Optimal Spectrum Utilization in Cognitive Network

Using Combined Spectrum Sharing Approach: Overlay, Underlay and Trading

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Abstract

Cognitive radio technology enables unlicensed users (secondary users, SUs) to access the unused licensed spectrum which is allocated to primary users (PUs). In the literature, there are three traditional spectrum sharing paradigms that enable SUs to access the licensed spectrum. These access techniques include underlay, overlay and spectrum trading, and have their own drawbacks. To combat these drawbacks, we propose a new approach for each of them and merge them into one combined complete distributed system for cognitive network that contains all cognitive network functions. Our overlay scheme provides quick access to the unused spectrum because of the advantages of a distributed system where there is no contention for a central resource. We propose a new cooperative sensing protocol to enable the overlay scheme to reduce the likelihood of interfering with PUs and to avoid service interruption. We propose using our underlay scheme when the traffic loads at PUs are high that enables SUs to transmit simultaneously with PUs. The scheme uses reinforcement learning (RL) to manage the power of SUs and to protect PUs against harmful interference. Our trading scheme allows PUs to trade the unused spectrum for the SUs that require better quality of service. RL is used to control the size and the price for the rented spectrum. The new combined scheme increases the size of spectrum in the cognitive network because of using different access techniques based on their availabilities and requirements. Simulation results show the ability of the new scheme to serve extra traffic in the cognitive network.

Index Terms—**Cognitive network, Spectrum Management, Spectrum Overlay, Spectrum Underlay, Spectrum Secondary Market, Spectrum Trading.**

I. INTRODUCTION

Nowadays, we have unexpected explosion in the demand for wireless radio resources due to the dramatic increase in the number of the emerging web-based services. A large number of services are presented using wireless Internet. These services require broadband access and service continuity protection. Users want to access the internet anytime-anywhere. As a result, the frequency spectrum becomes congested while supporting these web-based applications. Furthermore, guaranteeing the QoS for multimedia applications requires huge bandwidth resources (Akyildiz, Lee, Vuran, and Mohanty, 2006; Hossain, Niyato, and Han, 2009; Wu, Yang, and Lin, 2011) . Unfortunately, dedicated bandwidth becomes increasingly scarce and expensive.

In most countries, spectrum is allocated to the licensed user exclusively. However, if the licensed users (primary user, PU) do not use this spectrum, it will be considered as used while it is actually wasted. For example, some users, such as the military radio system, require spectrum infrequently. Inefficient spectrum usage necessitates rethinking of the new spectrum sharing paradigm that exploits the wasted spectrum. As a result, efficient spectrum utilization is an essential requirement to support emergent services. Toward efficient utilization, Federal Commission Communication (FCC) allows unlicensed users (secondary users, SUs) to utilize the unused spectrum provided that they respect PUs' rights.

Dynamic spectrum access (DSA) enables the implementation of cognitive radio (CR). Cognitive technology allows nodes to adapt to the radio environment by tuning their communication parameters. These parameters include operating frequency, power transmission and modulation scheme. In the cognitive network, secondary users (SUs) can access the free spectrum using overlay and underlay approaches, and by renting the free spectrum. In our system, we assume SUs use the unused licensed spectrum to build a secondary network. In the overlay approach, SUs detect the existence of PUs and specify the unused spectrum accurately. Developing an efficient scheme for utilizing spectrum using overlay approach faces many challenges. These challenges include: detecting PUs signals, exchanging spectrum data, coordinating among SUs, accessing unused spectrum, assigning the unused spectrum to the SUs, and evaluating the available spectrum. Using underlay approach, SUs are constrained to operate below the noise threshold of PUs. Protecting the PUs against interference and supporting QoS for SUs are the main challenges for this approach. In this approach, there is no need to detect PUs signals or to specify the unused spectrum. SUs may also buy the right to access free spectrum temporarily from PUs. Specifying the size and the price of the offered spectrum for renting is the main challenge for PUs in the trading approach. PUs are required to maintain their QoS while simultaneously satisfying SUs.

In addition to the challenges of developing spectrum access techniques in CR, there are other difficulties that face developing the secondary network such as the deployment of new infrastructure for the secondary network, managing the network, and hardware support. Wireless mesh networks (WMNs) are posed to be the best candidate for the infrastructure for the secondary network due to their advantages. WMNs help to solve a spectrum scarcity problem by extending Internet access and other networking services (Knieps, 2011). For the users, WMNs provide higher bandwidth, low cost and low power consumption. In this work we define and propose using mesh network for the secondary network.

The rest of the paper is organized as follows. A brief background on the related work on CR and challenges are presented in the next section. We then introduce our system requirements. Next, the proposed architecture and signaling protocols are presented. After that we describe the main functions in the physical and data link layer in our cognitive network. Next, we present some of the tests performed and show the behavior of the implemented system under different conditions. Finally, our last section concludes the paper and presents the future work.

II. BACKGROUND

A. Related Work and Technical Challenges

In this section, we introduce the literature review for the three spectrum access schemes. Several studies use overlay to enable SUs access the unused spectrum. Users cooperate in (Cao, and Zheng, 2008) to access free spectrum using a set of defined rules in the distributed spectrum management architecture proposed. Overlay approach is used in (Chowdhury and Akyildiz, 2008; Sun, Zhang, and Letaief, 2007) to enable users to access the unused spectrum. A cluster-based architecture is proposed for the secondary network. SUs sense the spectrum and send the results to their cluster heads. The cluster heads forward the results into a common receiver where the results are processed. In order to provide quality of service (QoS) for SUs in the secondary network, overlay scheme is used to assign unused spectrum for SUs in (Niyato, Hossain, and Wang, 2011).

Many studies propose using underlay approach to build the secondary network. A new framework of spectrum allocation is suggested in (Wang, Shin, Wang, 2010) with power control to utilize unused spectrum in cognitive radio networks (CRNs). The framework takes into account both interference temperature constraints and spectrum dynamics. The authors in (Xing, Mathur, Haleem, Chandramouli, and Subbalakshmi, 2007) consider spectrum sharing among SUs users with a constraint on the total interference temperature at a particular measurement point and a QoS constraint for each secondary link. Haidar et al (Haidar, Msakni, and Dziong, 2009) present a new scheme for managing SU's power in the WMN. SUs which are in the vicinity of a PU are allowed to transmit if they do not cause harmful interference for the PU.

Recently, many studies explore the issues of the economic aspect of dynamic spectrum sharing, which is also referred to as spectrum trading. Gandhi et al (Gandhi, Buragohain, and Cao, 2007) suggest a new framework for spectrum trading. An auction mechanism is used to manage spectrum access in this model.

However, the heterogeneity in consumer (buyer) type is not considered. Niyato et al study the spectrum trading (Niyato, Hossain, and Han, 2009) where multiple PUs compete to sell spectrum opportunities to multiple SUs. Game theory is used to model the evolution and the dynamic behavior of SUs. A non-cooperative game theory is also used to model the competition among the PUs for trading. An auction theory is used to trade the spectrum to SUs in (Yu, Gao, Wang, and Hossain, 2010). A non-cooperative game theory is used for uplink power control in cognitive radio networks. Game theory was also used in (Li, Wang, and Guizani, 2010) where SUs select the provider according to their preferences. Multiple SUs buy spectrums from multiple owners in (Li, Xu, Liu, and Wang, 2010). A game theoretic framework is used also to model the dynamic spectrum sharing in multi-owners and multi-users cognitive radio networks.

B. Contribution

The novelty of our work is presenting a new architecture for cognitive mesh network. The architecture combines all spectrum sharing techniques. Our architecture is flexible to use any spectrum sharing technique. One advantage of this architecture is that it allows SUs to access unused spectrum for free if there is a chance. However, in the case when there is no opportunity for free usage, SUs purchase the spectrum. For hard QoS applications SUs may buy the rights to access the spectrum from PUs. In order to reduce communication overhead, we divide the network into clusters where each cluster head manages spectrum for its members. The architecture is robust to any cluster head failure. For example, if a cluster head fails, cluster members can join another cluster. We propose an agile cooperative spectrum sensing scheme to guarantee the accuracy of detection results. In underlay access scheme, our system takes into account protecting PUs against the activities of the SUs. Moreover, the system tries to support the QoS for SUs as much as possible. In the literature, most of the underlay schemes are proposed for traditional wireless networks and they do not consider the requirements of a cognitive network such as the interference constraint and the QoS at the secondary network. For cognitive network, beside spectrum sharing, both QoS and interference constraint need to be met. These design constraints are taken into account in our architecture. Concerning the spectrum trading part of our architecture, our trading scheme helps PUs to adapt to high traffic load by changing the offered size and price of the spectrum dynamically to maintain QoS for PUs. Our trading scheme attempts to satisfy the QoS for all classes of SUs. In brief, this paper presents a complete system cognitive network where all spectrum access techniques are combined to serve the maximum number of SUs.

III. SYSTEM REQUIRMENTS

The basic requirements of our system are as follows:

1) Protecting PUs: spectrum is a valuable resource and PUs have invested a lot to acquire the exclusive right of the spectrum. Therefore, PUs will not allow sharing of their spectrum without getting some

financial benefit. The charge free usage of the PUs' spectrum is allowed as long as SUs do not interfere with PUs.

2) Spectrum availability: SUs use PU's spectrum to communicate.

3) PU's rights and responsibilities: we define a PU as a spectrum owner that has the right to access a given frequency band at any time exclusively. PUs do not need to communicate with SUs except if they decide to rent part of their spectrum. PUs are responsible for maintaining their QoS.

