



A Comparison of Techniques Used in CR for Spectrum Access

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Abstract— *It is a well known widely accepted fact that the static spectrum allocation has led to the under exploitation of the available frequency band. This problem can be mitigated by cognitive radio technology. It is a concept which with its learning ability is aware about its environment and intelligently adapts to it with objectives like reliable communication, efficient utilization of spectrum and minimal or no interference among users.*

Various techniques have been suggested in the research works to access the spectrum dynamically in a cognitive radio environment. These techniques basically use the concepts of Artificial Intelligence. Game theory, Markov chain models, Auctioning, Neural Networks, Multi Agent Systems and Fuzzy Logic approaches are some of the AI techniques for DSA and are compared in this paper.

Keywords—*Artificial Intelligence, Cognitive Radio, Dynamic Spectrum Access, Fuzzy Logic, Genetic Algorithm, Markov Model, Multi Agents, Neural Network.*

I. INTRODUCTION

The issue of spectrum underutilization in wireless communication can be solved in a better way using cognitive radio technology. It is an intelligent wireless communication system, which is aware about its environment and adopts the statistical variation in the input keeping objectives in mind that highly reliable communication with efficient utilization of radio spectrum without causing the interference to the primary user or licensed user. The term cognitive radio was given by Dr. J. Mitola in 1998 and since then it has been developed as a wireless standard IEEE 802.22 for using cognitive radio for Wireless Regional Area Network (WRAN). In a cognitive environment users have to communicate without causing interference to other co-existing users which is only possible if they have knowledge of the environment.

Learning about environment includes the knowledge of the use of frequency spectrum which is not uniform. It varies with time and geographical areas. Therefore SUs or unlicensed users using spectrum opportunistically must have the knowledge of peak usage times and idle times to use the spectrum efficiently. Hence this paper covers the research areas of cognitive radio as well as AI. The main objective is to intelligently manage spectrum resources to harness the unused spectrum using the Dynamic Spectrum Access techniques.

The first section of this paper deals with basic cognitive radio concepts. Section II conceptualizes cognitive radio. Section III covers areas of cognitive radio using different areas of AI. Section IV gives the different DSA techniques used in CR technology. Finally we compare these methods in a table to clearly visualize the merits and demerits of each technique.

II. COGNITIVE RADIO

The concept was first originated by Defence Advance Research Products Agency (DARPA) scientist, Dr. Joseph Mitola [11] and the result of that concept is IEEE 802.22, which is a standard aimed at using cognitive radio for Wireless Regional Area Network (WRAN) using unutilized spectrum band in the TV frequency spectrum while assuring that no harmful interference is caused in spectrum access, i.e., digital TV and analog TV broadcasting, and low power licensed devices. IEEE P802.22.1 is a standard being developed to enhance harmful interference protection for low power licensed devices operating in TV Broadcast Bands in the 700 MHz band. IEEE P802.22.2 is a recommended practice for the installation and deployment of IEEE 802.22 System. IEEE 802.22 WG is a working group of IEEE 802 LAN/MAN standards committee which is chartered to write the 802.22 standard. The two 802.22 task groups (TG1 and TG2) are writing 802.22.1 and 802.22.2 respectively. One of the most important components of the cognitive radio concept is the ability to measure, sense, learn, and beware of the parameters related to the radio channel characteristics, availability of spectrum and power, radio's operating environment, user requirements and applications, available networks (infrastructures) and nodes, local policies and other operating restrictions. In cognitive radio terminology, primary users (PU) can be defined as the users who have higher priority or legacy rights on the usage of a specific part of the spectrum also known as licensed user. On the other hand, secondary users (SU) also have known as unlicensed users, which have lower priority, exploit this spectrum in such a way that they do not cause interference to primary users. Therefore, secondary users need to have cognitive radio capabilities, such as sensing the spectrum reliably to check whether it is being used by a primary user.

A. Functions Of Cognitive Radio

Cognitive radio performs basically four functions, these functionalities of cognitive radio enable spectrum aware communication protocols, summarized as follows:

- Spectrum sensing
- Spectrum Management
- Spectrum Mobility
- Spectrum Sharing

1) Spectrum Sensing:

Detecting unused spectrum and sharing the spectrum without harmful interference with other users. In other words spectrum sensing aims to determine spectrum availability and the presence of the licensed users (also known as primary users). Spectrum sensing enables cognitive radio users to adapt to the environment by detecting spectrum holes without causing interference to the primary network.

