Cognitive Radio And Dynamic Spectrum Access – A Study

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ABSTRACT

A basic problem facing the future in wireless systems is where to find suitable spectrum bands to fulfill the demand of future services. While all of the radio spectrum is allocated to different services, applications and users, observation show that usage of the spectrum is actually quite low. To overcome this problem and improve the spectrum utilization, cognitive radio concept has been evolved. Wireless communication, in which a transmitter and receiver can detect intelligently communication channels that are in use and those which are not in use are known as Cognitive Radio, and it can move to unused channels. This makes possible the use of available radio frequency spectrum while minimizing interference with other users. CRs must have the capability to learn and adapt their wireless transmission according to the surrounding radio environment. The application of Artificial Intelligence approaches in the Cognitive Radio is very promising since they have a great importance for the implementation of Cognitive Radio networks architecture. Dynamic spectrum access is a promising approach to make less severe the spectrum scarcity that wireless communications face now. It aims at reusing sparsely occupied frequency bands and does not interfere to the actual licensees. This paper is a review and comparison of different DSA models and methods.

KEYWORDS

Wireless communication system, cognitive radio (CR), dynamic spectrum access (DSA), fuzzy logic, markovian chain, threshold policies, spectrum sharing and spectrum management.

1. INTRODUCTION TO COGNITIVE RADIO

Cognitive radios are the radio systems that autonomously coordinate the usage of radio band. They recognize radio spectrum when it is unused by the incumbent radio system and use this spectrum in an intelligent way. Such unused radio spectrum is called ‘spectrum opportunity,’ also known to as ‘white space.’[1].

The idea of cognitive radio (CR) was first presented officially in an article by Joseph Mitola III and Gerald Q. Maguire, Jr in 1999. It was a new approach in wireless communications that Mitola described as: “The point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs” [2]. This is an intelligent wireless communication system that is cognizant of its surrounding environment

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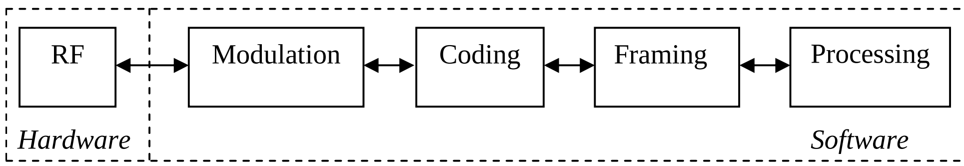
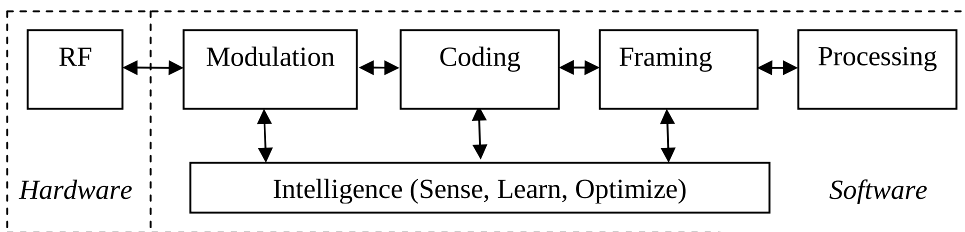
and uses a understanding methodology by building to learn from the environment, adapt its internal states to statistical change in the incoming radio frequency stimuli by making corresponding variation in certain operating parameters in real time and with two primary objectives: i) highly reliable communications whenever and wherever needed ii) efficient utilization of radio spectrum [3].

It was thought of an ideal goal towards which a software-defined radio (SDR) platform should develop: a fully reconfigurable wireless black-box that automatically varies its communication variables with network and user demands. [4]



a) SDR



b) CR

Figure 1. Block diagram contrasting (a) SDR and (b) Cognitive Radio

Cognitive radio (CR) is a form of wireless communication in which a transceiver can intelligently detect communication channels which are in use and which are not, and instantly move into unused channels while avoiding occupied ones. This optimizes the use of available radio-frequency spectrum while interference minimized to other users. CR technology is a paradigm for wireless communication in which transmission or reception parameters of network or wireless node are changed to communicate avoiding interference with licensed or unlicensed users. A spectrum hole (Figure 2) is generally a concept which is the latent opportunities for safe use of spectrum as non-interfering and considered as multidimensional areas within frequency, time, and space. The main challenge for secondary radio systems is to be able to sense when they are within such a spectrum hole [5].

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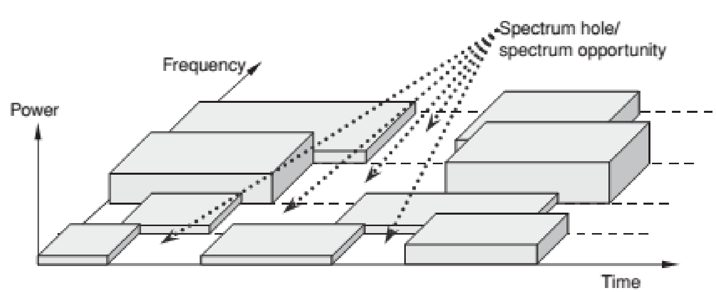

Figure 2. Spectrum Hole (or spectrum opportunity).