4) SU's responsibilities and rights: the rights and the responsibilities of SUs differ with respect to the access techniques they use to access the spectrum as follows:

- Overlay approach: in this approach, SUs can only access the unused portions of the spectrum and tune the communication parameters according to the state of the radio environment. SUs are responsible for detecting the unused portion of spectrum and they should vacate the spectrum as soon as the PU resumes its activities. Managing access to the free spectrum is the responsibility of the SUs. After specifying spectrum holes, SUs should follow a certain allocation scheme for utilizing the unused spectrum. In this approach, it is clear that the essential requirement for the SUs is monitoring the PUs' signals and specifying the spectrum status.
- Underlay approach: SUs can coexist with PUs in this approach. SUs can start transmission if they do not harm any PU. The PUs do not need to know about the presence of SUs. SUs should periodically check the PUs interference threshold and vacate the spectrum as soon as their signals interfere with PU signal. SUs are responsible for managing their power in the secondary network. They should monitor radio environment and adapt their transmission according to the changes in the wireless environment.
- Spectrum trading: SUs should inform the spectrum owner about the spectrum size and the duration of spectrum usage and the required QoS. After paying the PUs, SUs has the right to access the spectrum exclusively. SUs require information about their rights, the size and the price of the offered spectrum.

IV. SYSTEM ARCHITECTURE

In our system model, we assume two types of users: primary and secondary users. A secondary network has several mesh routers (MRs) and mesh clients (MCs). MRs have fixed locations whereas MCs are moving and changing their places arbitrarily. MRs and MCs are referred to as SUs in this article. PUs' spectrum is divided into non-overlapping channels which is the basic unit of allocation. We present the architecture of the secondary network and the signaling protocols in this section.

A. Secondary Network Architecture and assumptions

SUs form clusters in the secondary network. Each cluster can be imagined as a WLAN, where MRs play the role of access point and the MCs act as nodes served by MRs. MRs use the PUs' spectrum to serve MCs.

A.1 Forming Clusters in the Secondary Network

MCs need information about the MRs to select their cluster head. An MC executes a distributed algorithm to join a cluster. At set up time, each MR broadcasts a beacon that contains its ID. Upon receiving beacons from different MRs, a MC measures the signal strength of each beacon to choose its coordinator. The MC stores the ID and the signal strength for each MR in a table. We assume each node has a unique ID. After a certain period of time, each MC sends association request to the MR with the strongest signal. When an MR receives an association request, it registers the ID of MC and broadcasts the final list to all MCs in the cluster. Cluster-head (MR) manages inter-cluster communication and the available spectrum. The network architecture consists of several clusters as seen in Fig. 1.

In our system, cluster coordinators periodically exchange spectrum data (based on one-hop transmission) to keep themselves updated about the status of the entire spectrum. Cluster coordinator may fail for many reasons. If any user observes that its coordinator does not send any data during a time *t*, it sends a message to all cluster members about the coordinator failure. After receiving coordinator fail message, each SU looks up its table and subscribe to a cluster that has a coordinator with the strongest signal. In the case a cluster member does not send or receive any data during time *t*, a cluster head removes this user from its table and updates cluster members.

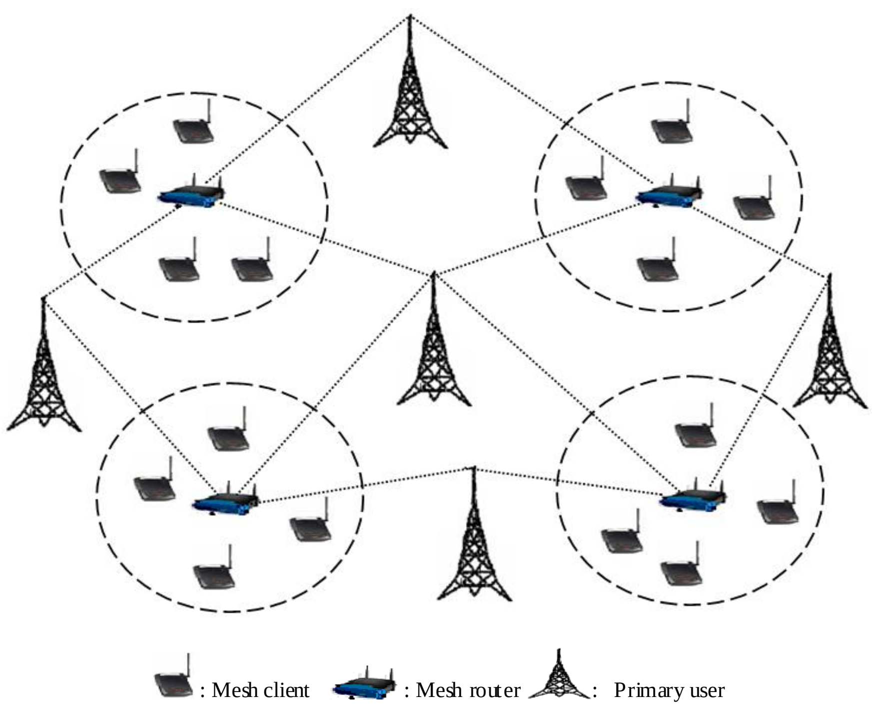

Fig 1.Network architecture

The functionality of MRs differ according to the access technique. In overlay approach, MRs manage cognitive cycle which includes spectrum sensing, processing sensing results and allocating spectrum to

MCs. MRs allow MCs to transmit and specify the strength of transmission in the underlay approach. Managing the power at the secondary network is the main function of MRs in this access scheme. In spectrum trading approach, MRs receive SUs requests' for spectrum and buy the spectrum to serve SUs.

A.2 Signaling Protocol

Signaling protocol is used in underlay and overlay approaches only. In spectrum trading, SUs do not need to sense spectrum and exchange its data but PU disseminates spectrum information and the required prices.

In the secondary network, MRs need information about signal powers of the PUs at each channel. This information is necessary to specify the status of radio environment and to adapt to the changes in the radio environment. In our signaling protocol, two channels are used to exchange spectrum information between cluster head and MCs. The first channel is used to exchange the radio environment status between MRs and MCs, where the second one is used (emergency channel) for backup when the owner of the channel (PU) starts using it. According to our signaling protocol, a cluster coordinator assigns all free channels for users to communicate except two predefined control channels. Control channels are selected by the cluster head and they are changed according to the status of spectrum. If a PU starts using any control channel then SUs switch to the emergency channel and the cluster head selects another and notifies SUs.

The frame structure in our MAC protocol consists of three periods: spectrum sensing period, collecting results period and processing results period. In sensing period, a coordinator requests SUs to gather spectrum data through a "sensing frame" that is broadcast to all cluster members. The sensing frame specifies the following:

- Duration of the spectrum sensing period.
- Duration of collecting sensing results.
- Control channel to send the results.

SUs send back ACK frame to the coordinator to confirm receiving a request packet. In collection results frame, each SU reports its results to the coordinator in the allocated slot. Next, the coordinator fuses the detection results and exchanges the results with other MRs. Finally, MR combines its results with other MR's results.

B. Modeling Spectrum Sharing in the Secondary Network

In our work, the network is assumed to consist of W PUs, N MRs and B MCs. Each PU has a set of K channels that are assigned to it in advance. For MR j we define the following components:

- Spectrum allocation vector SP_j :

$SP_j = \left\{ SP_j(m) \mid SP_j(m) \in \{0,1\} \right\}$ is a vector of spectrum status. If $SP_j(m) = 1$ then channel m is not currently available.

- Interference vector I_j:

$I_j = \left\{ I_j(h) \mid I_j(h) \in \{0,1\} \right\}$ is a vector that represents the interference among MR j and other MRs; if $I_j(h) = 1$ then MR j and MR h cannot allocate the same channel simultaneously to their clients.

- Channel throughput vector T_j :

$T_j = \left\{ t_j(m) \mid t_j(m) \in \{0, \infty\} \right\}$ describes the throughput of MR j channels; $t_j(m)$ is the throughput that a MC gets when it uses a channel m.

- Interference threshold vector F:

$F = \left\{ f_y \mid f_y \in \{0, \infty\} \right\}$ describes the interference threshold of PUs; f_y is the interference that y^{th} PU can tolerate.

V. REINFORCMENT LEARNING FOR RESOURCE ADAPTATION

We use reinforcement learning to extract a control policy to help MRs adapt to changes in the wireless environment. Reinforcement learning (RL) is a sub-area of machine learning concerned with how a system administrator takes action in different circumstances in a work environment to minimize long-term cost (Sutton, and Barto, 1998; Feng, Tan, Li, Gulliver, and Liang , 2011).

Let $X = \{X_0, X_1, X_2, X_3 \dots X_t\}$ be the set of possible states of an environment, and $A = \{a_0, a_1, a_2 \dots a_t\}$ be a set of actions a learning agent may take. In RL, a policy is any function: $\pi: X \to A$ that maps states to actions. Each policy gives a sequence of states when executed as follows: $X_0 \to X_1 \to X_2 \dots X_t$ where X_t represents the system state at time t and a_t is the action at time t. Given the state X_t , the learning agent interacts with the environment by choosing an action a_t. Then, the system transits to the new state X_{t+1} , according to the transition probability $P_{X,X_{t+1}}$, and the process is repeated. The goal of the agent is to find an optimal policy $\pi^*(X)$ which minimizes the total cost over time.

VI. COGNITIVE MESH NETWORK DESIGN – PHYSICAL LAYER

Our system design only includes two OSI layers: the physical and the link layer. Other layers can use standard protocols. All physical layer functions are described in this section.

A. Spectrum Sensing

In underlay and overlay approaches, spectrum status should be specified accurately using spectrum sensing which is a binary decision between the following two hypotheses:

H_1: Spectrum is busy.

H_0: Spectrum is idle.