2) Spectrum Management:

Capturing the best available spectrum to meet requirements of user's communication or to predict how long the spectrum holes are likely to remain available for use to the unlicensed users (also called cognitive radio users or secondary users).

3) Spectrum Mobility:

Seamless communication is required whenever there is case of transition to maintain the quality of service (QoS). Thus spectrum mobility is to maintain communication requirements whenever there is transition from that spectrum to better spectrum.

4) Spectrum Sharing:

Providing the fair spectrum scheduling method among coexisting secondary users, in other words spectrum sharing is to distribute the spectrum holes fairly among the secondary users. More specifically, the cognitive radio technology will enable the users to determine which portions of the spectrum is available and detect the presence of licensed users when a user operates in a licensed band (spectrum sensing), select the best available channel (spectrum management), coordinate access to this channel with other users (spectrum sharing), and vacate the channel when a licensed user is detected (spectrum mobility).

III. ARTIFICIAL INTELLIGENCE AND ITS USE IN COGNITIVE RADIO

An efficient CR can be designed for DSA using the concepts of machine learning. The interface is a transceiver which detects a new signal. The knowledge base keeps the states of the system and actions to be performed. The learning engine manipulates the observed data stored in knowledge base. The actions stored in knowledge base are then used by the reasoning engine to select the best action. Fig. 1 shows a basic CR system.

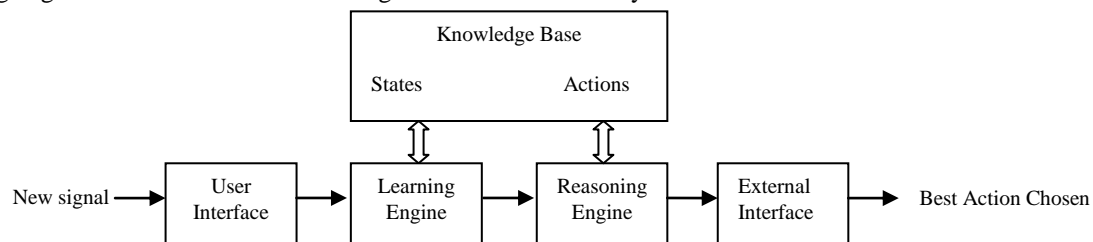


Fig. 1 Cognitive Radio System

Various AI techniques can be used for the CR networks depending on the nature of the network and problems faced by it. But whatever technique is employed it should make the system less complex and faster in operation.

Neural networks and hidden Markov models are techniques suitable for reasoning and decision making in cognitive radio.

CR networks employ machine learning, genetic algorithms and fuzzy logic to develop a knowledge base of observed states of wireless environment. This knowledge is then used by the inference engine to make decision of spectrum access. Consider the case of SUs observing the usage of spectrum by PUs by observing their transmission over the different channels. This observed data is used by the CR to build a knowledge base of PU usage on each channel. CR based on this knowledge decides which communication path to choose to get the desired performance i.e. maximum throughput of SU and minimum interference to PU and other SUs.

Neural networks could be used and have high ability for training and adaptation but also require a high processing time to train the weights and sensitivity to the quality of the training data. Similarly, the hidden Markov model can yield good decisions but faces basic problem in decoding, recognition, training and learning.

A. Neural Networks

Artificial Neural Networks are made up of interconnected artificial neurons resembling the human neural system. These neurons make the input layer, hidden layer and output layer of ANN architecture (Fig. 2). ANN provides a non

linear relationship between the inputs and outputs. Neural network model can learn from training data available. The data measured is in real time and hence learning requires large resources for computation although the output generated of such networks is much simpler to calculate and requires less overhead. This type of networks is suitable for a fast response to changing radio environment, a basic requirement for an SU. For instance whenever there is PU activity detected over the channel SU must stop its transmission to avoid collision. Studies show that neural networks can be used in spectrum sensing and adapting radio parameters in CR.

