Abstract—Cognitive radios are radios that improve spectrum efficiency and spectrum utilization by operating on unused spectrum channels in their neighborhood. These unused channels are detected through spectrum sensing, which must be performed to ensure the absence of the primary user, before a cognitive radio can utilize the channel. However, spectrum detection is a challenge to radios due to bandwidth constraints imposed on them and also due to degraded channel conditions such as multipath and shadowing. Secondly, these unused channels show different characteristics, and therefore, an appropriate channel needs to be chosen based on the characteristics it exhibits. In this paper, we propose algorithms and implementations for an Intelligent Mobile Agent-based approach for spectrum detection and decision, whereby, mobile agents are injected into the network to perform these two management functionalities, thus enabling the radios to utilize the channel without having to intermittently stop to check for the reappearance of the primary user and ensure non-interference to the primary user.

Keywords—Cognitive radio; Intelligent mobile agent; Spectrum detection; Spectrum decision

1. INTRODUCTION

Cognitive radio is a technology that enhances efficient spectrum usage, by utilizing temporarily idle spectrum [1]. This technology was introduced because it was found out that most licensed spectrum are not being properly and fully utilized. Spectrum is a finite and costly resource which is managed by government agencies both nationally and internationally, and these agencies use a fixed allocation method in allocating spectrum to particular users and for a particular use [1][2]. Meaning that, once spectrum is allocated to a particular user, that user alone has the right to operate on that band. This is good because it simplifies issues concerning ownership and makes the license owner confident enough to invest in infrastructure, which ultimately leads to better quality of service. However, studies by the federal communication commission (FCC) and other researchers [1][2][4][5], have shown that these licensed bands lie idle most of the time, leading to wastage of such a valuable resource. Thus, cognitive radios were introduced to utilize these idle channels but it has to be without interfering with the license owners.

To ensure non-interference to primary users (PU), cognitive radios or secondary users (SU) must sense the channel to detect the presence or absence of the primary user, and if absent, they can then make use of the spectrum. They also need to intermittently stop transmission to sense for the reappearance of the primary user. Spectrum detection, performed through spectrum sensing, is the key functionality to ensure efficient spectrum usage by cognitive radios.

It is however difficult for individual radios to reliably sense the occupancy state of the channel due to various channel degradation conditions such as multi-path fading and shadowing, leading to bad estimation of the occupancy state of the channel and false alarm. The dynamic nature of the radio spectrum therefore calls for the development of novel spectrum detection strategies to correctly estimate the occupancy state of a channel [5][6][7]. A feasible solution to this challenge faced by cognitive radio networks is to introduce agent based approaches for spectrum detection and decision.

Agents are programs that perform certain or specified tasks on behalf of the user. Mobile agents perform a user task by migrating and executing on several hosts connected to the network. The main difference between an intelligent agent and traditional agent is that the former perform not only actions pre-specified by a user but also those necessitated by later changes in the environment. Mobile agents introduce a new software and communication architecture, allowing a program to travel between machines for remote execution, even in heterogeneous cognitive radio networks. By transporting the agent code to the host machine in a distributed cognitive radio network, there is no need to bring intermediate signals and data across the network and thus a significant amount of network bandwidth use and communication delay can be avoided [8][9][10].

The detection accuracy in spectrum sensing has been considered as the most important factor to determine the performance of cognitive radio networks. Furthermore, idle spectrum bands in a network show different characteristics, so cognitive radios are supposed to select the proper spectrum band according to the application requirement.
In this paper, we present agent-oriented algorithms and implementations for spectrum detection and decision in cognitive radio networks, to efficiently detect and decide on the availability and appropriateness of a channel.