In the sensing period, SUs measure the signal strengths at all channels. If a SU decides the channel is busy then 1 will be stored at the allocation vector for the corresponding channel, otherwise 0 will be assigned. The SU decides the presence of a PU at a certain frequency if and only if the received signal strength is greater than a threshold γ. The received signal power is computed as follows:

$$S_m^{(i,y)}(d) = S_t - PL(d) \quad (1)$$

where $S_m^{(i,y)}(d)$ is the signal power measured on channel m by i^{th} MC at the y^{th} PU, S_t is the transmitted signal power, d is the distance between y^{th} PU and i^{th} MC, $PL(d)$ is the path loss at distance d and is computed as follows (Rappaport, 2002):

$$PL(d) = \overline{PL}(d_0) - 10n log\left(\frac{d}{d_0}\right) + x_\sigma \quad (2)$$

where n is the path loss exponent, d_0 is the close-in reference distance, $\overline{PL}(d_0)$ is the average path loss at distance d_0, x_σ is a zero-mean Gaussian distributed random variable with standard deviation σ. Standard deviation σ describes the path loss model for an arbitrary location. Linear regression is used to estimate the value of σ. A SU fails to detect PUs' signal if the received power is less than γ. We assume the received power $S_m^{(i,y)}(d)$ has a Gaussian distribution. For each SU, the probability of detecting a PU signal is P_d and the missing probability is P_m. The detection probability is computed as follows:

$$P_d = P(S_m^{(i,y)}(d) \geq \gamma | H_1). \quad (3)$$

Using Bayes theorem:

$$P_d = \frac{P\left(S_m^{(i,y)}(d) \geq \gamma\right) P(H_1)}{P(H_1)} = P\left(S_m^{(i,y)}(d) \geq \gamma\right), \quad (4)$$

$$P\left(S_m^{(i,y)}(d) \geq \gamma\right) = \int_\gamma^\infty \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{(S-\mu)^2}{2\sigma^2}} ds. \quad (5)$$

The miss probability in our scheme is computed as:

$$P_m = P\left(S_m^{(i,y)}(d) < \gamma \middle| H_1\right) = \frac{P\left(S_m^{(i,y)}(d) < \gamma\right) P(H_1)}{P(H_1)} = P\left(S_m^{(i,y)}(d) < \gamma\right), \quad (6)$$

$$P\left(S_m^{(i,y)}(d) < \gamma\right) = \int_{-\infty}^\gamma \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{(S-\mu)^2}{2\sigma^2}} ds. \quad (7)$$

After sensing the spectrum, each SU prepares the allocation vector that contains the new status of spectrum and uploads it to its coordinator. After collecting allocation vectors, a cluster head fuses all results to obtain the final status of the spectrum.

B. Spectrum Evaluation

In radio environment, the quality of the available spectrum holes fluctuates over time. It is important for the spectrum allocation scheme to evaluate the quality of the free spectrum first then allocate the appropriate spectrum band to SUs. Recent studies on spectrum allocation in cognitive network use capacity and interference to evaluate the quality of the free spectrum. However, other factors should be taken into account to better serve SUs. These factors include PU activities, channels error bit rates, delay due to mobility. In our spectrum evaluation model, we define the following component:

- $\mathcal{P}_m^y$ is the probability of channel m, which belongs to the y^{th} PU, to be idle. This probability can be estimated from a database which contains the idle times of channel m.
- $L(v,m)$ is the adaptation time that a MC needs to start using channel m when it releases channel v. This time is normalized as follows:

$$\acute{L}(v,m) = \frac{L(v,m)}{\max_{L(x,y)\in ST}\{L(x,y)\}} \tag{8}$$

where ST is the list of switching times between channels in the network. $\acute{L}(v,m)$ and its weight are set to 1 if the MC does not change its channel.

- C_m is the capacity of channel m and is computed using Shanon's formula. The normalized capacity of channel m is computed as follows:

$$\acute{C}_m = \frac{C_m}{\max_{C_i\in CH}\{C_i\}} \tag{9}$$

where CH is the list of channels in the network of PUs.

- E_m is the error rate of channel m.
- Γ_m is the rank of channel m and is computed as follows:

$$\Gamma_m = \frac{\Omega\mathcal{P}_m^y\Psi\,\acute{C}_m}{\acute{\alpha}E_m\,\theta\,\acute{L}(v,m)} \tag{10}$$

where Ω is the weight of the idle time probability, Ψ is the weight of the channel capacity, $\acute{\alpha}$ is the weight of the channel error rate, and θ is the weight of the switching time.

C. Power Management

In the secondary network, MRs manage the power of MCs so that the long-term measure of the secondary network throughput is maximized and, at the same time, the PUs are protected against interference. We assume that SUs have a minimum signal power requirement and a maximum power constraint. Each PU y can tolerate a maximum predetermined interference level f_y. The main challenge facing MR is to satisfy the following conflicting objectives: satisfying the desired QoS for MCs and avoiding interference with PUs. MR should check the transmitted power constraint before permitting a MC i to transmit. This constraint can be expressed as follows:

$$S_L^{(i)} \leq S_t^{(i)} \leq \min_{\forall f_y\epsilon F} f_y \tag{11}$$

where $S_L^{(i)}$ is the minimum acceptable signal power that can support the requested data rate D_i. The aggregate interference level at the PU j should not exceed a predefined f_y as follows:

$$\sum_{i=1}^{B} S_m^{(i,y)}(d) \leq f_y \text{ , } \forall y\epsilon\{1,2,3 \dots W\}. \tag{12}$$

When the $MC's$ request is accepted, this MC can receive and transmit. However, when the request is queued, MC cannot transmit or receive traffic. As a result, the QoS for the MC is degraded and other MCs in the queue will experience latency. Nevertheless, this action protects the right of the PUs to use the spectrum exclusively.

VII. COGNITIVE MESH NETWORK DESIGN – LINK LAYER

The main functions at the data link layer are described in this section. These functions include spectrum data management using the three spectrum approaches, and spectrum allocation.

A. Spectrum Data Management using Overlay Approach

In the spectrum data processing phase, a coordinator solves spectrum data inconsistency and produces a final allocation vector that contains the current status of the spectrum. A coordinator receives allocation vectors from all users and combines them using logical OR operation. A decision function for our scheme can be described using the following two functions:

$$\varrho_{i,m}=\begin{cases}1, & S_m^{(i,y)}(d)>\gamma\\ 0, & otherwise\end{cases} \tag{13}$$

$$\xi_m=\begin{cases}1, & \exists S_m^{(i,y)}(d)\geq\gamma\\ 0, & \forall S_m^{(i,y)}(d)<\gamma\end{cases} \tag{14}$$

where $\varrho_{i,m}$ is the decision that is taken by MC i for a channel m. Each user i compares the signal strength at channel m to a pre-defined thresholdγ. ξ_m is a decision function that is executed by a coordinator to decide whether channel m is idle or not. A coordinator decides whether channel m is used by the PU based on whether SU detects the signal of a PU at this channel. Whenever at least one MC decides that channel m is busy, the presence of the PU is accepted by all SUs and none of the SUs will transmit on this channel.

The collected information about the spectrum at the coordinators can be used for managing the whole network. MRs exchange information periodically (based on one-hop transmission) to improve the system performance.

B. SpectrumManagment using Underlay Approach

In the secondary network, MCs generate different requests for data rates. If a MR cannot serve the request, it places it in a FIFO queue. MR uses an optimal admission policy to serve MCs. In order to use underlay approach, we manage the power of MCs using RL. For the basic formulation of RL, we describe the elements that facilitate the definition of the RL model. These elements are states, actions, transition probabilities and cost function.

B.1 State Space

For power management, MR adopts a policy which does not require any prior knowledge of the workload but can observe, learn, and adapt to the changes in wireless environment, which means that the decision to admit or reject the MC's requests depends on the current state. In our model, the state of the system X_t represents the number of accepted MCs' requests in the queue at time t. Let $\{X_t, t \geq 0\}$ denote a random variable which represents system states. All possible states are limited by the following constraints:

1- $\sum_{i=1}^{B} S_m^{(i,y)} \leq f_y$, $\forall y \epsilon \{1,2,3 \ldots W\}$

2- $X_t \leq QS$.

where QS is the queue size. The first constraint specifies that the sum of interference at the y^{th} PU should not exceed f_y. The second constraint reveals that the number of accepted MCs requests should not exceed the queue size. From a state, the system cannot make a transition if the constraint conditions are not met.

B.2 Cost Function

In this section, we define objective function for RL. To maximize throughput of the secondary network and serve the maximum number of MCs, each MR manages MCs' power so that the total path loss at time *t* is minimized as much as possible. The cost function for RL is defined as follows:

$$min_{SP_j} \sum_{t=0}^{\mathcal{D}} PL \,, \ \forall j \epsilon \{1,2,3 \ldots N\} \qquad (15)$$

where $\mathcal{D}$ is the time horizon. Each MR determines the transmitted power based on the physical layer function and expressed in equation (11). At each state X_t, MR calculates the interference threshold at each PU as follows:

$$f_y = f_y - S_m^{(i,y)}(d), \ \forall y \epsilon \{1,2,3 \ldots W\}, \ \forall i \epsilon \{1,2,3 \ldots B\}. \qquad (16)$$

Because our work concerns with QoS in the secondary network, MRs try to find the optimal power which minimizes the path loss under QoS and interference constraints.

