DDH-MAC : A Novel Dynamic De-Centralized Hybrid MAC Protocol for Cognitive Radio Networks

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***Abstract*—The radio spectrum (3kHz - 300GHz) has become saturated and proven to be insufficient to address the proliferation of new wireless applications. Cognitive Radio Technology which is an opportunistic network and is equipped with fully programmable wireless devices that empowers the network by OODA cycle and then make intelligent decisions by adapting their MAC and physical layer characteristics such as waveform, has appeared to be the only solution for current low spectrum availability and under utilization problem. In this paper a novel Dynamic De-Centralized Hybrid "DDH-MAC" protocol for Cognitive Radio Networks has been presented which lies between Global Common Control Channel (GCCC) and non-GCCC categories of cognitive radio MAC protocols. DDH-MAC is equipped with the best features of GCCC MAC protocols but also overcomes the saturation and security issues in GCCC. To the best of authors' knowledge, DDH-MAC is the first protocol which is hybrid between GCCC and non-GCCC family of protocols. DDH-MAC provides multiple levels of security and partially use GCCC to transmit beacon which sets and announces local control channel for exchange of free channel list (FCL) sensed by the co-operatively communicating cognitive radio nodes, subsequently providing secure transactions among participating nodes over the decided local control channel. This paper describes the framework of the DDH-MAC protocol in addition to its pseudo code for implementation; it is shown that the pre-transmission time for DDH-MAC is on average 20% better while compared to other cognitive radio MAC protocols.**

Keywords-Cognitive Radio; MAC Protocols; Common Control Channel; Security; Co-operative 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. It is necessary for every wireless application to purchase some portion of spectrum; Federal Communication Commission (FCC) allocates the spectrum for fee for such services. This has led to the problems like scarcity of spectrum to use in new wireless services and lack of radio resource 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 [1]. Cognitive Radio (CR) Technology 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 observing (O), orienting (O), deciding (D) and acting (A), commonly known as OODA, on the network is repeated continuously in a cycle [2-5].

Cognitive Radio Networks serve as a frame work in accessing the spectrum allocation dynamically where the vacant channel can be accessed by sensing the spectrum. Spectrum opportunity deals with the usage of a free channel that is part of radio spectrum which is not currently being used by primary users (PUs) [6-9]. The licensed user or primary user of the frequency band are the wireless application who purchases the portion of radio spectrum from FCC for fee, and those who utilizes spectrum opportunistically for communication without interference to primary user are called Cognitive Users or Secondary Users (SUs). Cognitive devices are equipped with sensor(s) which help them to create the FCL after scanning the spectrum. PUs when not transmitting creates free channels in the spectrum, these free channels or empty spaces also called white spaces/spectrum holes, are used by SUs opportunistically. Figure 1 show usage of spectrum band by PUs and creation of white spaces.

A Common Control Channel (CCC) is a free channel required by cognitive devices to exchange FCL and to initialize communication among co-operating cognitive nodes. Before the pair of SUs starts sending and receiving actual data, firstly they have to coordinate and decide by communicating on the CCC about the chosen white space(s) for subsequent transmission. The pair of SUs exchanges initial information such as how to send FCL requests, which white spaces to be used and how long will the communication last etc. This information could also include exchange of Ready-To-Send (RTS) and Clear-To-Send (CTS) control frames in order to solve hidden terminal problem and avoid collisions in random access protocols, mostly used by cognitive radio devices for exchange of control information. The selection criteria for the CCC can be Static or Dynamic; under the static case, SUs use the unlicensed industrial, scientific, medicine (ISM) band

provided by FCC for exchange of control information such as FCL.

