DYNAMIC SPECTRUM ACCESS SCHEME FOR DECENTRALIZED COGNITIVE RADIO NETWORK

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ABSTRACT Cognitive radio technology promises to mitigate the inflexibility of existing spectrum regulations. A Distributed Cognitive Radio Network should be able to independently and dynamically sense the available spectrum opportunities without a central coordinator. Taking in consideration the hardware limitations and channel dynamics, we propose a dynamic medium access scheme for cognitive Decentralized radio networks. The main objective is to make efficient decisions on which channels to sense and access, that ensure maximization of the throughput of the cognitive user. This paper describes the framework of the proposed MAC protocol in addition; the simulation and results of the proposed protocol are presented.

Keywords Cognitive radio, Dynamic Spectrum Access, POMDP, MAC Protocol

I. INTRODUCTION

The current spectrum management scheme always uses a fixed spectrum allocation policy. The main advantage of static allocation of the frequencies in a spectrum band is that devices developed for those wireless applications can be used globally. However the problems caused by the static way of spectrum allocation can be summarized as:

- Congestion on some of the spectrum bands, e.g., the ISM band.
- Spectrum underutilization in other bands, e.g., the TV band in rural areas
- Scarcity of spectrum for new wireless applications
- Lack of radio resource for those who are more appropriate and needy

Real time spectrum measurements done by the Federal Communications Commission (FCC) measurements in some of the major cities of the United States found the temporal and geographical variations in the utilization of the assigned or licensed spectrum ranging from 15-85% [5]. On the other hand the rapid popularity of other spectrum bands like the Industrial Scientific and Medical (ISM) band (e.g. 2.4 GHz) have resulted in congestion in those over used bands.

Cognitive Radio technology introduces a new effective design to better utilize the radio spectrum but it also introduces new challenging problems which are not present in conventional wireless networks, specifically the changing availability over time of channels in CR networks. Medium Access Control has an important role in several cognitive radio functions.

The term Cognitive Radio was first coined by Mitola [15] as an extension of software defined radio SDR. CRs are essentially SDRs that poses knowledge of their environment through sensing and artificial intelligence making them capable reacting to changes in the environment efficiently.

Cognitive radio system has been defined by the International Telecommunication Union (ITU) as follow [17]:

Cognitive radio system (CRS): A radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established
policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained.

One of the important design problems of the MAC layer of CR is how secondary users should take decisions about which channel they will use and at which time in order to enable secondary user communication while avoiding collision with the primary users by analysing sensing information provided by the physical layer. This problem becomes even more difficult in decentralized wireless networks where there is no central control mechanism like base stations, access points and central servers. Thus an intelligent opportunistic Cognitive Medium Access Control protocol is required for decentralized wireless networks which decides which channels to sense and which to access based on the behaviour of the primary network users.

In this paper, a Time slotted Medium Access Control protocol for decentralized cognitive radio networks using Partially Observable Markov Decision Process as a spectrum access decision engine is proposed.

II. RELATED WORK

CR MAC can be divided into two main groups Centralized and Decentralized Mac protocols. Centralized CR network has a base station which usually governs the cognitive functions in the network. IEEE 802.22 [7] is presented as the first worldwide wireless standard for cognitive radios. The dynamic spectrum access protocol (DSAP) [2] scheme is another centralized spectrum allocation scheme which is similar to the DIMSUMNet [3] in architecture. Since Decentralized MAC (ad-hoc network) is our main concern, we can further classify it into two groups single and multi-transceiver where each group can either have a Common Control Channel (CCC) or not.

In DOSS MAC [12], the design of the protocol largely depends on assuming a global control channel to be allocated in an unlicensed band (e.g. ISM band). This approach can lead to control channel saturation problem if a large number of spectrum holes are available or rapidly occurring. Also it will make the network less secure and more exposed to denial of service attacks. Several MAC layer schemes use the same network topology like [9], [18].The HC-MAC proposed in [9] considers the hardware constraints in a node. In the cross-layer opportunistic MAC [18], the spectrum sensing policy at the physical layer and the packet scheduling at the MAC layer are integrated Other MAC protocols will use a local Control Channel which is established by dynamically selecting one of the available whitespace in a network or by dividing SUs into different groups or clusters that have different CCCs.