B.3 State Action Space

At each decision epoch, MR has to decide among all possible actions. In our work, when any change in the wireless environment is perceived, MR has to decide whether it is possible for the MC at the head of the queue to start transmission or wait. The action space is given by:

$$A = \{a: a \in \{0,1\}\} \qquad (17)$$

where a = 0 denotes that MC has to wait in the queue, a = 1 indicates that the MR permits a MC to start transmission. The state transition probability is given by:

$$P_{X_t, X_{t+1}}(a) = \left\{ \begin{array}{ll} P(S_m^{(i,y)}(d) < \min_{\forall f_y \epsilon F} f_y) & , X_t = X_t - 1 \\ P\left(S_m^{(i,y)}(d) \geq \min_{\forall f_y \epsilon F} f_y\right) & , Otherwise \end{array} \right\} \qquad (18)$$

For each policy π, the average path loss is calculated as follows:

$$\overline{PL}(\pi) = \frac{\lim_{\mathcal{D}\to\infty}\sum_{t=1}^{\mathcal{D}} PL}{\mathcal{D}}. \quad (19)$$

An optimal policy is a policy that achieves the minimum cost over the long run. In our model, MR adopts the optimal policy to manage MCs power. A policy π outperforms $\bar{\pi}$ if its cost is less than $\bar{\pi}$. We apply a value iteration algorithm to find an optimal policy. The optimal value function is given (Sutton, and Barto, 1998) as:

$$V^*(X_t) = PL + \max_{a\in A}\gamma \sum_{X_{t+1}\in X} P_{X_t,X_{t+1}}(a)V^*(X_{t+1}) \quad (20)$$

The optimal policy is given as follows (Sutton, and Barto, 1998):

$$\pi^*(X_t) = \arg\max_{a\in A} \sum_{X_{t+1}\in X} P_{X_t,X_{t+1}}(a)V^*(X_{t+1}) \quad (21)$$

We define an optimal policy π^*as follows:

$$\overline{PL}(\pi^*) \le \overline{PL}(\pi). \quad (22)$$

C. Spectrum Trading for Spectrum Management

In the secondary network, MRs serve different classes of MCs. We assume that spectrum request arrival follows Poisson distribution and each MC class q has arrival rate λ_q. The service time for each request of q^{th} class is assumed to be exponentially distributed with service time μ_q. For trading model, each PU_y, $y=1, 2, \ldots, W$, specifies the size of spectrum for renting, its QoS requirements (blocking probability) and the price of spectrum. We assume that these parameters are changed over time corresponding to the network conditions (traffic load, spectrum demand, spectrum cost), therefore a PU needs to change the price and the size of the offered spectrum when needed. MRs can access a licensed spectrum if they rent it. Each MC of q^{th} class pays a price $\wp_q$ for a spectrum unit. In our model, the spectrum allocation vector for PU_y is $\mathcal{A}_y$, the interference vector is $\mathcal{I}_y$, and O is the vector of PUs in the primary network.

In our spectrum trading framework, a spectrum adaptation algorithm is required in conjunction with the admission control algorithm. When the demand for the spectrum at a PU is less, the admission control policy can admit more MRs' requests and offer more spectrum for trading to increase the profit as much as possible. However, the demand for spectrum at PU may increase significantly and the QoS for PU will be degraded. In this case, MRs requests should be rejected and the size of the offered spectrum should be reduced to maintain the QoS for PUs. Then, if some MCs have to release some channels, the PUs should decide which requests should be accepted and which should be rejected. We use RL to help the PUs to adapt to different situations. The agent is developed to be implemented at the PU level. It provides the trading functionality. Each agent uses its local information and makes a decision for the events occurring in the PU in which it is located. In order to apply RL, we need to identify the system states, actions, and rewards.

C.1 State Space

In our system, an event can occur in a PU when a new request for spectrum arrives or a SU releases its spectrum. These events are modeled as stochastic variables with appropriate probability distribution. At any time the PU is in a particular configuration defined by the size of the offered spectrum for trading, the price of spectrum, the number of admitted SUs for each class. In our work, the state of the PU_y at time t is defined as follows:

$$Z_y^t = \left\{ \begin{array}{l} B = (b_1, b_2, \dots, b_q, \dots\dots b_Q) \\ \mathcal{A}_y \end{array} \right\} \tag{23}$$

where b_q is the number of accepted requests of q^{th} class of SUs. All possible states are limited by the following constraints:

- $\sum_{q \epsilon Q} b_q \leq B$
- $\sum \mathcal{S} \leq KW$

where $\mathcal{S}$ is the size of the spectrum at the secondary network and Q is a set of SUs classes. From a state, the system cannot make a transition if the constraints conditions are not met.

C.2 Reward Function

When an event occurs, a PU has to decide among all possible actions for spectrum trading. In our work, when a SU arrives, a PU either serves the request or rejects it. The action space in (17) is used for this problem. A PU_y incurs cost C_y of renting its spectrum to the SUs, which is computed as follows:

$$C_y = \check{S}_y * \delta \tag{24}$$

where δ is the cost of one spectrum unit, and $\check{S}_y$ is the size of spectrum for renting. The average reward for PU_y is given by:

$$\bar{R}_y = \sum_{q \epsilon Q} \wp_q \bar{\lambda}_q \tag{25}$$

where $\bar{\lambda}_q$ is the average rate of accepting SUs requests of class q and $\wp_q$ is the spectrum price for class q. The PU_y average net revenue is computed as follows:

$$\bar{V}_y = \bar{R}_y - C_y = \sum_{q\epsilon Q} \wp_q \bar{\lambda}_q - C_y. \tag{26}$$

At state Z_y^t, the received revenue is computed as follows:

$$V_y\left(Z_y^t, a_t\right) = a_t\left(\sum_{q\epsilon Q} \wp_q b_q \mu_q - C_y\right) \tag{27}$$

where μ_q is the service rate of q^{th} class. The key objective for the PU is the maximization of revenue function $V_y\left(Z_y^t, a_t\right)$, under the condition that the blocking probabilities for a PU_y $(\mathcal{B}_y)$ does not exceed $\mathcal{B}_y^C$. Then, revenue maximization problem can be formulated as follows:

$$max_{\check{S}_y} \sum_{t=0}^{\mathcal{D}} V\left(Z_y^t, a_t\right) \tag{28}$$

subject to $\sum_{y=1}^{W} \mathcal{A}_y \leq KW,$

$\mathcal{A}_y(m)\mathcal{A}_j(m)\mathcal{I}_y(j) = 0,$

$B_y \leq B_y^C.$

In this formulation, the maximization of revenue can be achieved by adapting the size and the price of the spectrum periodically based on (26) and the blocking probability of PUs. Our goal of RL is to choose a sequence of actions that maximizes the total value of the received revenue for a PU_y:

$$\mathcal{T}_y(\pi) = \lim_{\mathcal{D}\to\infty} \sum_{t=0}^{\mathcal{D}} V_y(Z_t, a_t) \tag{29}$$

where $\mathcal{T}_y$ indicates the total net revenue of PU_y when policy π is executed.

At each state Z_y^t, $c_q(Z_t)$ is the dynamic cost of serving new requests of class q. It is used to decide which users to admit. A PU chooses the requests with maximum positive gain as follows:

$$g(Z_t) = \max_{q=1,\ldots,Q}(\wp_q - c_q(Z_t)) \tag{30}$$

If there is no request with positive gain, all requests are neglected.

C.3 Spectrum Size Adaptation in Radio Environment

The conditions of the system are changing randomly. These conditions include traffic level, spectrum demand from SUs and the size of available spectrum. Therefore, PUs should adapt their resources to achieve their objectives. Several parameters can be tuned by the PU to adapt to the new conditions. These parameters include price and the size of the offered spectrum. Revenue maximization can be achieved by spectrum size adaptation. In this case, the necessary condition for optimal solution can be formulated as a requirement of having the network revenue gradient with respect to PUs offered spectrum equal to zero vector:

$$\nabla\bar{V}(O) = \left(\frac{\nabla\bar{V}_1}{\nabla\check{S}_1}, \frac{\nabla\bar{V}_2}{\nabla\check{S}_2}, \frac{\nabla\bar{V}_3}{\nabla\check{S}_3}, \ldots\ldots, \frac{\nabla\bar{V}_W}{\nabla\check{S}_W}\right) = 0. \tag{31}$$

In our model, the PU_y revenues sensitivity to the number of the offered spectrum size can be derived from (26) as follows:

$$\frac{\partial \bar{V}_y}{\partial \check{S}_y} = \left(\frac{\partial \bar{R}_y}{\partial \check{S}_y}\right) - \left(\frac{\partial C_y}{\partial \check{S}_y}\right) = \left(\frac{\bar{R}_y}{\partial \check{S}_y}\right) - \delta. \qquad (32)$$

We assume the average reward sensitivity to the offered spectrum size can be approximated by the average spectrum price of the SUs class with unit spectrum requirement, $\frac{\bar{R}_y}{\partial \check{S}_y} = \bar{p}(\check{S}_y)$. As a result, equation (32) can be written as:

$$\frac{\partial \bar{V}_y}{\partial \check{S}_y} = \bar{p}(\check{S}_y) - \delta \qquad (33)$$

where $\bar{p}$ is the average spectrum price and is computed as follows :

$$\bar{p} = \frac{\sum_{q \in Q} \bar{\lambda}_q p_q}{\sum_{q \in Q} \bar{\lambda}_q} \qquad (34)$$

The PU's revenue is maximized when spectrum size equals the root of:

$$\frac{\partial \bar{V}_y}{\partial \check{S}_y} = \bar{p}(\check{S}_y) - \left(\frac{\partial C_y}{\partial \check{S}_y}\right) = 0. \qquad (35)$$

We used Newton's method of successive linear approximations to find the root of equation (35). The new spectrum size $\check{S}_{n+1}$(PU index is omitted in the notation) at each iteration step *n* is computed as follows:

$$\check{S}_{n+1} = \check{S}_{n+1} - \frac{\bar{p}_n - \delta}{\frac{\partial(\bar{p}(\check{S}) - \delta)}{\partial \check{S}}}. \qquad (36)$$

Approximating the derivative in equation (36) at step *n*:

$$\frac{\partial(\bar{p}(\check{S}) - \delta)}{\partial \check{S}} = \frac{\partial \bar{p}(\check{S})}{\partial \check{S}} = \frac{\bar{p}_n - \bar{p}_{n-1}}{\check{S}_n - \check{S}_{n-1}} \qquad (37)$$

and substituting (37) in (36), the new spectrum size will be :

$$\check{S}_{n+1} = \check{S}_n - (\check{S}_n - \check{S}_{n-1}) \frac{\bar{p}_n - \delta}{\bar{p}_n - \bar{p}_{n-1}}. \qquad (38)$$

Spectrum size adaption is then realized using the following algorithm:

AdaptSpectrumSize ($\bar{p}_n$, $\check{S}_{n+1}$, $\check{S}_n$, ε)
begin
    if ((*Abs*($\bar{p}_n$ - δ) < ε))
        return $\check{S}_{n+1}$, $\bar{p}_n$;
    else
    {
        $\check{S}_n = \check{S}_{n+1}$;
        compute $\bar{p}_n$, $\check{S}_{n+1}$;
        AdaptSpectrumSize ($\bar{p}_n$, $\check{S}_{n+1}$, $\check{S}_n$, ε);
    }
end;

where ε is the tolerable error.