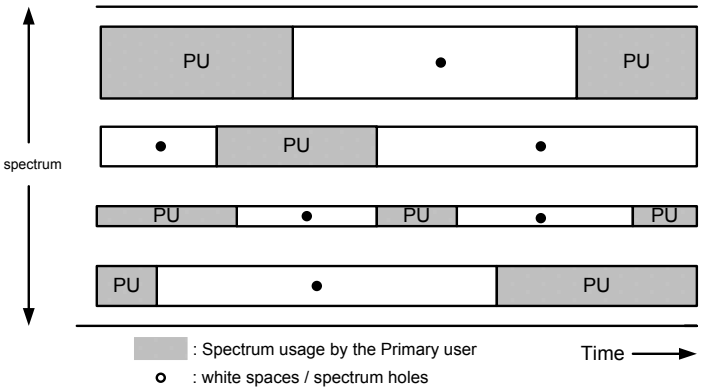

Figure 1. Spectrum Usage by PU

CCC is called Global/Universal/Common Control Channel (GCCC) when SUs use ISM band for control information exchange. In the dynamic case, the control channel usually represented by the notation CCH (to differentiate from static CCC), could be one of the empty spaces from the list of sensed spectrum holes (i.e. FCL) among different cognitive radio nodes. Based on the static or dynamic assignment of control channel, Cognitive Radio MAC protocols can be classified as those which use a Global CCC (GCCC) e.g. 2.4GHz ISM band and which do not use GCCC usually called non-GCCC, rather using one of the empty spaces as control channel for control information exchange (Figure 2).

This paper is organized as follows. Section II provides some of the related work and highlights the drawbacks of protocols using GCCC before the DDH-MAC protocol is explained in section III. Section IV and V provides pseudo code and performance evaluation for proposed MAC protocol respectively where as paper is concluded in section VI.

II. Related Work

The challenging issue in Cognitive Radio Network is to design an efficient MAC protocol that is capable of empowering the cognitive radio systems to handle cross layer parameter changes at physical layer, eliminating the collisions as much to avoid frame retransmissions and save mobile energy and improve the network throughput by routing the packets to the destination with minimal delay. Since inception, a number of MAC protocols for Cognitive Radio Networks have been designed and developed. Apart from base parameters for cognitive radios like, number of transceivers, spectrum access method and sensing policies, Cognitive Radio MAC protocols are broadly classified as centralized and decentralized MAC protocols (Figure 2). The former category makes use of a dedicated central entity to govern cognitive functions while in the latter case every cognitive node implies and shares its intelligence with other cognitive radio nodes in the range.

CREAM MAC is a decentralized CR MAC that applies a four way handshake with communicating nodes on the control channel and assumes that control channel is always available and reliable [10]. In OC MAC and SCA MAC initially all nodes reside on a global common control channel and performs three way handshake to select data channel from the FCL and confirms the data transmission through an acknowledgement [11,12]; whereas C-MAC selects R channel within the white spaces and sets this channel as a control channel and manage the communication on R channel [13]. DOSS-MAC makes use of 3 transmitters and presents a control channel algorithm to enable coordination among cognitive nodes and implements network layer multicasts [14]. DUB-MAC uses a different unlicensed spectrum band other then ISM and employs one frequency in GSM band as control channel and other to transmit data [15]. SYNC-MAC chooses one of the channels common between itself and neighbors to exchange control signals while other to send data [16]. The CR MAC protocol presented in A-MAC use the most reliable common channel between communicating pair as the control channel and performs the four way handshake to switch on to the data channel [17]. Whereas DCCPC, PCCA are centralized CR MAC protocols which make use of a central entity to govern cognitive operations [18,19]. The authors of CogMesh present a cluster based framework to form a wireless mesh network. Clusters are constructed by neighbor nodes and sharing local common channels and the network is formed by interconnecting the clusters gradually [20].