In C-MAC [6] and EDA MAC [8], a rendezvous channel is established and channels are divided into a number of superframes. The superframes consist of a beacon period and a data transmission period. CogMesh [4] and HD-MAC [19] are based on the idea of clustering. The CogMesh addressed issues like node discovery, spectrum access, inter-cluster and intra-cluster communications. Usually, the probability of a channel being common to nodes all the nodes in a cognitive network is comparatively small. This stimulated the need for MAC protocols that will not need a CCC. However network coordination in the distributed CRN without a
dedicated control channel is very difficult. Hence network connectivity is not guaranteed and large overheads will be used to achieve network coordination. The decentralized MAC [20] (DC-MAC) scheme proposed uses Partially Observable Markov Decision Process POMDP to allocate channels for a data transmission. In the SYN MAC [10], a group of time slots is established and repeated over time, where the number of slots in a group is equal to the number of channels. But, only one pair can start a transmission in a particular slot.

Table 1: Summery of some of the cognitive MAC protocols discussed

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Topology</th>
<th>No. of Transponders</th>
<th>CCC</th>
<th>Synchronization</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 802.22</td>
<td>Centralized</td>
<td>1</td>
<td>non</td>
<td>yes</td>
<td>[7]</td>
</tr>
<tr>
<td>C-MAC</td>
<td>Decentralized</td>
<td>1</td>
<td>yes</td>
<td>yes</td>
<td>[6]</td>
</tr>
<tr>
<td>HC-MAC</td>
<td>Decentralized</td>
<td>1</td>
<td>Glob al</td>
<td>no</td>
<td>[9]</td>
</tr>
<tr>
<td>DOSS</td>
<td>Decentralized</td>
<td>3</td>
<td>Glob al</td>
<td>no</td>
<td>[12]</td>
</tr>
<tr>
<td>SYN-MAC</td>
<td>Decentralized</td>
<td>2</td>
<td>no</td>
<td>yes</td>
<td>[10]</td>
</tr>
<tr>
<td>DC-MAC</td>
<td>Decentralized</td>
<td>1</td>
<td>no</td>
<td>no</td>
<td>[20]</td>
</tr>
<tr>
<td>EDA-MAC</td>
<td>Decentralized</td>
<td>1</td>
<td>yes</td>
<td>yes</td>
<td>[8]</td>
</tr>
<tr>
<td>HD-MAC</td>
<td>Decentralized</td>
<td>1</td>
<td>yes</td>
<td>yes</td>
<td>[19]</td>
</tr>
<tr>
<td>CogMesh</td>
<td>Decentralized</td>
<td>1</td>
<td>yes</td>
<td>yes</td>
<td>[4]</td>
</tr>
<tr>
<td>DIMSUM</td>
<td>Centralized</td>
<td>1</td>
<td>Glob al</td>
<td>yes</td>
<td>[3]</td>
</tr>
</tbody>
</table>

III. SYSTEM MODEL AND PROTOCOL DESCRIPTION

The Proposed protocol will use Partially Observable Markov Decision Process (POMDP) as the basis engine for choosing which channels to sense and access in a multichannel environment. POMDP is used to automate the decision-making process among cognitive radio. A POMDP model formalizes the interaction between agents and environments [11]. Where it takes observations of the environment and produces actions specifications to an agent that produces the best possible reward to the agent.

A. Assumptions

The proposed MAC Protocol will be developed based on the following assumptions:

- Two types of channels are assumed: a CCC and data channels. The CCC is used as a rendezvous channel by SUs for coordinating access to the medium. We assume that is statically assigned.
- N data channels are available for use, each with bandwidth $B_i$ ($i = 1,\ldots,N$). These N Channels are licensed to a primary network.
- Each SU is equipped with one transceiver (TRx).
- The active period of the PUs is substantially longer than the length of the CR beacon interval.
- The interfaces are capable of dynamically switching their channel.
- We assume that the state of a primary channel does not change within a single time slot.

B. Primary Network Model

Based on POMDP frameworks, channel sensing and channel access scenarios model the channel opportunity of the network system as a discrete time Markov chain with number of channel states which can be formulated as $M = 2^N$ states, where N is the number of channels.

A channel state diagram for $N = 1$ is illustrated in the above Figure, where the state ($S=0$) indicates that the channel is occupied by the primary user (unavailable) and the state ($S=1$) indicates that the channel is available to be accessed (available).channel i transits from state 0.