C.4 Support QoS for PUs

The presented solution for revenue maximization does not take into account the QoS for PUs. The request of spectrum from the PU is blocked if it arrives while a PU is already using its entire spectrum. Therefore, the probability of blocking for PU_y is computed as follows (Beckmann, 1977):

$$\mathcal{B}_y = \frac{\rho^K}{K!} \left(\sum_{m=0}^{K} \left(\frac{\rho}{m!}^m\right)^{-1}\right) \tag{39}$$

where ρ is computed as follows:

$$\rho = \frac{\lambda}{\square} \tag{40}$$

The blocking probabilities of PUs may exceed their constraints in some scenarios. The offered price in the secondary network should be adapted to meet the blocking constraints for the PUs. It is clear when a PU increases the price the arrival rates of SUs will be decreased. Hence, the spectrum demand at the secondary network will be decreased. The surplus spectrum can be used to serve applications of the PUs. The arrival rate of SUs classes depends on the offered price. The new arrival rate of q^{th} class is calculated as follows (Gallego and Ryzin, 1994):

$$\lambda_q = \tau e^{-\omega_q \acute{p}_q} \tag{41}$$

where τ is the maximum number of users arriving at a PU, ω_q represents the rate of decrease of the arrival rate as spectrum price increases and $\acute{p}_q$ is the new price for the q^{th} class. Here we assume ω_q is given a priory. There is an inverse relationship between the price and the demand for the spectrum. A PU has to meet its blocking probability constraint $\mathcal{B}_y^C$. Blocking probability is a function of the number of available channels and the traffic load. PU continues increasing the prices in the secondary market till its blocking probability is met. PUs tries to minimize the price increment as much as possible to keep the PUs revenues positive. A PU calculates the new revenue as follows:

$$\Delta V_y' = \sum_{q\in Q} \lambda_q (\acute{p}_q - p_q) \geq 0. \tag{42}$$

This leads to the following problem formulation:

$$max_{\check{S}_y}\, \bar{V}_y = \sum_{q\epsilon Q} \acute{p}_q \bar{\lambda}_q - C_y - min_{\acute{p}_i} \sum_{q\epsilon Q} \lambda_q (\acute{p}_q - p_q) \tag{43}$$

subject to: $\sum_{y=1}^{W} \mathcal{A}_y \leq KW,$

$$\mathcal{A}_y(m)\mathcal{A}_j(m)\mathcal{I}_y(j) = 0,$$

$$\mathcal{B}_y \leq \mathcal{B}_y^C,$$

$$\Delta V_y' = \sum_{q\epsilon Q} \lambda_q (\acute{p}_q - p_q) \geq 0.$$

In our proposed adaptation scheme, the new values of spectrum prices reflect the amount of spectrum required by a PU. Because of the competition in the market, a price increment is limited due to the possibility of losing customers. If the blocking constraint of a PU is not met, a PU increases the values of all service prices by applying a common multiplier γ to all spectrum prices. After each increment, a PU computes its blocking probability and if it is not met it continues increasing the prices till its blocking constraint is met. If a blocking constraint for a PU is met then it tries to meet the blocking constraint for SUs. A PU verifies the class blocking constraints. If some of the SUs blocking constraints are not met, it decrease the service prices while increase those of SUs classes for which blocking probability are smaller than constraints, in such a way that total offered spectrum price is maintained.

D. Spectrum Allocation

In the overlay and the underlay approaches, MRs sort the free channels in decreasing order, according to their rank Γ_m, and assign them for the MCs. At the same time, MCs are sorted according to their data rates in decreasing order by MRs. In the underlay approach, each MC is assigned a channel if it does not interfere with PUs. The overlay scheme assigns the unused spectrum to the SUs. The objective of our channel assignment is to maximize throughput in the secondary network and to serve the maximum number of SUs. This problem can be formulated as a non-linear integer problem as follows:

$$max_{SP} \sum_{j=1}^{N} T_j^t \, SP_j \tag{44}$$

subject to $\sum_{j=1}^{N} SP_j \leq KW,$

$SP_j(m) SP_i(m) I_j(i) = 0.$

where T_j^t is the transpose of the throughput vector T_j and SP is a feasible assignment. Another objective of our algorithm is to maximize spectrum utilization as follows:

$$max_{SP} \sum_{j=1}^{N} SP_j \, . \tag{45}$$

In this objective, we try to maximize the total number of SUs; hence, efficient utilization will result and the spectrum holes will be reduced significantly. In the underlay scheme, if the received power from any MC at any PU exceeds the interference sensitivity value, MR returns that MC to the queue. In spectrum trading, MRs accept requests from different classes of MCs and buy channels to serve these requests.

VIII. SPECTRUM ALLOCATION USING COMBINED SCHEME

In the combined scheme, the main objective is to maximize the availability of channels for users while they are communicating in the secondary network. Combined scheme merges the three spectrum access techniques in to one spectrum access scheme. After receiving the requests for spectrum, MR places the free-charge requests which are not charged for spectrum usage in a low-priority queue and other requests which are charged for spectrum in a high-priority queue.

First, MR uses the trading scheme to serve the requests in the high-priority queue. It uses the spectrum that rented from PUs to serve the high-priority requests. If this spectrum is not sufficient to serve high-priority requests, the combined scheme uses underlay and overlay schemes to serve the remaining high-priority requests while continuing to serve the low priority-requests which are already in service. If the overlay and underlay schemes cannot serve the high-priority requests, it preempts some of the lower-priority requests and uses their spectrum to serve the high-priority requests. The combined scheme work as follows:

Parameters:
$\mathbb{L}_{\mathbb{q}}$: *low-priority queue*; $\mathbb{Y}_{\mathbb{q}}$: *high-priority queue.*
$\mathbb{S}_{\mathbb{t}}$: *The available spectrum for trading scheme;* $\mathbb{S}_{\mathbb{o}}$: *overlay spectrum;* $\mathbb{S}_{\mathbb{u}}$: *underlay spectrum.*
Trade($\mathbb{G}, \mathbb{B}$*): a trading scheme that uses the spectrum* $\mathbb{B}$ *to serve the requests in queue* $\mathbb{G}$.
Overlay_Underlay($\mathbb{G}, \mathbb{B}$*): a scheme that uses the overlay and underlay schemes to serve the requests in queue* $\mathbb{G}$ *using spectrum* $\mathbb{B}$.
size_req($\mathbb{G}$*): a function that gives the size of spectrum required to serve all requests in queue* $\mathbb{G}$.
preempt($\mathbb{V}$ *): a function to preempt the low-priority requests of size* $\mathbb{V}$.

---

while (*size_req*($\mathbb{Y}_{\mathbb{q}}$) $\neq 0$)
  if($\mathbb{S}_{\mathbb{t}} \geq$ *size_req*($\mathbb{Y}_{\mathbb{q}}$))
  {
    Trade($\mathbb{Y}_{\mathbb{q}}$, $\mathbb{S}_{\mathbb{t}}$)
    Overlay_Underlay($\mathbb{L}_{\mathbb{q}}$, $\mathbb{S}_{\mathbb{o}} + \mathbb{S}_{\mathbb{u}}$)
  }
  else
    if(*size_req*($\mathbb{Y}_{\mathbb{q}}$) $- \mathbb{S}_{\mathbb{t}} \leq \mathbb{S}_{\mathbb{o}} + \mathbb{S}_{\mathbb{u}}$)
    {
      Trade($\mathbb{Y}_{\mathbb{q}}$,$\mathbb{S}_{\mathbb{t}}$)
      Trade($\mathbb{Y}_{\mathbb{q}}$,$\mathbb{S}_{\mathbb{o}} + \mathbb{S}_{\mathbb{u}}$)
      Overlay_Underlay($\mathbb{L}_{\mathbb{q}}$, $\mathbb{S}_{\mathbb{o}} + \mathbb{S}_{\mathbb{u}}$)
    }
  else
    {
      Trade($\mathbb{Y}_{\mathbb{q}}$,$\mathbb{S}_{\mathbb{t}}$)
      preempt(*size_req*($\mathbb{Y}_{\mathbb{q}}$))
      Trade($\mathbb{Y}_{\mathbb{q}}$,*size_req*($\mathbb{Y}_{\mathbb{q}}$))
    }
endWhile
Overlay_Underlay($\mathbb{L}_{\mathbb{q}}$, $\mathbb{S}_{\mathbb{o}} + \mathbb{S}_{\mathbb{u}}$)