2. RELATED WORK

This section outlines similar works that has been accomplished in the area of spectrum management in cognitive radio networks using agent technology. The approach proposed by [11] is on using embedded agent modules, whereby, agents are embedded in the radio devices that coordinate their operations to benefit from network and avoid interference to the primary user. Agents carry a set of module to gather information about the terminal status and the radio environment and act accordingly to the constraints of the user application. The approach is based on agents with common interest who collaborate by sharing their knowledge and expertise to increase their collective and individual gain. Group or coalition formation will identify the environmental information without requiring huge computational effort at the cognitive radio terminal. This helps in conserving the energy resources of autonomous cognitive radio terminal. Also keeping in mind the dynamic state of the radio resource and secondary users, the embedded agents in each cognitive radio device can build their preference models in terms of selecting a device with high level quality of service. These preference models will allow conserving time in dynamic and changing network conditions. In other words, the agents will know in which part of the network it can find information for making a proper decision.

A very interesting approach is proposed in [12] where the authors have applied reinforcement learning RL on single-agent (SARL) and Multi-Agent (MARL) to achieve the sensitivity and the intelligence. They show in their results that the SARL and MARL perform a joint action that gives better performance across the network. They finally said reinforcement learning algorithm is adapted too be applied in most application schemas.

In the solution proposed in [13], a learning mechanism as the local MARL is available for each agent. The Local Learning provides a reward for each agent so that it can make the right decision and choose the best action. They modeled each SU node as a learning agent because the transmitter and receiver share a common result of learning or knowledge. The authors presented the LCPP (Locally Confined Payoff Propagation) which is an important function of reinforcement learning in MAS to achieve optimality in the cooperation between agents in a distributed CR network.

A channel selection scheme without negotiation is considered for multi-user and multi-channel in [14]. To avoid collision incurred by non-coordination, each SU learns to select channels based on their experiences. The MARL is applied in the context of Q-learning by considering the SUs as part of environment. In such a scheme, each SU senses channels and then selects a slowed frequency channel to transmit the data, as if no other SU exists. If two SUs choose the same channel for data transmission, they will collide with each other and the data packets cannot be decoded by the receiver. However, the SUs can try to learn how to avoid each other.

3. IMACRN SYSTEM MODULE FOR SPECTRUM RESOURCE MANAGEMENT

Basically, our system, Intelligent Mobile Agent for Cognitive Radio Networks (IMACRN), design is built on five different interlinked parts that form the working of our proposed system to take care of spectrum detection, spectrum decision, spectrum sharing and spectrum mobility. However, this paper deals with spectrum detection and decision only. Spectrum sharing and mobility will be explained in a subsequent paper. These agent parts are explained below:

a) Spectrum Sensing Agent (SSA): the function of SSA is to sense the radio spectrum holes and continuously monitor the primary user signals. SSAs cooperatively sense the channel and measure it against the threshold. Since it is not possible to know what time a spectrum band is occupied or when it is free, the sensing is done by considering a real-time dynamic environment. Factors that are taken into consideration include spectrum traffic, primary user signal power and associated noise and sampling time intervals.

b) Spectrum Decision Agent (SDA): SDAs characterizes the spectrum hole and its function is to arrange the idle spectrum information received through the SSAs according to channel capacity and channel information.

c) Secondary Consumer Agent (SCA): SCAs function is to send Spectrum Request (SR) messages to the Agreement Agent, whenever a secondary user indicates that it needs to use a portion of the spectrum. The message sent is of the form: req(s,t), where s represents the size of spectrum needed by the secondary user and depends on its application, for a duration of time t. SCAs also coordinate or share the spectrum amongst secondary users in the network after it has been acquired from the primary user.

d) Agent Memory Module (AMM): AMMs gets the primary user signal characterization from SDAs and stores it in its database. This database list is regularly maintained and updated, thus it is not a permanent list. This module also serve as database for available spectrum and their characteristics.

e) Agreement Agent (AA): AAs manage the agreement and cooperation between primary and secondary users for spectrum sharing.
4. IMACRN-BASED SPECTRUM DETECTION

Dynamic Spectrum Access (DSA) by cognitive radio-enabled secondary devices is one of the promising approaches to increase utilization of underutilized licensed spectrum bands. However, DSA approach requires that the secondary users should not violate any acceptable interference bounds specified by the primary users. Therefore, the main challenge involved in devising DSA scheme for cognitive radio devices are as follows:

a) The cognitive radio nodes should be able to identify the white spaces in the spectrum and utilize them without interfering with the primary user.
b) The DSA scheme should minimize the channel sensing (and therefore, the energy consumed in the sensing operations) by the secondary node.
c) Cognitive radios cannot transmit while sensing the channel, which undermines the goal of DSA because spectrum is wasting and therefore spectrum efficiency is decreased.