We assume that the licensed spectrum consists of $N$ independent channels with bandwidth $B_n = (1,\ldots,N)$. And the primary user has the authority to communicate over these channels in a time slot structure. Also each channel is divided into T time slots. The network state in slot $t$ ($t = 1,\ldots,T$) is given by $[S_1(t),\ldots,S_N(t)]$, where $s_n(t)=1$ when the channel is free and $s_n(t)=0$ when the channel is busy. The objective is to maximize the throughput of the secondary network without causing
interference to the primary network by using the sensing history and spectrum occupancy statistics.

C. Timing Structure

The timing structure of our proposed protocol is divided into fixed-length beacon intervals in which we can distinguish two phases:

The ATIM (AD HOC TRAFFIC INDICATION MESSAGE) window: During the ATIM window, the nodes perform spectrum scan and exchange control information

The DATA window: The DATA window is used for data exchange

ATIM Window: During the ATIM window, all nodes participate in the following:

1) POMDP calculations;
2) Scanning the licensed channels (Spectrum sensing);
3) Two way ATIM handshakes (RTS/CTS)

DATA Window: The DATA window is used for data exchange and acknowledgment.

D. Data Structure

Each CR maintains two data structures: one is called the spectral opportunities vector of PUs (SOV), and the other is the secondary users channel Preference (SCP) vector. The SOV vector contains the node's local view on the spectrum. It has the following two types of entries.

1) No PU is active on channel c (SOV[c] = 0)
2) A PU is active on channel c (SOV[c] = 1)

The SCP vector is used for choosing the communication channel. It contains the expected reward of CR communication determined by POMDP. When a node wishes to transmit, the receiver picks the common spectral opportunity with the highest SCP.

E. Operation

As mentioned before the time slot is divided into two frames the ATIM window and the Data Window.

At the beginning of the ATIM all nodes will start sensing the available spectrum for access opportunities followed by local POMDP calculations based on the nodes local observations of the spectrum. Then all nodes will tune to the CCC. When a node have a packet to send it will contend to send a request to send (RTS) packet on the CCC to the receiver using 802.11 DCF (Distributed Coordination Function) he RTS packet contains the transmitters local view of the spectrum (SOV), the intended receiver and the expected NAV (Network Allocation Vector) timing of the handshake so that all other CR users would clear the CCC for this time.

When the intended node receives the RTS packet it will search for the common spectrum opportunity that has the highest reward from the receivers POMDP calculations. Then the receiver will send a CTS packet containing the selected data channel, all nodes that receive the CTS packet will change the selected data channel to not free this will ensure that the multichannel hidden terminal problem is averted. And all nodes that have either packets to transmit of receive will wait until the start of the data window, all other packets will enter a doze state until the next time slot. By allowing the terminals to enter a doze state when no communication is taking place, the MAC protocol achieves energy-efficient communication. The control channel can be used for data transmission but it will have the lowest possible reward value (fixed value) in the SCP frame.

The DATA window is used for data exchange and acknowledgment. Data exchange. Both the transmitter and the receiver will tune to the selected data channel, and then the transmitter will send the data packed when the receiver gets the packet it will transmit an acknowledgment packet back to the transmitter containing the achieved reward form this transaction. Then the two nodes will enter a doze state until the next time slot.

IV. POMDP FORMULATION

We begin this section first by describing the main components used to solve our POMDP problem this work is based on the formulation done in [13].
The main POMDP components are:

**States** for a network that consists of N channels and in T time slots the state of the network can be defined as follows:

\[
\begin{bmatrix}
S_1(1) & S_1(2) & \cdots & S_1(T) \\
S_2(1) & \vdots & \ddots & \vdots \\
\vdots & \vdots & \ddots & \vdots \\
S_N(1) & \cdots & \cdots & S_N(T)
\end{bmatrix}
\]

Where network state in channel n and slot t is represented by \( S_n(t) \) and a row vector \( S_n(1),S_n(2),\ldots,S_n(T) \) is a vector state of channel n. So we get a total of \( S=2^{NT} \) different states.

**Sub-States**: To reduce the computational complexity due to the size of the state matrix, a subset of states as a column vector state is defined. So for slot t: \( S_t=[S_1(t),S_2(t),\ldots,S_N(t)]^T \).

So a network with N channels is presented by \( S=2^N \) different sub states foe each time slot.

**Actions**: It’s the set of actions that the secondary user can do based on its observations, consisting of \( 2^N \) possible actions. For example, if N=2 the CR node has 4 possible actions:

1) Do not transmit
2) Channel one is available (transmit on Ch1)
3) Channel two is available (transmit on Ch2)
4) Both Channels are available (transmit on Ch1 or Ch2)

**Reward**: Each used channel will give an amount of reward

\[
r(t) = \sum_{n=1}^{N} S_n(t)B_n(t)
\]

Where \( S_n(t) \in 0,1 \) is the state of channel n in slot t, and \( B_n(t) \) is the channels bandwidth.