The performance of the overlay scheme is highly dependent on the PUs pattern usage. Hence, guaranteeing spectrum using overlay scheme is impossible. For each overlay channel $\mathbb{s}_{\mathbb{o}}$, there exists an underlay channel $\mathbb{s}_{\mathbb{u}}$ that can be used to replace $\mathbb{s}_{\mathbb{o}}$ if the PU starts using the $\mathbb{s}_{\mathbb{o}}$. This can be expressed as follows:

$$\mathbb{s}_{\mathbb{o}} \in \mathbb{S}_{\mathbb{o}} \rightarrow \exists \mathbb{s}_{\mathbb{u}} \in \mathbb{S}_{\mathbb{u}} \tag{46}$$

where $\mathbb{S}_{\mathbb{o}}$ is the overlay spectrum, and $\mathbb{S}_{\mathbb{u}}$ is the underlay spectrum. Each spectrum request consists of more than one link in a path. Overlay_Underlay scheme consists of two phases: allocation phase, and maintenance phase. In the spectrum allocation phase, the scheme uses the overlay channels first to serve a request. If the overlay channels are not sufficient to serve all links, Overlay_Underlay scheme uses the underlay spectrum to serve the links that are not served. In the maintenance phase, MR monitors all communication in the network and if any failure occurs because of PU activity, Overlay_Underlay scheme replaces the overlay channel by its corresponding underlay channel. Overlay_Underlay scheme is presented as follows:

Parameters:

Overlay($\mathbb{r}$, $\mathbb{B}$) : *an overlay scheme to serve the request* $\mathbb{r}$ *using spectrum* $\mathbb{B}$

Underlay($\mathbb{r}$, $\mathbb{B}$) : *an underlay scheme to serve the request* $\mathbb{r}$ *using spectrum* $\mathbb{B}$

NotComplete($\mathbb{r}$) : *a function to check if all the links of the request* $\mathbb{r}$ *are served by overlay scheme*

```
while ((𝕊𝕠 + 𝕊𝕦) > 0 and size_req(𝕃𝕢) ≠ 0)
Overlay(𝕣, 𝕊𝕠)
 if NotComplete(𝕣) then
     Underlay(𝕣, 𝕊𝕦)
endif
endWhile
```

IX. Performance Evaluation

In this section, we show the simulation results to demonstrate the performance of our proposed system. In our simulation we randomly place 100 MCs and 10 MRs for the secondary network. We study the behavior of our system under different parameter settings.

A. Overlay scheme performance

In this experiment, we compare the performance of our overlay scheme (cluster-distributed scheme) with the conventional method where all secondary users send their sensing results to a centralized server and the cluster-centralized scheme used in (Akyildiz, and Wang, 2009).

The speed of spectrum sensing and the processing time of spectrum detection results are the most important factors for the success of the overlay approach. The unused spectrum should be utilized as soon as possible before the PU resumes its activities. Some results about the speed of the clustered-distributed sensing scheme are reported in (Alsarhan, and Agarwal, 2009). Our scheme needs less time to access the unused spectrum because there is no contention for the pre-defined control channel which is used for exchanging spectrum data in the other methods. In the scheme used in (Sun, Zhang, and Letaief, 2007) cluster heads contend for a control channel. Moreover, in the conventional method all SUs contend for a control channel to send spectrum detection results.

The key success factor for the overlay scheme is the speed of utilizing the unused spectrum and reducing the chance of service interruption in the secondary network. The available spectrum in the secondary network under different values of load traffic at PUs for the three overlay schemes is shown in Fig. 2. The figure shows that the available spectrum decreases as the traffic load increases at the PUs. A higher traffic at the PUs increases the likelihood of service interruption in the secondary network. Because our scheme needs less time to access the unused spectrum, its spectrum size is more than that of the other schemes.

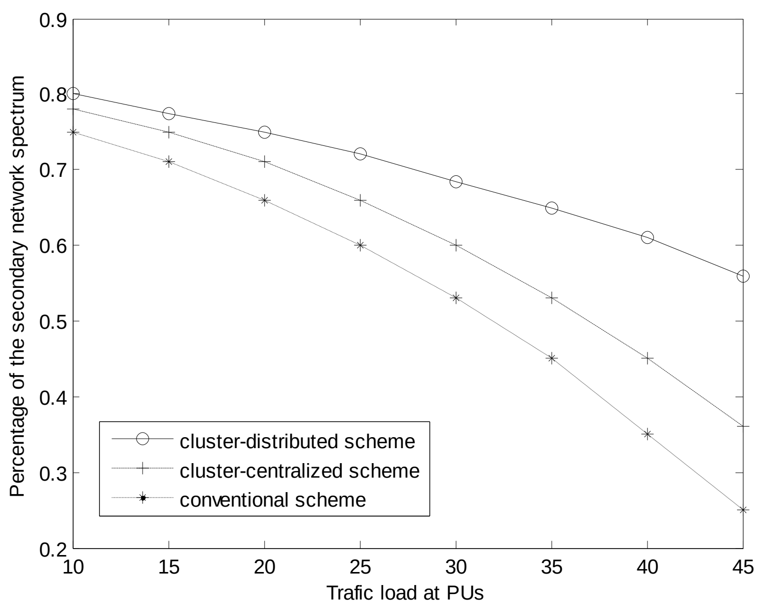

Fig 2. Overlay Scheme: Spectrum used for different values of traffic load at PUs

The throughput comparison of the three different overlay schemes is shown in Fig. 3. The figure shows that the throughput decreases as the traffic loads at the PUs increase. Small values of work load at PUs means that the PUs rarely need the spectrum. Therefore, interruption of the SUs is rare in this scenario. The results show that our scheme outperforms other schemes when the number of SUs is increased and also for different traffic loads. By increasing the traffic load at PUs the available spectrum in the secondary network is decreased significantly. Hence, the requirements of the PUs prevent overlay scheme to keep increasing the throughput. These results stress the need for other spectrum sharing techniques that can guarantee QoS in the secondary network.

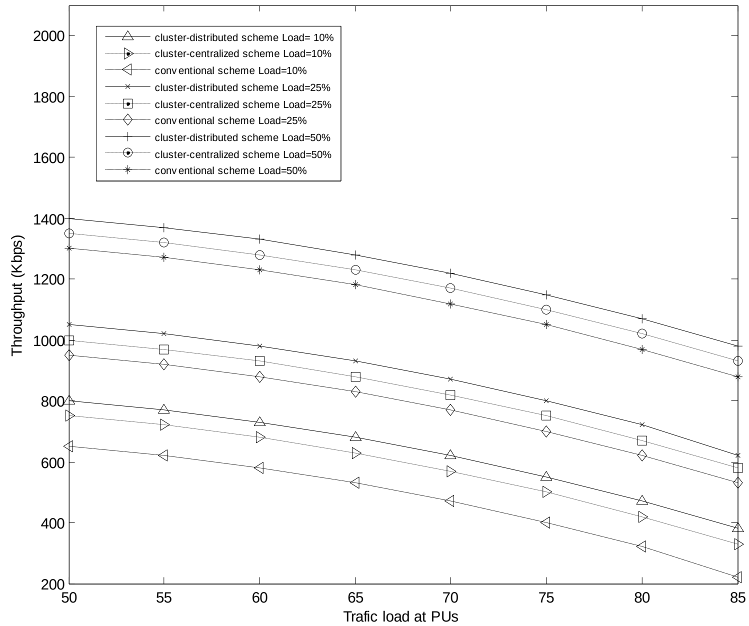

Fig 3. Overlay Scheme: Throughput comparison for different values of traffic loads at PUs

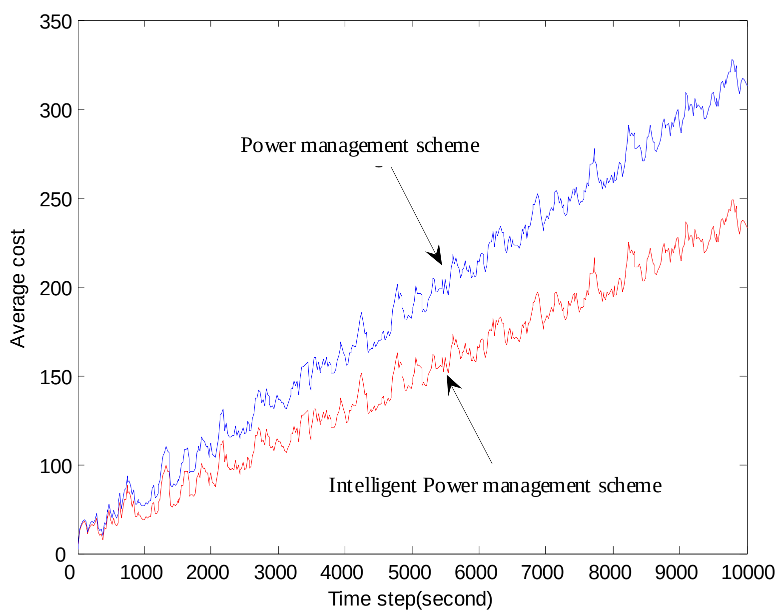

Fig 4. Underlay Scheme: Average cost comparison as a function of time

B. Underlay scheme performance

In Fig. 4, we compare the performance of the policy obtained through RL for our underlay scheme (intelligent power management scheme) with the algorithm used in (Haidar, Msakni, and Dziong, 2009) (power management scheme). We compute the average cost as a function of time. Fig. 4 shows that the average cost increases because of serving more requests. By serving more requests, the likelihood of interfering with the PUs increases, which results in more path loss because of decreasing the signal powers of the MCs. To protect the PUs, the power management scheme should reduce the signal power when MCs transmission harms PUs. Because our scheme considers a path loss when assigning channels, it has the lowest cost. The scheme in (Haidar, Msakni, and Dziong, 2009) does not attempt to minimize the path loss when allocating the spectrum.

Fig. 5 shows a comparison of the reported throughput of our proposed power management scheme with the scheme proposed in (Haidar, Msakni, and Dziong, 2009) and our overlay scheme as a function of time. At the beginning, and for about 2000 seconds, the total reported throughput for all schemes is similar. The throughput is increased as the traffic load increases in the secondary network. As time elapses however, our intelligent power management scheme outperforms other schemes. The justification is that our scheme always allocates the spectrum for the SUs if they do not interfere with the PUs. Hence, more requests are allowed in the network, and therefore the total throughput increases for this scheme.