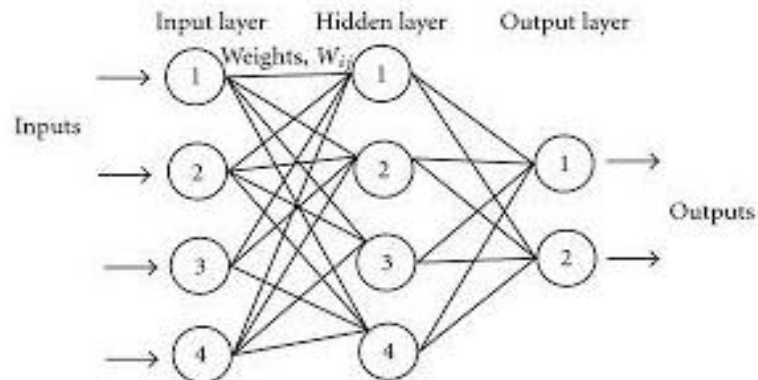


Fig. 1 Artificial Neural Network

B. Fuzzy logic

Fuzzy logic is an attractive technique particularly in cases where target problems are difficult to model with traditional mathematical models, but are easier to understand by human at the same time. With the characteristic of future cognitive radio in mind, the capability of fuzzy logic offer good potential to be applied. Instead of using complicated mathematical formulations, fuzzy logic uses human-understandable fuzzy sets and inference rules (e.g. IF, THEN, ELSE, AND, OR, NOT) to obtain the solution that satisfies the desired system objectives. The main advantage of fuzzy logic is its low complexity. Therefore, fuzzy logic is suitable for real-time cognitive radio applications in which the response time is critical to system performance. A fuzzy logic control system can be used to obtain the solution to a problem given imprecise, noisy, and incomplete input information. In general, there are three major components in a fuzzy logic control system: fuzzifier, fuzzy logic processor, and defuzzifier (Fig 3). While the fuzzifier is used to map the crisp inputs into fuzzy sets, the fuzzy logic processor implements an inference engine to obtain the solution based on predefined sets of rules. Then, the defuzzifier is applied to transform the solution to the crisp output. Fuzzy logic is often used in decision making to select the best suited SU for spectrum access at a given time. This technique when combined with neural networks is used in CR networks, multihop routing or for detecting unauthorized users.

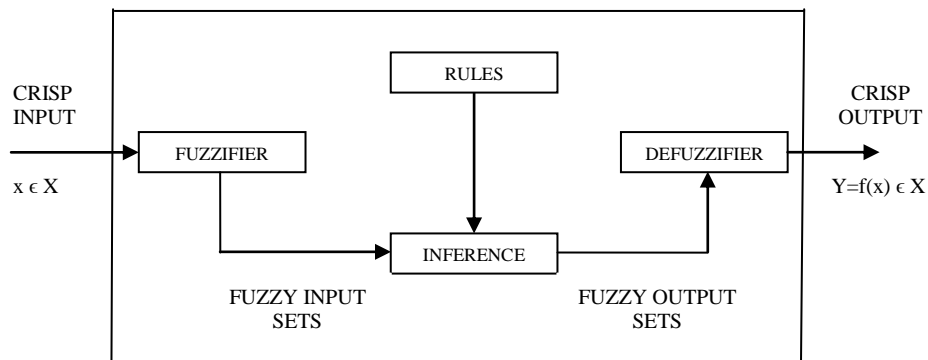


Fig. 3 Fuzzy Logic Control System

C. Genetic Algorithms

Genetic algorithm is an evolutionary computational technique which works on Darwin's theory of evolution. It defines the radio parameters in the form of chromosomes and genes. Genes of the chromosome represent the adjustable parameters in a given radio. By genetically manipulating the chromosomes using Darwin's theory methods like crossover, mutation, inheritance, selection, and fitness, the genetic algorithms (GA) can find a set of parameters that optimize the radio for the user's current needs.

The main advantage of using genetic algorithm over other techniques is the parallelism which can really speed up the simulation result.

The following are some other significant advantages of the GA:-

- Continuous or discrete variables can be optimized with the GA.
- It doesn't require derivative information.
- It can deal with a large number of variables.
- It suits well with parallel computers.
- It does not only provide a single solution but a list of optimum solutions.