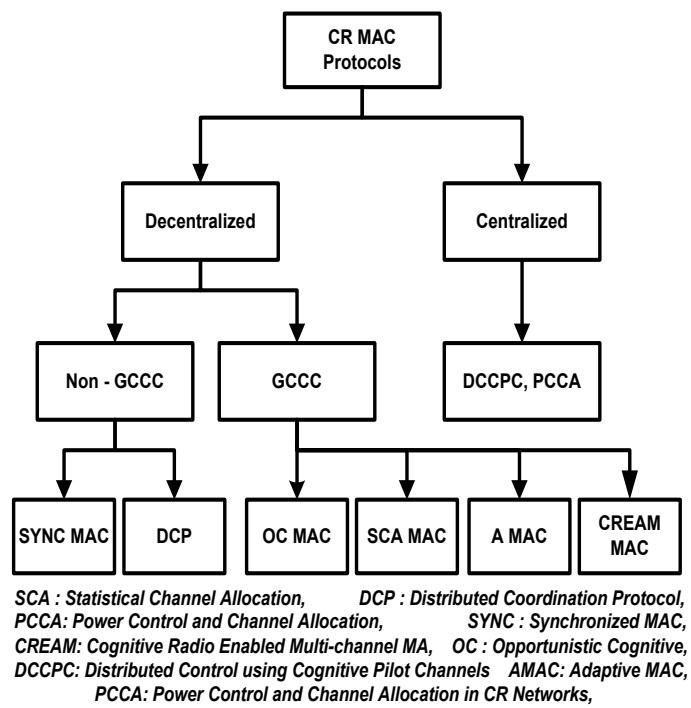

Figure 2. Classification of CR MAC protocols

To summarize, decentralized MAC protocols makes use of either GCCC or non-GCCC to exchange control information such as FCL before they can actually start communication; the GCCC class of MAC protocols suffers all the drawbacks discussed in the section below, Drawbacks of GCCC. Although some of the CR MAC protocols such as C-MAC, SYNC-MAC, DCP-MAC etc are non-GCCC based, but the clear methodology about the selection of the CCH is missing and emphasis is given on the actual data transmission rather

selection of the very important CCH, because we believe CR nodes can only switch to actual data transmission once successful and secure FCL transactions have taken place, whereas exchange of FCL in turn is heavily dependent upon CCH security and quality.

Previous section briefly described the need of CCH in a cognitive Radio environment. The next section describes the advantages and disadvantages of using ISM as a control channel to exchange initial dialogue (RTS/CTS) between two SUs to transmit data.

Advantages of Using a GCCC

- CCC is available 24X7: since GCCC can be any band described in ISM so it is always available and can be used by any type of wireless application.
- No need to purchase the license to use the GCCC. The GCCC is within the ISM band so the user don't have to pay any licensing fee or ask for permission to use the GCCC
- The pair of SU can find the best channel based on policy of channel selection and agreed transmission parameters to transmit data; this will impact null or minimum interference with the PU. Using CCC to exchange RTS/CTS decreases the probability to zero that it will interfere with the PUs[16].
- Multichannel hidden terminal problem in cognitive network environment [17] is solved by having a CCC which allocates special time slots to the communicating pair. The pair of nodes gets updated from its neighboring nodes about any hidden terminals in their vicinity.

Drawbacks of GCCC

Some of the major drawbacks of using GCCC could be described as follows.

- No traffic differentiation, First Come First Served (FCFS) mechanism to access the GCCC.
- Higher the saturation of GCCC, higher will be the computational cost and back off algorithm to access it. It also lowers the probability of availability of GCCC and it can subsequently have serious effects on the QoS requirements of CR devices.
- The increased number of wireless applications has created huge demand for more radio spectrum; in these circumstances having a dedicated channel for exchange of FCL and control frames is waste of precious resource.
- An adversary can impose the denial of service (DoS) attack on well known dedicated GCCC by intentionally flooding it, thus it is a major security drawback [21].

The shortcomings of a GCCC can be avoided by having a dynamic local control channel (called CCH in section I). This has led to our motivation explained in section III below, where we have intelligently avoided shortcomings and have made usage of some of the rare advantages of the GCCC for development of novel CR MAC protocol, called DDH-MAC. Detailed explanation of DDH-MAC is given in the following section.