**Belief state** It is referred to as the summery statistic of all past decisions and observations:

\[
\pi(t) = [\lambda_1(t),\lambda_2(t),\ldots,\lambda_N(t)]
\]

Where \( \lambda_n(t) \) is the conditional probability that the channel n is available in slot t.

At the beginning of each time slot using the belief state \( \pi(t) \), the secondary user decides to access the channel:

\[
n^*(t) = \arg\max_{n=1,\ldots,N} [\lambda(t)]
\]

The belief state is updated at the beginning of each time slot with the application of Bayes’ rule:

\[
\pi(t+1) = [\lambda_1(t+1),\lambda_2(t+1),\ldots,\lambda_N(t+1)]
\]

The conditional probability \( \lambda_n(t+1) \) depends on the channel transition probabilities \( P^{01} \) and \( P^{11} \) and the channel transition probabilities are assumed to be random variables that update their values at the start of each time slot. The channel transition probabilities are updated according to the history of state transitions [14] as follows:

\[
S_n^{00}(t) = \sum_{i=1}^{t-1} (1-S_n(i))(1-S_n(i+1))
\]

\[
S_n^{01}(t) = \sum_{i=1}^{t-1} (1-S_n(i))S_n(i+1)
\]

\[
S_n^{10}(t) = \sum_{i=1}^{t-1} S_n(i)(1-S_n(i+1))
\]

\[
S_n^{11}(t) = \sum_{i=1}^{t-1} S_n(i)S_n(i+1)
\]

Where \( S_n^{00}(t) \) is number of state transitions from busy to busy, \( S_n^{01}(t) \) busy to free, \( S_n^{10}(t) \) free to busy and \( S_n^{11}(t) \) free to free at time t. Depending on the state transition count the channel transition probabilities are updated as follows:

\[
P^{01}(t) = \frac{S_n^{00}(t) + S_n^{01}(t)}{t}
\]

\[
P^{11}(t) = \frac{S_n^{10}(t) + S_n^{11}(t)}{t}
\]

The initial belief state is given as the stationary distribution of the channel occupancy state

\[
\pi(0) = \frac{1}{1 + P^{01} - P^{11}}
\]

Next we consider the conditional probability of the availability of a channel as

\[
\lambda_n(t+1) = \lambda_n(t)P^{11} + (1-\lambda_n(t))P^{01}
\]
V. RESULTS AND SIMULATION

In the simulation of our proposal we compare the performance of the proposed protocol against a random access cognitive MAC using the throughput as performance metric. Every data channel has a pair of primary users one, and operates on a particular data channel according to state transition probabilities.

![Figure 5: Throughput Proposed Mac vs. Random at N=2](image)

The figure shown uses two data channels. For this scenario we have set $P_{11} = P_{01} = 0.5$. The results show a superior throughput when using the proposed MAC (blue) over the random (red).

Also it shows a steady increase with time as the proposed protocol is gaining more knowledge of the primary users’ behaviour.

In the second simulation we consider different transition probabilities for the primary channels. As the transition probability $P_{11}$ increases this means that the data channel will be idle for a longer time and so the expected throughput should increase.

We test $N=2$ scenario at $P_{11} = 0.9, 0.5, 0.2 & P_{01} = 0.1, 0.5, 0.8$ receptively.

![Figure 6: Throughput at different transition probabilities](image)

Also when we compare the error count between the proposed MAC and the Random approach we find that the proposed protocol will have less error rate. That’s because the error count is the count of missed opportunity to receive data packets and in the proposed Mac with time learns which channel is likely to be free.

![Figure 7: Error Count proposed Vs Random at N=3](image)

VI. CONCLUSIONS

In this paper, we have presented a POMDP-based cognitive MAC approach for decentralized networks. Using multiple channels and assuming a slotted structure for the primary network, we proposed that cognitive user opportunistically makes optimal decisions for sensing and access based on the information state. By updating the belief vector that summarizes the knowledge of the network state based on all past decisions, observations and then the transition probabilities,
the secondary user perform more efficiently. Our results demonstrate an improvement in the throughput random approach. However, sensing errors are ignored in this work. False alarm and miss-detection probabilities need to be considered in future work.

REFERENCES