- It may encode the variables so that the optimization is done with the encoded variables.
- It works with numerically generated data, experimental data, or analytical functions.

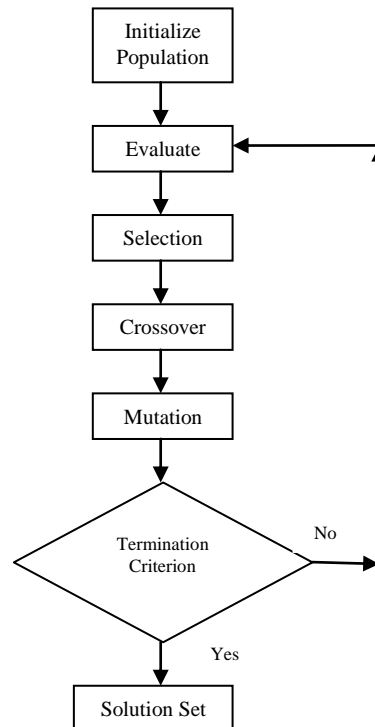


Fig. 4 Genetic Algorithm Evolution Flow Chart

IV. OTHER DSA TECHNIQUES AND THEIR USE IN COGNITIVE RADIO

A. Spectrum Access Using Auction Theory

Auction theory can also be applied to access the spectrum dynamically. In cognitive radio networks the auction is done for free channel or channel space by the primary users who behave as sellers to either sell or rent their unused spectrum. The bidders are the SUs looking for free spectrum for transmission. The whole process of spectrum auction is governed by regulatory authority. Since the unused spectrum is rented by PUs this approach appears to be a very promising one in today's scenario. The payments done by SUs as charges to use the spectrum can be in terms of money or services. For instance a PU is not charging money from the bidding SUs using the spectrum but the price to pay is waiting time. Another approach can be a choice given to SU to either pay for a good QoS or use free unused spectrum with an open risk of interference or unreliable connection. Another way to use auctions is proposed in [22], where the authors have shown that in some scenarios the spectrum is used efficiently when multiple SU gain access to a single channel, this is what distinguish their method with the traditional auctions where only one user can win.

In these solutions, user behaviours can be false, so the centralized manager can't maximize the utility function of the overall network.

B. Game Theoretical Methods of Spectrum Access

Game theory can be defined as the study of mathematical models of conflict and cooperation between intelligent and rational decision makers. Modern game theory gained prominence after the work of Von Neumann in 1928 and later. Game theory became an important field during World War II and the Cold War that follows, culminating with the famous Nash Equilibrium. The objective of the games as a decision tool is to maximize some utility function for all decision makers under uncertainty since this technique does not explicitly accommodate multiple criteria for selection of alternatives.

Depending on the scenario under consideration, the dynamic spectrum access (DSA) is modelled by different types of games following both a non-cooperative and a cooperative approach. In the first case, each radio device aims to selfishly maximize an individual performance metric (e.g., individual data rate), while in the second case such maximization concerns global network parameters (e.g., network sum-rate). In each case, we analyze network equilibrium, which allow network designers, operators, or manufactures to predict the behaviour and performance of cognitive networks and/or terminals.

- Cooperative (coalition) Games: all players are concerned about all the overall benefits and they are not very worried about their own personal benefit. Some few recent works in CR consider the use of cooperative game theory to reduce transmission power of SUs in order to avoid generating interference to PU transmissions.
- Competitive Games: every user is mainly concerned about his personal payoff and therefore all its decisions are made competitively and moreover selfishly. In the existing literature, we found that game theoretical concepts have been extensively used for spectrum allocations in CR networks, where the PU and SU participating in a game, behave rationally to choose strategies that maximize their individual payoffs.

The most known property of game-theoretical approaches is called Nash Equilibrium (NE). In NE, each player is assumed to know the equilibrium strategies of the other players, and no player has anything to gain by changing his or her own strategy. However it is important to mention that even cooperative and competitive games focus on solving the NE and analyzing its properties, they don't provide any details about the players' interaction to reach this equilibrium.