III. DYNAMIC DE-CENTRALIZED HYBRID MAC PROTOCOL

The critical and most important aspect of the cognitive radio network is how to advertise the FCL between the participating cognitive nodes. Some protocols make use of GCCC for FCL exchange and suffers from all the disadvantages explained in II above [10,11,12,17]; the other method is to intelligently decide a local CCH within the available spectrum holes and advertise this to other nodes. This method which is already used by [16,20] however lacks clear methodology of finding the CCH within the white spaces amongst cognitive nodes. Especially authors of [10,17,21] has made a clear assumption that control channel is already found before the actual protocol starts operation, it is important to note no such assumption could be made because finding a control channel is the primary task of a CR MAC protocol and cannot be assumed as it is the fundamental requirement in CR nodes before any subsequent communication can take place. This motivated us to design a CR MAC protocol which is hybrid between the GCCC and non-GCCC. The DDH MAC makes partial use of GCCC to advertise the information about CCH established within the white spaces amongst cognitive nodes and efficiently set one of the white spaces as Primary Control Channel (PCCH) to exchange control information with other cognitive nodes and other as Backup Control Channel (BCCH) in case there is a PU claim on PCCH.

DDH-MAC Operation:

DDH-MAC presents a novel design for Cognitive Radio MAC protocol which provides two levels of selection and multiple levels of security. Since our focus is on the MAC layer, prior to the operation of the DDH-MAC it is assumed that spectrum has been sensed by the physical layer and FCL has been created at each node and cognitive devices are aware of each other range, IDs and services they can provide to each other. DDH-MAC makes partial use of GCCC to launch beacon frame (BF). BF is a control frame containing small piece of information about sending node_id, PCCH and BCCH. Launching BF in GCCC is the first level of selection and used to let cognitive nodes know which two white spaces to use as PCCH and BCCH. The second level of selection starts once the PCCH and BCCH is decided, cognitive nodes actually switch to that empty space to use it to exchange control information, i.e. FCL.

The first level of security is achieved by encrypting the BF using either public or private cryptographic schemes, and integrity of the messages is obtained by making use of message authentication codes. Since the FCL is not exchanged in GCCC rather it is secretly communicated in PCCH which is only locally available and is known to the participating cognitive nodes, this provides the DDH-MAC second level of security, though FCL could still be encrypted for increased confidentiality. Another level of security could be achieved by inclusion of time stamp and its hash value in the actual data frames transmitted by the CR nodes, the receiver cognitive nodes in this case always check and compare the time stamp / hash for integrity of the sent messages. DDH-MAC provides fourth level of security by dynamically adapting new PCCH for every transaction, since PCCH is primarily used to exchange FCL and has been established within the white spaces so a PU

re-claim is not unusual, in this case switching to BCCH is performed for seamless activity. In the worst case scenario when both PCCH and BCCH have been re-claimed, the recalculation of the PCCH and switching to new white space set as PCCH makes it secure against any malicious attacks on CCH. In DDH-MAC each cognitive node is equipped with two half duplex transceivers, G-Transceiver (GT) which continuously scan the GCCC to search for BF, whenever beacon is found in GCCC the information is either learnt or the FCL is updated, the cognitive node then switches to the PCCH and use the D-Transceiver (DT) to perform two operations such as, sense/ scan the PCCH and subsequently exchange FCL, and when the FCL is exchanged start the data transmission with the partner node over the agreed data channels available in the exchanged FCL.

Full operation of the DDH-MAC is explained with the help of Flow chart drawn in figure 3. At the start up the cognitive nodes are in steady state and the FCL is already established. Let N represent set of cognitive nodes in the network $N= \{N_1, N_2, N_3, ...N_n\}$ and C be set of white spaces within each node $C = \{Ch_1, Ch_2, Ch_3, ...Ch_m\}$ then the FCL CR nodes can have is

$$\sum_{i=1}^{n} \sum_{j=1}^{m} N_i, Ch_j \qquad (1)$$

Upon initialization, cognitive nodes implementing DDH-MAC use GT to scan the GCCC for BF. If the node does not find any BF then the node is responsible for the following three operations, i) To decide which white spaces to be used as PCCH and BCCH, ii) Formation of a BF and subsequent application of cryptographic operations, iii) launching BF in the GCCC. Any CR node which is going to launch BF in DDH-MAC must meet the following criteria,