In practical multi-user environments, cognitive radio operation is governed by interference tolerance and sensing limits at the primary and secondary users. The interference limits at the primary and secondary users indicate the amount of protection needed at each primary and secondary user from the multi-user interference to maintain a certain rate. On the other hand, the sensing limits (minimum SNR needed for detection) at the secondary users reflect the amount of protection that each secondary user is individually able to provide to the primary users. In these scenarios the key is to strike a balance between the two conflicting goals: minimizing the interference to the primary users, and maximizing the performance of the entire system. To overcome these detection challenges, Intelligent Mobile Agents (IMAs) strategy is devised to help in reliably detecting idle channels, thus limiting the number of secondary users sensing the channel. The scheme ensures non interference to the primary user and radios can concentrate on transmission while the agents sense the channel for the reappearance of the primary user.

Spectrum Sensing Agents (SSA) in IMACRN are encoded to sense and detect primary user signals and send the information to the cognitive radio network. SSAs function is to sense the radio spectrum holes and continuously monitor the primary user signals. A predefined set threshold $Y$, is also input in the code for use in measuring the observed signal. This will help the radios to concentrate more on using the available spectrum without having to intermittently check for the presence of the primary user. The agents will individually or collaboratively detect active primary user transmissions over the band, and decide if the sensing results indicate that all the primary user transmitters are inactive at that band.

A. Spectrum Detection Algorithm

To buttress the points made, let us represent spectrum sensing by IMACRN agents using the algorithm below and the flowchart in Fig.1

\[
\text{let; } Y = \text{a set threshold} \\
\text{Where} \\
Y = \text{Energy observed on the primary user signal} \\
\text{let; } s = \text{result obtained from sensing the spectrum} \\
\text{if } s > Y \text{ then } H_1 \text{ Primary User is Present} \\
\text{else} \\
\text{if } s < Y \text{ then } H_0 \text{ Primary User is Absent.} \\
\text{// The set threshold } Y \text{ will be used to determine and measure the reliability of the collected results. When the collected signal } S_i \text{ exceeds the threshold } Y, \text{ decision } 1 \text{ will be made which assumes that the primary user is present; otherwise, decision } 0 \text{ will be made. The decision } D_i \text{ of the agents is then given by:} \\
D_i = 0; \text{ where } 0 < S_i < Y \\
\text{and } \\
D_i = 1; \text{ where } S_i > Y
\]

![Fig. 1. Agent Spectrum Detection Flowchart](image-url)
5. IMACRN-BASED SPECTRUM DECISION

The free spectrum bands detected through spectrum detection show different characteristics according to radio environment. Since cognitive radio networks can have multiple available spectrum bands having different channel characteristics, they should be capable of selecting the proper spectrum bands according to the application requirements, this is called Spectrum Decision. Spectrum Decision Agents (SDA) characterizes the available spectrum hole and each spectrum band is characterized based on not only local observations of cognitive radio users but also statistical information of primary networks. Through the local measurement, SDAs can estimate the channel conditions such as capacity, bit error rate (BER), delay and jitter. After the spectrum characterization, the best and appropriate spectrum band is chosen.