Some of the existing works using game theory for the DSA are mentioned here. For example, in [20], the authors assume that PUs are aware of their environment and of the SUs existence. PUs adopt the roles of leaders by selecting a subset of SUs and granting them spectrum access. Whereas in [7], a framework using game theory where PUs don't have the knowledge about their neighbourhood, so they are unaware of the presence of SUs, and SUs are only allowed to access the spectrum opportunistically (users are modelled as rational, selfish and think only to maximize their profits).

An interesting game is proposed in [9] where the PU first determines the spectrum price based on the quality of spectrum and then, the SU decides how much spectrum to buy by observing the price.

In the bargaining games, the individual players have the opportunity to cooperate in order to reach a mutual agreement. At the same time, these players can have conflicts of interest and no agreement can be made with any individual player without its approval. For CR networks, the bargaining games are applied to allocate spectrum bands in centralized and decentralized network settings; the author in [3] proposes to design secured autonomous networks where terminals and base stations interact and self-adapt in an intelligent manner without needing a central controller or a regulator. The network design is done at the equilibrium state.

C. Markov Chain Models for Spectrum Access

Fuzzy Game theoretical approaches don't model the interaction between SUs and PUs for spectrum access. This modelling can efficiently be performed using Markov chains.

Few research have been done in this field, for example, In [2], a Markov model is presented, where each SU randomly selects its own channel rather than exchanging control messages with the neighbouring SUs. A very interesting approach using Markov models is developed by the authors in [1] to analyze the different policies proposed for spectrum sharing. Markov models can be used in the behaviour prediction of open spectrum access in licensed and in unlicensed bands.

The Hidden Markov Model (HMM) is a mathematically tractable statistical model to describe and analyze the dynamic behaviour of a complex random phenomenon. The HMM generates sequences of observation symbols by making transitions from state to state. However, the states are hidden, and only the output is observable.

HMM are used for example by the signal classifier using pattern recognition and for spectrum sensing duration scheduling or to predict the interference temperature of the channel and for the spectrum occupancy prediction.

Some works used the Continuous Time Markov Chains (CTMC) model because it achieves good statistical tradeoffs between fairness and efficiency. Presented works in [1] [23] used CTMC to capture the interaction between primary and SUs. Both queuing and without queuing models are analyzed and the throughput degradation due to SUs interference is compensated.

The authors in [18] modified the Markov model proposed in [15] and included spectrum handoff capability. In this system, PUs are prioritized as well as the secondary users are having spectrum handoff. SUs capacity in the presence of unrestricted PUs is modelled using three dimensional Markov chains. It is shown through the analysis done in [18] that the non-random channel assignment gives a better result compared to the random channel assignment.

In [14], a HMM-based channel prediction and selection algorithm is constructed based on a frequency-hopping algorithm to solve the interference problem. The proposed achieves the goal of reducing the interference time and increasing the throughput.

D. Multi Agent System (MAS)

The association of MAS and the CR can provide a great future for the optimal management of frequencies (in comparison with the rigid control techniques proposed by telecommunications operators). In the case of use of unlicensed bands, CR terminals have to coordinate and cooperate to best use the spectrum without causing interference.

In [19], the authors propose architecture based on agents where each CR terminal is equipped with an intelligent agent, there are modules to collect information about the radio environment and of course the information collected will be stored in a shared knowledge base that will be accessed by all agents. The proposed approach is based on cooperative MAS (the agents have common interests). They work by sharing their knowledge to increase their collective and individual gain. (Fig. 5)

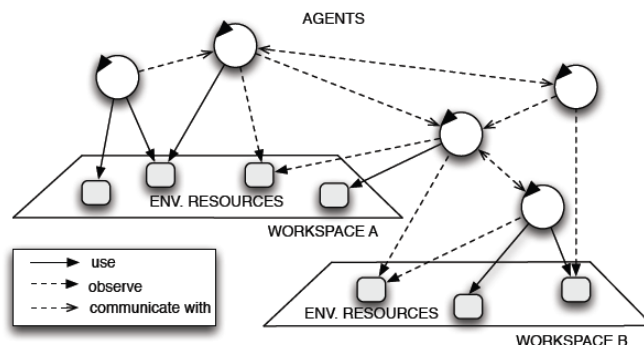


Fig. 5 Multi Agent System

Agents can be deployed on PUs and SUs terminals and then these agents cooperate with each other. By cooperative MAS, we mean that PU agents exchanged t-uples of messages in order to improve themselves and the neighbourhood of SU agents. Here, the SUs should make their decision based on the amount of available spectrum when they find a suitable offer (without waiting for response from all PUs). In other words, the SU agent should send messages to the appropriate neighbour PU agent and of course the concerned PU must respond to these agents to an agreement on sharing the spectrum. After the end of the spectrum use, the SU must pay the PU.