$$\mu \geq 3 \qquad (2)$$

where μ is minimum number of available empty spaces within a CR node, one to be used as PCCH, other as BCCH and the last one for the actual data transmission. It is important to note that BCCH in DDH-MAC is a reserved/secondary control channel and is used only when there is a PU re-claim on PCCH. Dedicating a white space as BCCH may firstly give an impression of a loss of a white space but actually it improves the overall network convergence time by simply switching to BCCH if required, it helps reducing the computational cost of the protocol and avoids the rescanning of the GCCC which in turn can help CR nodes conserve energy too. The criterion to set one of the channels in the FCL as PCCH and BCCH can be arbitrary or it can satisfy the following equation.

$$\text{PCCH}\left(\sum_{j=1}^{m} Ch_j\right) = \text{Max}_{\text{Chj} \in \text{m}} \left\{ fn\ (\text{CHG}) \mid \sum_{j=1}^{m} Ch_j \right\} \qquad (3)$$

where fn (CHG) is the function to calculate the channel grade and is defined as [17]

$$\text{CHG} = Max_{AB,\ SNR,\ FER} \{ N_1Ch_1 + N_2Ch_2 + N_3Ch_3 + ... N_nCh_m \mid N_1Ch_1 \cap N_2Ch_2 \cap N_3Ch_3 \cap ..... N_nCh_m \}_{i=1,\ 2,...,n} \qquad (4)$$

Where AB is the available bandwidth, SNR is the signal to noise ratio and FER is the frame error rate.

Once the node decides about the PCCH and BCCH it waits for a time T before launching the BF in GCCC, where T is the time in seconds and is equivalent to time required by a node to sense at least three white spaces (Equation 2). This wait of T is there just to avoid doubling of BF in GCCC which might be launched by other CR node, (1 in the provided flow chart). If the node finds the BF it reads the information about PCCH and BCCH, update its FCL and switches to PCCH for subsequent control information exchange, otherwise it considers itself as the starting node and launch the BF in GCCC after creation as already explained above.