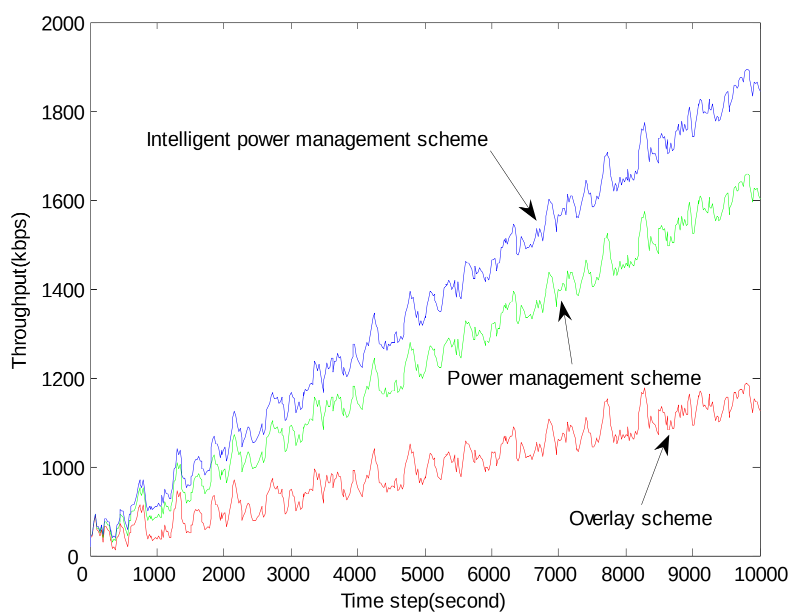

Fig 5. Throughput comparison for the Overlay and Underlay schemes as a function of time

The power management scheme achieves good throughput, but it does not consider the usage pattern for the PUs or the quality of channels when allocating them for the SUs and, therefore, the likelihood of channel releasing is larger than ours. Our overlay approach focuses only on identifying and avoiding PUs' signals. On the other hand, the underlay approach seeks to share the same frequency band, at the same time, between SUs and PUs. As a result, it provides a robust and scalable communication, which enables it to outperform other schemes, as can be seen in Fig. 5.

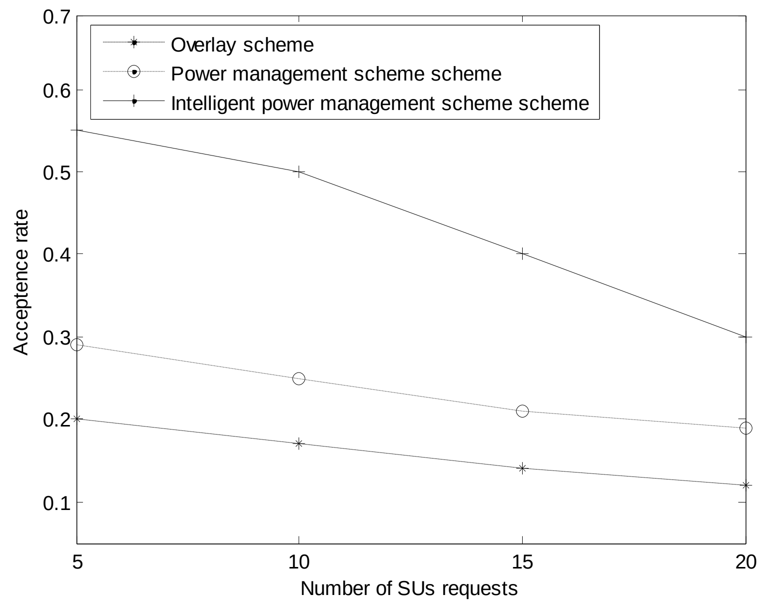

Fig 6. Acceptance rate of the SUs requests for the Overlay and Underlay schemes

Fig. 6 shows the acceptance rate of the accepted number of SUs' requests versus the number of requests (spectrum demand). The figure shows that the intelligent scheme outperforms other schemes. The acceptance rate in all schemes is decreased as the spectrum demand increases because of the constraints of using the spectrum. Unfortunately, the performance of the underlay scheme depends on the interference threshold for the PUs. In the above figures, we assume the interference threshold I that can be tolerated at the PU to be $I = 5I_0$, where $I_0 = 10^{-15}$ W.

In Fig. 7 we plot the network throughput under different interference thresholds settings. As expected, the throughput is degraded significantly when the interference constraint is made more stringent. The results stress that the performance of the underlay approach depends mainly on the interference constraint. Another factor that degrades the performance of the secondary network is the interference from the PUs. The SUs suffer from the PUs' interference and their QoS is degraded significantly. This spectrum sharing paradigm does not require the PUs to cooperate with the SUs. The key result when looking at Fig. 7 is that the performance of the underlay approach is very sensitive to the interference threshold of the PUs. We can however improve the results by finding a strategy that allows the PUs to cooperate with the SUs, as will be shown using our trading scheme.

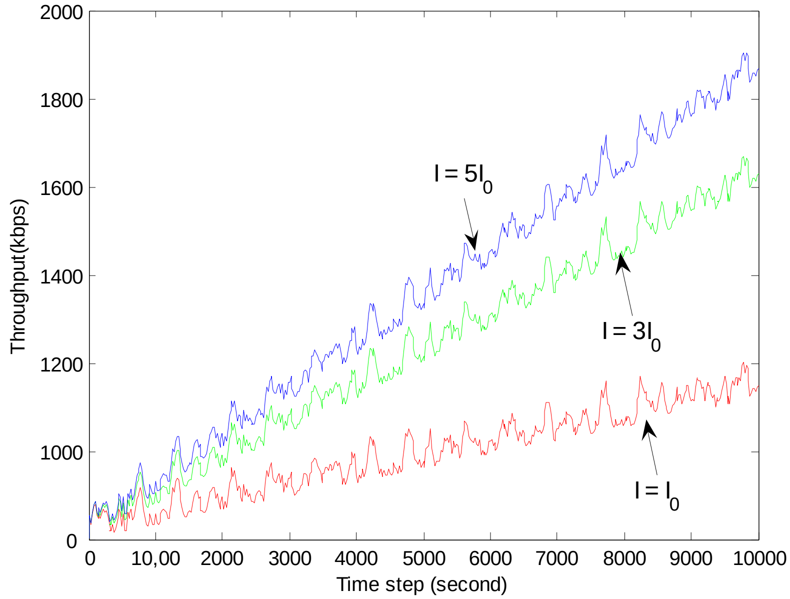

Fig 7. Underlay scheme: Throughput comparison for different interference constraints

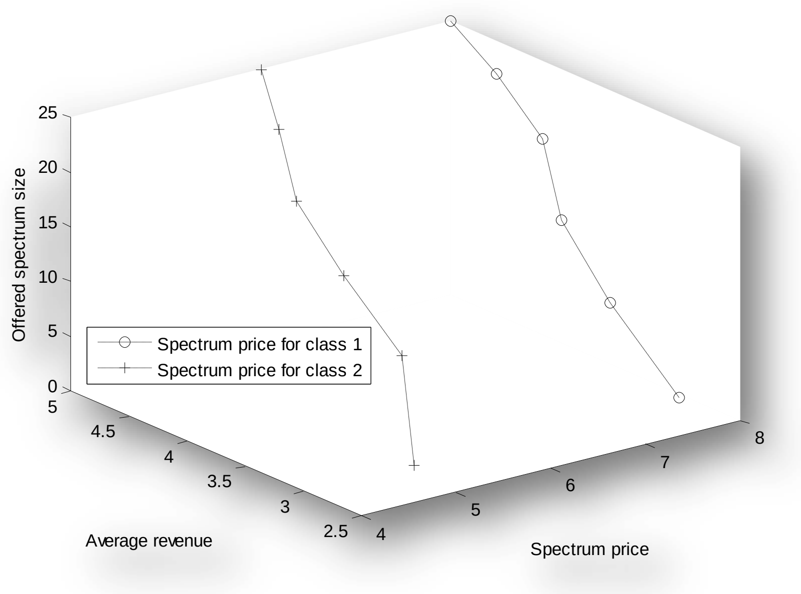

Fig 8. Trading scheme: Adapting spectrum price for different offered spectrum size to optimize revenue

C. Trading scheme performance

Due to the dependency of the spectrum price on the traffic load at the PUs, the reported revenue will vary based on the new prices. Fig. 8 shows how a PU varies the prices of spectrum to reduce the amount of the offered spectrum in the secondary network and uses the new available spectrum to serve the applications of the PUs. Because it gets more revenue from class 1, the PU tries to increase the price for class 2 more than class 1. However, to maintain the QoS of class 2, the PU sometimes also increases the price of class 1. Fig. 9 shows the acceptance ratio of both SUs classes under different traffic loads at the

PU. It can be observed the admission scheme rejects more requests under large traffic loads. Furthermore, the likelihood of rejecting class 2 requests is higher than class 1 because of the higher revenue.