A comparison is made between an agent and a CR and shown in Table 1. Basically, both of them are aware of their surrounding environments through interactions, sensing, monitoring and they have autonomy and control over their actions and states. They can solve the assigned tasks independently based on their individual capabilities or can work with their neighbours by having frequent information exchanges.

TABLE I COMPARISON BETWEEN AN AGENT AND A COGNITIVE RADIO

S.No.	Agent	Cognitive Radio
1	Environment awareness via past	Sensing empty spectrum portions and PU
2	Acting through actuators	Deciding the bands/channels to be selected
3	Interaction via cooperation	Interaction via beaconing
4	Autonomy	Autonomy
5	Working together to achieve shared goals	Working together for efficient spectrum sharing
6	Contains a knowledge base with local and neighbouring agents'	Maintains certain models of neighbouring PU's spectrum usage

To make the CR systems practical, it requires that several CR networks coexist with each other. However, this can cause interference. The remedy to this problem is, the SU can cooperate to sense the spectrum as well as to share it without causing interference to the PU. For this, they propose schemes to protect the PU from interferences by controlling the transmission power of the cognitive terminal.

In [10] [21], the authors propose cooperation between PUs and SUs and between SUs only. Agents are deployed on the user's terminals to cooperate and result in contracts governing spectrum allocation. SU agents coexist and cooperate with the PU agents in an Ad hoc CR environment using messages and mechanisms for decision making. Since the internal behaviours of agents are cooperative and selfless, it enables them to maximize the utility function of other agents without adding costs result in terms of exchanged messages.

However, the allocation of resources is an important issue in CR systems. It can be done by making the negotiation among SUs [13]. In [13] the authors propose a model based on agents for the spectrum trading in a CR network. But instead of negotiating spectrum directly with the PU and SU, a broker agent is included. This means that the equipment of PU or SU does not require much intelligence as it does not need to perform the spectrum sensing. The objective of this trading is to maximize the benefits and profits of agents to satisfy the SU. The authors proposed two situations, the first uses a single agent who will exploit and dominate the network, in either case there will be several competing agents.

The authors in [8] study the use of CR in wireless LANs and the possibility of introducing the technology of agents, in other words they try to solve the problem of radio resources allocation by combining resources management WLAN in a decentralized environment, this by using MAS. For this, they propose an approach based on MAS for sharing information and decisions distribution among multiple WLANs in a distributed manner.

Interference from the acquisition of the channels in a cellular system during handoffs can be reduced by using a CR to manage the handoff. Indeed, the mobility of the device imposes a different behaviour when changing zones. The terminal must ensure service continuity of applications and the effective spectrum management. The authors propose an approach that uses negotiation, learning, reasoning and prediction to know the needs of new services in modern wireless networks. They propose an algorithm to be executed by the mobile terminal during the cognitive phase of handoff.

The MAS contains several intelligent agents interact with each other. Each agent can sense and learn. The agent can select behaviours based on local information and attempt to maximize overall system performance. In [16], they described a new approach based on multi-agent reinforcement learning which is used in CR networks with ad hoc decentralized control. In other words, they set up several CR scenarios and affect each case a reward or penalty. The results of this approach have shown that with this method, the network can converge to a fair spectrum sharing and of course it reduces interferences with PUs.

A very interesting approach is proposed in [17] 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 to be applied in most application schemas.

In the solution proposed in [5], 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 modelled 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 can be considered for multi-user and multi-channel. To avoid collision incurred by non-coordination, each SU learns to select channels based in 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.