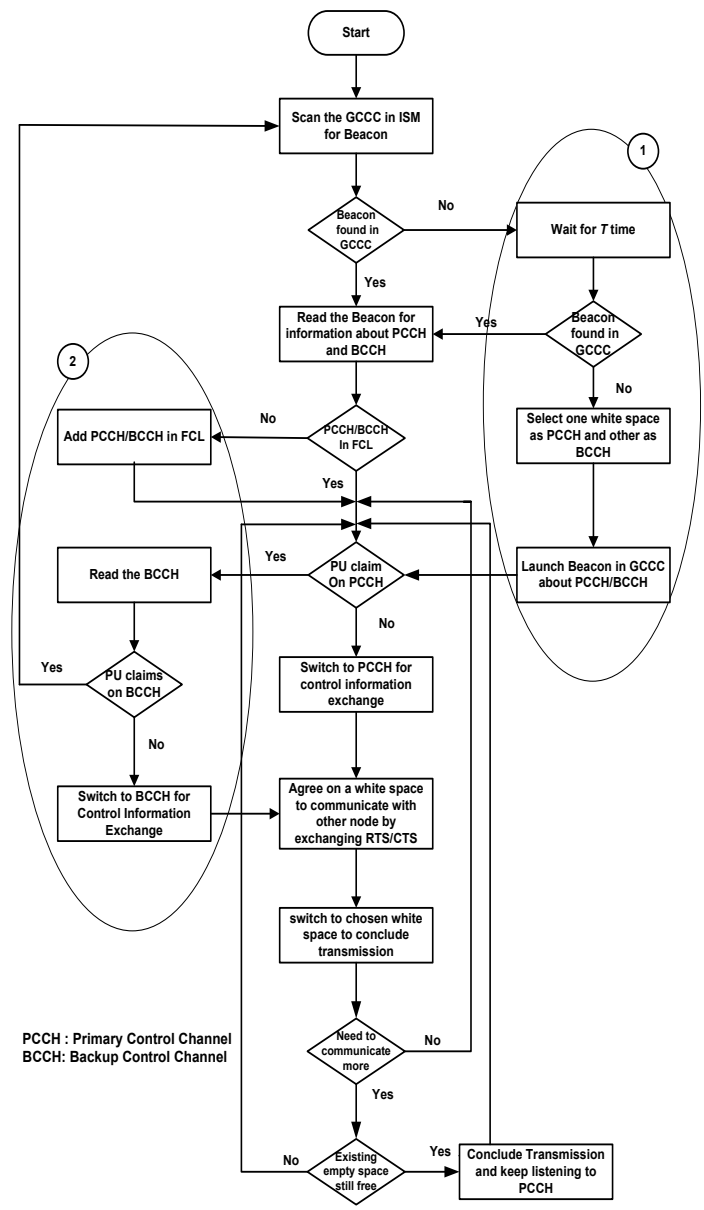

Figure 3. Flow chart Diagram DDH-MAC

During the initial scanning, If the BF is successfully found by a CR node in GCCC, it decrypts the information using the relevant decryption scheme to learn about the chosen PCCH and BCCH, once equipped with this information the node accordingly updates its FCL by setting the PCCH and BCCH for control information exchange and rest of white spaces as data channels for the subsequent data transmission. In addition to the flow chart shown in Figure 3 which provides complete operation of DDH-MAC, the process of BF launch/scanning and later on FCL update by different CR nodes is shown in Figure 4. The communicating CR nodes always verify the re-claim of PCCH by PU before they actually switch to it for further exchange of FCL. After successful exchange of FCL on chosen PCCH, the CR nodes eventually switch to agreed empty space to be used as data channel for the actual data transmission. The CR nodes may come up with a case when there is a re-claim by PU(s) on both PCCH and BCCH; in this case the nodes go to the initial state where it scans the GCCC for any new BF (2 in the provided flowchart).

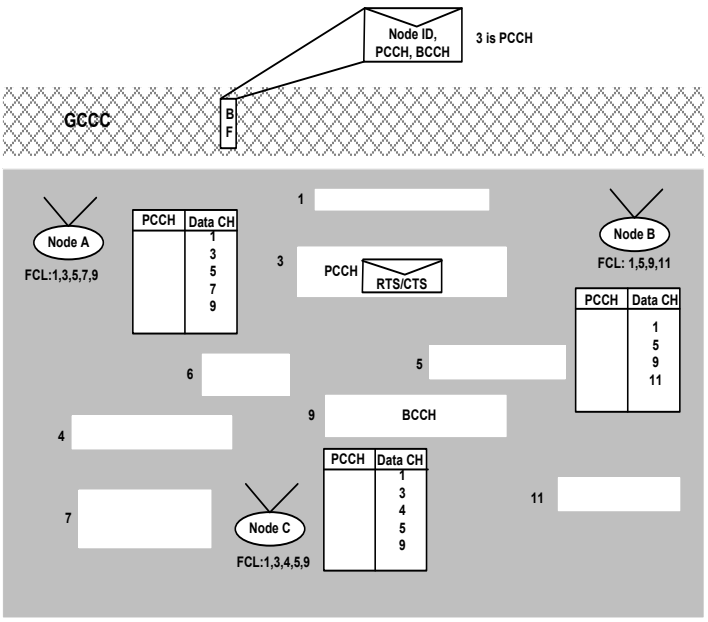

Figure 4. BF scan/launch and FCL update

Network Convergence Time:

Once BF is launched in the GCCC, CR nodes may take a bit of time to converge on the information of PCCH and BCCH contained in the BF before any FCL update can take place. The network convergence time can be either maximum or minimum, where as the former will be due to the requirement of backoff by CR node launching BF in GCCC, in case GCCC is initially unavailable.

$$N.C.T_{Max} = Tx\ Delay + Backoff\ Delay + (Propagation\ Delay)*Ni + Rx\ Delay + Computational\ Delay \quad (5)$$

$$N.C.T_{Min} = Tx\ Delay + (Propagation\ Delay)*Ni + Rx\ Delay + Computational\ Delay \quad (6)$$

A full operation of DDH-MAC and network convergence time has been described already; the next section provides the pseudo code for DDH-MAC for its implementation which is already underway.

