteria for the best channel in this case would be arbitrary. The control channel is divided into time slots of fixed length. Each time slot has a listen period and a transceiving period. All CR nodes in the network are synchronized in the listening period of each time slot. FCL is exchanged in the transceiving period between secondary user communication pair (SUCP). The duration of the time slot is carefully selected by calculating the average time required for each secondary pair to complete negotiation on the common control channel. We strongly argue that due to the starving nature of cognitive radio networks, CR nodes are likely to always have data to transmit so there would be no wastage of time slot and this will also give the other SUs a fair access to the common control channel.

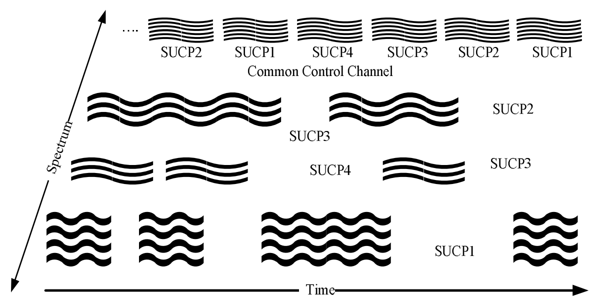

Figure 5. Allocation of CCC in the DNG-MAC Protocol

The overall waiting time for the SUs to access CCC in DNG-MAC is shorter than the waiting time in any of other MAC protocols. Here every SU is given the confidence that it is in the queue to access the CCC. In this way more than one secondary communicating pair can access the CCC at the same time. The vacant channels on the spectrum can be simultaneously used by more than one communicating pair by having a shorter waiting time to access the CCC, thus improving the overall throughput of the CR nodes.

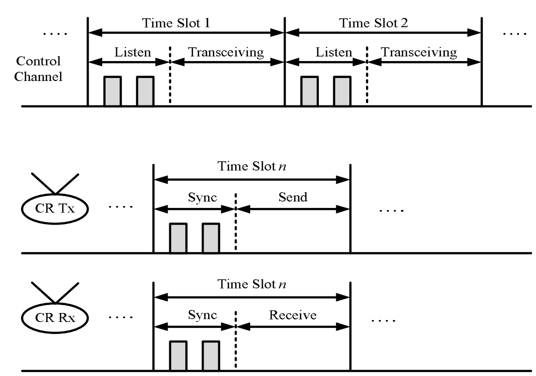

Figure 6. Multi-Channel Timing Structure in the DNG-MAC Protocol

B. Simulation Model and Results

The proposed protocol has been simulated in OPNET Modeller 14.5. An office scenario with span of 100x100 meters has been considered where CR nodes are in coalition with wireless LAN nodes. This ad-hoc based scenario contains 10 CR nodes. All the devices in the given scenario have capability to transmit at 1Mbps by consuming 0.005 transmission power, and all pairs are using DPSK (Differential Phase-Shift Keying) modulation type. The size of control frames are set to 20 bytes keeping IEEE 802.11b as benchmark.

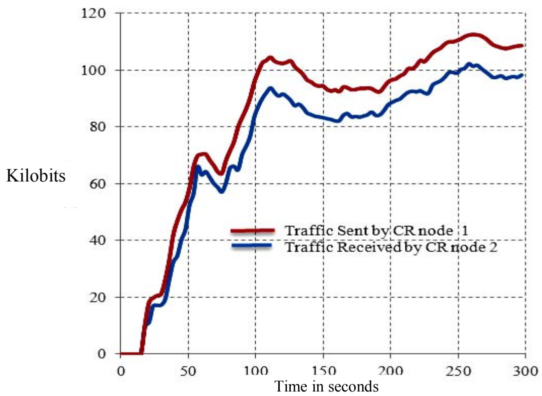

Figure 6. Traffic sent and received by two CR nodes in DNG-MAC Protocol

The physical layer parameters of Direct Sequence Spread Spectrum (DSSS) have been deployed. The time slot has been set to 10ms based on average negotiation time required by cognitive radio secondary users on control channel. To prove the functionality and suitability of the novel DNG-MAC protocol, the simulation was run for 300 seconds for each experiment and 10 experiments have been performed to obtain the average results. The global statistics obtained between two CR nodes have been plotted in Figure 6. Due to burst traffic nature with exponential increase, uneven curves have been generated. Since a CR node cannot transmit until a negotiation has taken place and the opportunity to transmit has to be seized, the traffic sent remains less than 40Kbps in first 100sec and gradually increases in next half of the simulation time.

VI. Conclusion

Cognitive radio technology serves as a framework to address the spectrum scarcity issues. One of the important features of a CR network is the exchange of control information (FCL). Different protocols have been developed which exchange the FCL on either GCCC or non-GCCC for subsequent transmission. A novel MAC protocol has been proposed which fairly allocates the non-GCCC to all CR nodes. The simulation results have revealed the suitability of the proposed scheme where CR nodes co-exist with other wireless LAN nodes in the vicinity. Currently, DNG-MAC is under extensive simulation in which it will be compared with some other MAC protocols for performance comparison and evaluation.

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