The authors in [6] are interested to the use of IEEE 802.22, and proposed an algorithm called "Decentralized Q-learning" based on the multi-agent learning theory to deal with the interference problem caused to PUs. They modelled the secondary network using MAS where the different agents are base stations of the IEEE 802.22 WRAN. They proved that the proposed MAS are able to automatically learn the optimal policy to maintain protection for PU against interference.

The authors in [12] used the MAS to design a new cognition cycle with complex interaction between PUs, SUs and wireless environments and they used the hidden Markov chains to model the interactions between users and the environment. The results of this approach have shown that the algorithm can guarantee fairness among users.

What could make the use of MAS in the CR interesting and more concrete is the existence of a simulation framework to test the proposed works and approaches. This platform allows studying the emerging aspect and the behaviours of heterogeneous CR networks.

A comparison of DSA techniques in terms of Advantages and limitations:-

TABLE 2 ADVANTAGES AND DISADVANTAGES OF DYNAMIC SPECTRUM ACCESS TECHNIQUES IN CR.

Method	Advantages	Disadvantages
Neural networks	<ul style="list-style-type: none"> - Need few memory - Quick - Easily scalable - Excellent for classification 	<ul style="list-style-type: none"> - Complex - Training required
Fuzzy logic	<ul style="list-style-type: none"> - Application to systems that are difficult to model - Simple implementation and Interpretation - Good for device control with unclear quality boundaries 	<ul style="list-style-type: none"> - Stability, accuracy and optimality of the system are not guaranteed - Performance is measured a posterior - Settings are made by trials/errors
Genetic algorithms	<ul style="list-style-type: none"> - Parallel processing - Simple calculations because they use just the values of the function to optimize 	<ul style="list-style-type: none"> - Slow - Choice of parameters is difficult
Auctions theory	<ul style="list-style-type: none"> - Simplicity - Equitable and transparent 	<ul style="list-style-type: none"> - Licence fees high
Game theory	<ul style="list-style-type: none"> - Easy reading of the outcomes - High cost strategies - Models agent's behaviour in situations of choice 	<ul style="list-style-type: none"> - High cost - Does not make rational choices
Markov models	<ul style="list-style-type: none"> - Modelling complicated processes. - Prediction from experience - Well for classification 	<ul style="list-style-type: none"> - Don't take into account the hidden states - Cannot deal with a large number of states
Multi Agent Systems	<ul style="list-style-type: none"> - Modularity - Quick - Reliability and flexibility 	<ul style="list-style-type: none"> - High cost - Lack of methods

V. CONCLUSION

For an efficient license allocation, spectrum utilization must be efficient too. It is within this context that we have provided the advantages and limitations of each method of spectrum access we have presented previously. To solve the

problem of spectrum congestion, we should use one of dynamic spectrum access techniques rather than using nothing and satisfy the first received request.

Auctions theory known by its simplicity facilitates rare resources allocation. The auctions-based systems rely on simple, transparent and well defined rules which are applied to all users in the same way.

Currently, there are several auction protocols, those done in a single round such as First-price sealed-bid auctions and those done in multiple rounds such as English auctions. It is preferable to use a single round auction especially if we seek to satisfy applications that require an immediate response, because the use of multiple rounds auctions can make us lose a few seconds since the procedure is slightly longer and slower.

Game theory can predict and determine the most relevant auctions procedure. It has been widely used for spectrum sharing and remains an interesting field of research for spectrum management in the context of CR. Game theory is the most appropriate technique to obtain the equilibrium solution to the problem of the spectrum in such a scenario.

A Markov chain is a sequence of random variables which allow modeling the dynamic evolution of a random system. The fundamental property of Markov chains is that its future evolution depends on the past only through its current value. Otherwise, in the case of CR, this method allows to model the interaction between users (PU and SU). MAS are scalable and adaptive which allow adding or removing agents from the system without causing problems. In the wireless networks, CR nodes can be modeled as agents where each time they switch to another area (handoff) the MAS changes. MAS are known by their speed because the agents can work in parallel for solving problems.

Different approaches using the MAS in the CR are studied, those offering cooperation between SUs only, others offer a cooperation between primary and SUs and those proposing to include a broker agent to negotiate the spectrum , knowing that the most works studied are using reinforcement learning.

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