IV. PSEUDO CODE FOR DDH-MAC

The pseudo code for DDH-MAC protocol has been given below.

```
beacon = info of(node_id+PCCH+BCCH)  //fields of BF
    while
    begin (the action of the secondary user)
    {
       case join group:
       listen to GCCC;
       if {
       at least receive a Beacon frame in GCCC
       read the beacon;
       case 1
       PCCH in FCL        //white space already known
              If      {
              no claim on PCCH, go to PCCH and
              sense control information;
              agree on white space for data
              transmission;
              conclude transmission with partner
              node;    }
              else     {
                       if {
                       no claim on BCCH; go to BCCH;
                       sense control information;
                       agree on white space for data
                       transmission;
                       conclude transmission with
                       partner node;
                            }
                       else
                            {
                               listen to GCCC;
                            }
                        }
       case 2
       PCCH not in FCL:
       update the FCL;
       go to case 1;
           }
       else {
              if {
              no. of white spaces ≥ 3
              //threshold to make itself first node
              wait till T expires;
              //time required to scan 3white spaces
              create group and make itself first
              node;
                // node one launches beacon in GCCC
              make PCCH and BCCH;
              create beacon;
              launch beacon in GCCC;
              wait till the network converges;
              //time required by other nodes to
              update information
              go to case 1;
                  }
              else
                  {
                     listen to GCCC;
                  }
    }
  end while;
```

V. PERFORMANCE EVALUATION

In this section pre-transmission time for different DDH-MAC scenarios (figure 3) has been computed and compared with several other MAC protocols [10,11,17] taking IEEE802.11b as benchmark. Pre-transmission time which is plotted in figure 5 has been calculated and compared for four different types of frames such as management (beacon frame-BF), control frames (RTS/CTS) and FCL.

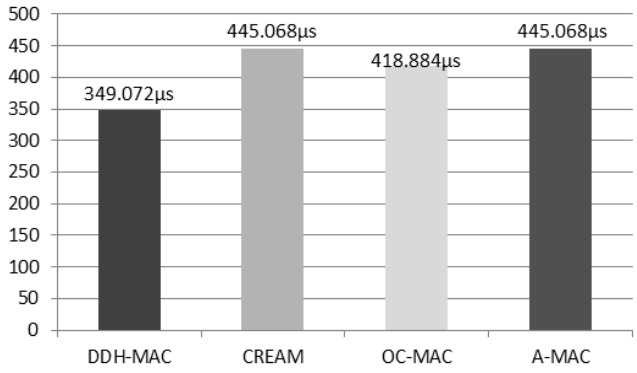

Figure 5. Comparison of average pre-transmission time

Clearly pre-transmission time for DDH-MAC is on average 20% lesser while compared to other MAC protocols (figure 5). It is important to note that reduced pre-transmission time not only result in efficient energy consumption but will also help DDH-MAC to have better QoS as nodes will not have to wait long before they could transmit.

VI. CONCLUSION

Cognitive Radios have emerged as a solution to the problem of spectrum scarcity for wireless applications. It is a key technology that will enable flexible, efficient and reliable spectrum use by adapting the radio's operating characteristics to the real-time conditions of environment. A novel design for CR MAC protocol, DDH-MAC has been presented in this paper which makes use of both GCCC and non-GCCC MAC protocols for increased performance and security. To the best of authors' knowledge this is the first protocol which is both dynamic and adaptive in its behavior, thus making it more secure and resilient in the presence of security threats such as DoS attacks etc. So far pre-transmission time for DDH-MAC is computed and found to be 20% lesser then the time required by other CR MAC protocols. Currently the proposed framework implementation is underway using the provided pseudo-code in OPNET network simulator. The security part of the implementation will be achieved by ensuring efficient and secure authentication among the communicating CR nodes by employing principles of confidentiality whereas the hash functions will serve to furnish the integrity of the information exchanged.

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