A. Spectrum Decision Algorithm

Mobile agents should select the best available channel by characterizing each spectrum hole based on Spectrum Band Information such as (operating frequency; bandwidth; interference level; channel error rate; path loss; link layer delay; wireless link errors; holding time) and Channel Conditions such as (capacity; bit error rate (BER); delay; jitter), and then make decisions D1 (yes) or D0 (No). Depending on the application and the code parameters, two options are available in IMACRN for spectrum decision:

// Option 1: In IMACRN, channel can be characterized based on capacity C. this is calculated using Shannon’s theorem:
\[ C = B \log_2(1 + \text{SNR}) \]
Where C = channel capacity
B = bandwidth of the channel
S = average signal power over the bandwidth
S/N = Signal-to-Noise Ratio (SNR)
[Secondary user agents characterizes each primary user on the basis of capacity]
For each \( i \in \text{PU} \) do
Evaluate (\text{SNR}(i))
Evaluate (B(i))
\[ C(i) = B(i) \log_2 [1 + \text{SNR}(i)] \]
[C: is the capacity calculated using Shannon theorem]
If acceptable
then D1
Else D0
End For

// Option 2: IMACRN characterizes spectrum based on the whole spectrum band information and channel capacity. Here the agent needs to check each parameter separately and then go to the next one. When all parameters have been evaluated and the result is satisfactory depending on the application that needs to use it, decision D1 will be made, otherwise, decision D0 will be made.

```plaintext
if \( s < Y \)
then D0
Check spectrum band information (b)
for \( b = 1 \) to 11
if operating frequency; bandwidth; interference level; channel error rate; path loss; link layer delay; wireless link errors; holding time; bit error rate; delay; jitter
Acceptable
then D1
else D0
```

The flowchart depicting the above algorithm is given in Fig. 2:

6. IMACRN AGENT CREATION

IMACRN agents are developed in Java Agent Development Environment (JADE), a software environment used for developing agents which comply with Foundation for Intelligent Physical Agents (FIPA) specifications. FIPA is a
non-profit international association that produces specifications and standards for agent technologies. IMACRN agents creation is achieved by defining a class extending the jade.core.agent class and implementing the setup() method. This method was used to create IMACRN agents as can be seen in Fig. 3.

A. IMACRN Agent Identifiers
An Agent Identifier (AID) is used to identify IMACRN agents and this identifier is an instance of the jade.core.AID class. Retrieving the agent identifier is made possible through the getAID() method of the agent class. IMACRN AIDs include a name and an address for each agent, and has the form <name>@<platform name>, the platform name being the address. As can be seen in figure 3, the created IMACRN agents are all living in the platform named NnennaC-HP, so as an example, the spectrum sensing agent (SSA) called SSA living in the platform have SSA@NnennaC-HP as its distinguished name.

B. Agent Communication
The communication method used by IMACRN agents is the asynchronous message passing. Using this method, each agent has a mail box where messages sent by other agents are posted by the JADE runtime. For message exchanges, IMACRN agents use Agent Communication Language (ACL) format defined and approved by FIPA for agent interactions [15][16]. The specified ACLs used by IMACRN agents include:

- i) identity or name of the sender
- ii) identity or name of the receiver(s)
- iii) the purpose of the communication (known as performative), showing what the sender wants to achieve. For instance, in IMACRN:
  a) if the sender requires the receiver to perform an action, the REQUEST performative is sent
  b) if the sender wants to notify the receiver of a fact, the INFORM performative is sent
  c) if the sender wants to know the truth of a given condition or statement, QUERY-IF performative is used
  d) if the sender wants to initiate negotiation, the CFP (Call for Proposal) performative is sent
  e) if the sender and receiver are negotiating, the PROPOSE, REJECT_PROPOSAL, ACCEPT_PROPOSAL

7. EXPERIMENTAL RESULTS
In this section, numerical results obtained and used to evaluate the multi-agent approach are presented. The simulation time is set at 120 minutes. All the simulations are conducted in Java Application Development Environment (JADE), over two PCs with 3.40GHz and 2.30GHz processor and 4GB memory. The parameters used are as shown in Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of spectrum portion</td>
<td>4MHz</td>
</tr>
<tr>
<td>Simulation time</td>
<td>120 minutes</td>
</tr>
<tr>
<td>Max. number of PUs</td>
<td>30</td>
</tr>
<tr>
<td>Max. number of SUs</td>
<td>30</td>
</tr>
<tr>
<td>Max. number of each type of agent</td>
<td>5</td>
</tr>
</tbody>
</table>