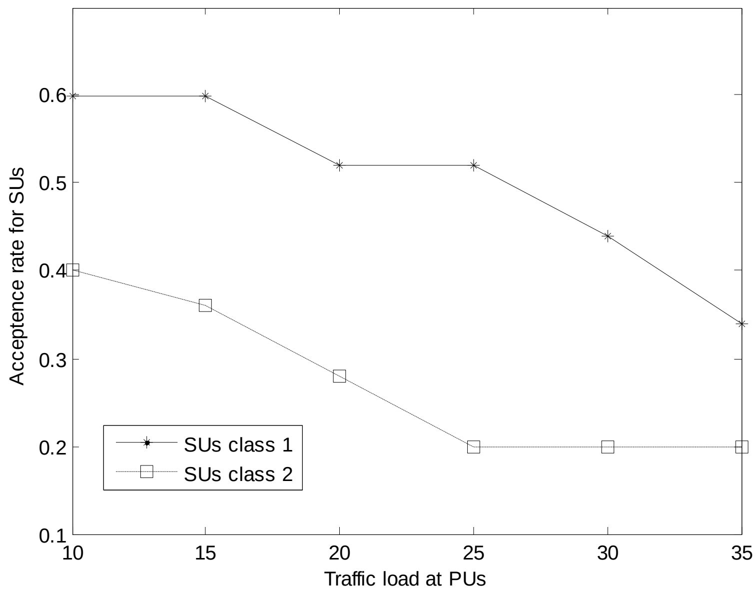

Fig 9. Trading scheme: Acceptance rate for SUs classes for different traffic loads

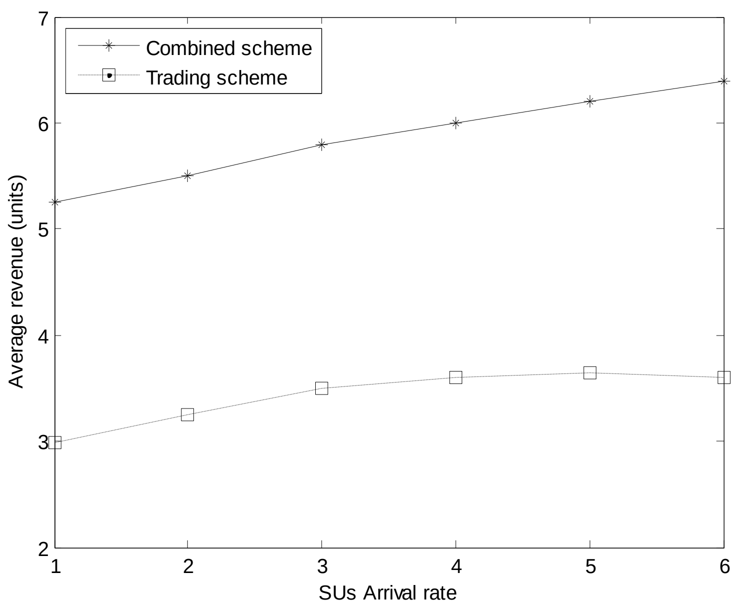

Fig. 10. Average revenue for the combined scheme and trading scheme for different arrival rates of SUs

D. Combined scheme performance

We compare the performance of the combined scheme with performance of trading scheme. Fig. 10 shows the reported revenues for the combined scheme and the trading scheme for different values of spectrum demand of SUs. It can be observed that the combined scheme outperforms the trading scheme, since it uses the rented spectrum as well as the free spectrum available using the overlay and underlay approaches more efficiently. Because it accesses more spectrum, the combined scheme generates more

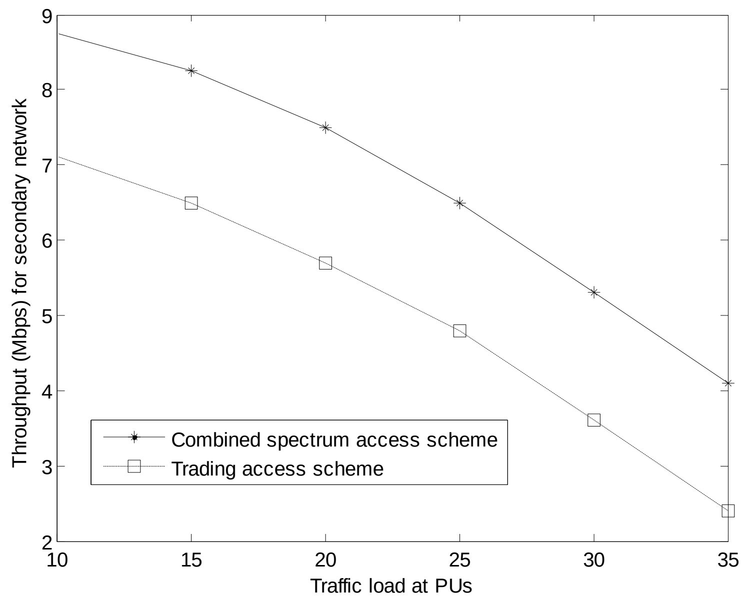

Fig 11. Throughput comparison for the combined spectrum access and trading technique under different traffic loads.

revenues than the trading scheme. Furthermore, the combined scheme utilizes the unused spectrum if the usage does not harm the PUs. However, for the trading scheme, the requests are rejected if there no spectrum. From the throughput point of view, we measure the throughput for the two schemes under different values of traffic loads at PUs in Fig. 11. From the figure, we notice that the combined scheme achieves more throughput than the trading scheme. Combined scheme uses more access techniques which enable it to utilize more spectrum. Using more access schemes enable combined scheme to serve more users in the secondary network. Fig. 12 shows the acceptance rate of SUs of both queues when using the combined scheme. As expected, the acceptance rate of the SUs' requests in the high-priority queue is more than the acceptance rate of the requests in the lower-priority queue because of revenues. The acceptance rate of the lower-priority requests decreases as the spectrum demand increases because of revenue. The combined scheme tries to maximize the revenue as much as it can. Hence, it gives the priority for the requests which are charged for the spectrum as can been seen from Fig. 12.

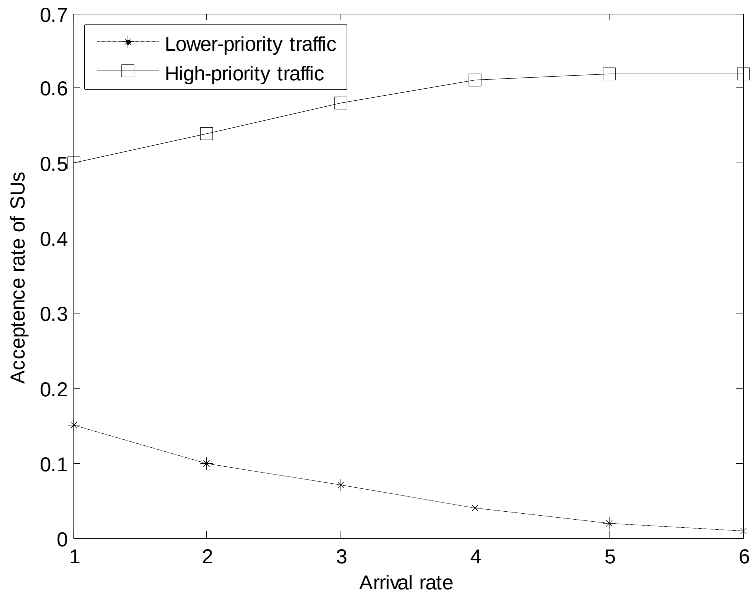

Fig. 12. Acceptance rate for different requests priorities

CONCLUSION

The main objective of this paper is to propose a complete system for cognitive network. The system contains all of cognitive cycle functions such as spectrum sensing, collecting sensing results, processing the results and managing the spectrum. Our new system combines the three known spectrum access techniques in one access scheme. For the architecture of the cognitive network, we use a clustered mesh network as proposed in (Alsarhan, and Agarwal, 2009), which is based on a novel sensing method. The sensing method is collaborative and it enables the system to specify the unused spectrum accurately and use it resourcefully. Our overlay scheme is employed to access the unused spectrum. The results show the scalability of the new scheme and its ability to utilize the spectrum more efficiently than other schemes. Although the proposed scheme outperforms other schemes in terms of throughput and spectrum utilization, its performance depends on the PUs' activities. For higher load traffic at the PUs, the performance of the overlay scheme is degraded significantly. To solve this problem, we use the underlay access scheme to enable SUs to transmit concurrently with PUs. For the underlay scheme, RL based self-optimization algorithm is used to enable users to adapt to the changes in the network conditions. The RL algorithm enables the integration of the admission control algorithm in our scheme. The admission algorithm is used to exclude SUs' requests that may harm PUs so that the QoS for the SUs and the interference constraint for the PUs are met. Simulation results show the feasibility of the underlay solution. However, some results stress the sensitivity of the underlay performance to QoS and interference constraints. For some settings, the performance degrades significantly. To provide better service to SUs, we propose a spectrum trading where PUs cooperate with SUs. In this scheme, PUs rent adaptable sizes of the spectrum to the SUs based on their requirements. The key objective of this scheme is to adapt the size and the price of the spectrum to maximize the PUs revenues while providing the required QoS for the PUs and SUs. The trading model is based on the RL algorithm that allows the integration of the adaptation of the spectrum size, price and admission algorithm. Simulation results show the ability of the proposed scheme to adapt to different network conditions and to achieve the required objectives. The results also confirmed the QoS requirements for the PUs can be met by the proposed price adaptation algorithm. To take advantages of all previous schemes, we propose a combined scheme. The combined scheme integrates all spectrum sharing paradigms. Integrating all schemes enables accessing to more spectrum and serving more SUs. The numerical results reveal the usefulness of considering more than one spectrum sharing scheme on the performance of the secondary network. The performance of our overlay scheme can be improved by reducing sensing errors. For example the sensing errors due to fading channel can be reduced by selecting control channels with less noise. In our work we assume the PUs have fixed locations. In the future we can extend the model to incorporate the mobility of PUs. For underlay scheme, we will study the revenue of PUs and propose the methodology that can help MR to maximize the revenue. For spectrum trading scheme, one possible extension to the current work includes studying spectrum prices under different behavior of PUs. In competitive pricing model, each PU tries to maximize the individual profit, and there is a competition among PUs to sell the spectrum for SUs. This will give an opportunity to investigate how PU can adapt their spectrum prices to other PUs prices.

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