A. Spectrum Detection
For spectrum detection to take place, two agents must be communicating through messages. The two agents in the experiment are Spectrum Sensing Agent (SSA) in Fig. 4(a) and Secondary Consumer Agent (SCA) in Fig. 4(b). The agents use a set threshold in their estimation for the presence or absence of the primary user. As can be seen in Figure 4(a) to Figure 4(c), the spectrum sensing agent and the secondary consumer agent communicated using messages.
For the purpose of this experiment and for communications to take place between agents, the threshold was set randomly at 3, and on sensing a signal at 1 as shown in message in Fig. 4(b), the SSA sent the information to the SCA indicating that the spectrum is available for use. And on receiving the message, the SCA acknowledged receipt by replying as shown in Fig. 4(c). The experiment was performed with a single and later with a multiple number of agents and the results obtained are reported in Table 2.

![Fig. 4(a). Spectrum Detection Message from SSA](image)

![Fig 4(b). Message Received by SCA](image)

![Fig 4(c). Acknowledgement Message from SCA](image)

From the results in Table 2, it can be shown that agents were able to correctly detect the occupancy state of the channel, when there are multiple numbers of agents.

With results shown in Table 2, the correlation between the number of agents and their corresponding number of channels correctly detected is graphically represented in Figure 5.

### Table 2. Spectrum Detection Data

<table>
<thead>
<tr>
<th>Number of Channels Sensed</th>
<th>Correct Detection (1 SSA)</th>
<th>Correct Detection (5 SSA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>15</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>20</td>
<td>13</td>
<td>17</td>
</tr>
<tr>
<td>25</td>
<td>20</td>
<td>23</td>
</tr>
</tbody>
</table>

![Fig. 5. Spectrum Detection Data](image)
B. Spectrum Decision

The detected spectrum needs to be characterized to ensure that it is in good condition and appropriate for use. The agents were able to correctly decide on the appropriate spectrum band based on the characteristics of the available channels. Here, agents also use messages to pass information to each other. The results obtained based on a single agent decision and a multiple number of agents are as shown in Table 3. The SDA, after characterizing the channel, sent a message to the SCA indicating that the channel is usable, as shown in Figure 6.

Table 3. Spectrum Decision Data

<table>
<thead>
<tr>
<th>Number of Available Channel</th>
<th>Correct Decision (1 SDA)</th>
<th>Correct Decision (5 SDA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>15</td>
<td>10</td>
<td>14</td>
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<tr>
<td>25</td>
<td>20</td>
<td>24</td>
</tr>
</tbody>
</table>

Graphical representations of the correlation between the number of agents and decisions made correctly are shown in Fig. 7. From the results, it can be seen that multi-agents characterized the channels more correctly than a single agent. This is due to the cooperative nature of IMACRN agents in spectrum detection and decision. Each agent shares its detection and decision observation with other agents through messages, these observations are combined and decision made based on collective agreement.

8. CONCLUSION

Spectrum detection and decision are important functionalities to realize dynamic spectrum access principles. Cognitive radios have to correctly estimate the primary user’s signal before utilizing the spectrum as incorrect estimation may lead to collision and false alarm. Presented in this paper are algorithmic approaches and implementation for intelligent mobile agent-based spectrum detection and decision. Our mobile agent system design is made up of five interlinked paths that take care of spectrum detection, spectrum decision, spectrum sharing and spectrum mobility, which are the spectrum management functionalities. The agents are injected into the network to
perform these functionalities for the radios in order to improve cognitive radio network performance. The approaches in this paper, for spectrum detection and decision, are step by step process which the agents use in carrying out their tasks. A set threshold is input into the mobile agent codes for use in detecting an idle or free spectrum and mobile agents evaluate the channel based on spectrum band information and channel capacity. Using the methodologies proposed, the primary user’s signal can be correctly detected and evaluated. A subsequent paper deals with algorithmic approaches and implementation for the two remaining spectrum management functionalities; spectrum sharing and spectrum mobility.

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