There are two types of cognitive radio, i) full cognitive radio and ii) spectrum-sensing cognitive radio. Full CR considers all parameters, a wireless node or network can be aware of every possible parameter observable by a wireless node or network is considered. Spectrum-sensing cognitive radio detects the channels in the radio frequency spectrum and considers radio frequency spectrum. The requirements of the performances for cognitive radio system are: i) authentic spectrum hole and detection of primary user, ii) precise link estimation between nodes, iii) fast and accurate frequency control and iv) method of power control that assures reliable communication between cognitive radio terminals and non-interference to the primary users [3].

There are two main characteristics of the cognitive radio and can be defined

- *Cognitive capability*: The ability of the radio technology is to capture or sense the information from its radio environment. [6].
- *Reconfigurability:* Spectrum awareness is provided by the cognitive capability whereas the radio to be dynamically programmed according to the radio environment are enabled by the reconfigurability. [6].

1.1. Major Functions of Cognitive Radio

1.1.1. Spectrum Sensing

The first step is spectrum sensing determines if a primary user is present on a band. The spectrum, the cognitive radio can share the result of its detection with other cognitive radios after sensing [7].

The goal of spectrum sensing is to determine spectrum status and the licensed user's activity by periodically sensing the target frequency band. In particular, a cognitive radio transceiver detects a spectrum which is unused or spectrum hole (i.e. band, location, and time) and also determines the accessing method of it (i.e. transmitting power and access duration) without interfering of a licensed user's transmission. Spectrum sensing may be either centralized or distributed. In the centralized spectrum sensing, a sensing controller (e.g. access point or base station) senses the target frequency band, and the information obtained is shared with other nodes in the system. For example, the sensing controller may be unable to detect an unlicensed user at the edge of the cell. In distributed spectrum sharing, unlicensed users sense the spectrum independently, and the spectrum sensing is achieved either used by individual cognitive radios (non-cooperative sensing) or shared with other users (cooperative sensing). Even though cooperative sensing deals with a communication and processing overhead, the accuracy of spectrum sensing is greater than that of non-cooperative sensing [8]. So spectrum sensing techniques may be classified into three categories: Transmitter detection, Cooperative detection and Interference based detection [9].

1.1.2. Spectrum Management

In order to meet the communication requirements of the users spectrum management captures the best available frequencies. The CRs should decide the best band of the spectrum in order to meet the Quality of Service (QoS) desires all available frequency bands; therefore, the functions of the spectrum management are important for the CRs. These management functions can be classified as follows [10].

a. Spectrum analysis

The sensing of spectrum results is analyzed to estimate the spectrum standard. Here one issue is how to measure the quality of spectrum accessed by a SU. This quality can be characterized by the Signal to Noise Ratio (SNR), the average correlation and the white spaces availability. Information on the available spectrum quality for a Cognitive Radio user can be inaccurate and noisy.

b. Spectrum Decision

Spectrum access requires a decision model. The complexity of this model is depended on the parameters considered in the spectrum analysis.

The decision model becomes more complex when a Secondary User has multiple objectives. For example, a SU may want to maximize performance while minimizing disturbance caused to the PU. A stochastic optimization method is an interesting tool to model and solve the problem of spectrum access in a Cognitive Radio. When users (both primary and secondary) are in the system, preference will influence the decision of the spectrum access. These users can be cooperative or non-cooperative in spectrum access. Each user has its own purpose in a non-cooperative environment. In a cooperative one, all users can work together to achieve the goal.

In a cooperative environment, CRs cooperate with each other, make a decision for accessing the spectrum and maximizing the objective function considering the common constraints. In such a scenario, a central controller coordinates the spectrum management. [10].

1.1.3. Spectrum Mobility

Spectrum mobility is a function related to the variation of operating frequency band of CR users. When a licensed user begins to access a radio channel which is currently being used by an unlicensed user, the unlicensed user can change idle spectrum to a active spectrum band. This change in operating frequency band is known as spectrum handoff. The protocol parameters at the different layers in the protocol stacks have to be adjusted to match the new operating frequency band during spectrum handoff. Spectrum handoff must try to ensure that the unlicensed user can continue the data transmission in the new spectrum band [8].

1.1.4. Spectrum Sharing

Since there is number of secondary users want to use available spectrum holes, cognitive radio has to maintain balance between its self-goal of information transferring efficiently and selfless goal to share the available spectrum with other cognitive and non-cognitive users. This is done by policy rules determining behaviour of cognitive radio in radio environment [3]. The fair spectrum scheduling method, open spectrum usage in the spectrum sharing is one of the major challenges. In existing systems, it regards to be similar to generic media access control MAC problems [11]

2. DYNAMIC SPECTRUM ACCESS

The concept of dynamic spectrum access is the identification of spectrum holes (a frequency band which is free enough to be used) or white spaces and uses them to communicate [7].

Dynamic spectrum access is the most vital application of cognitive radios. The PU bands are opportunistically accessed by the SU networks such that the interference caused to the PUs is negligible. Fig.3 shows the scenario for dynamic spectrum access (DSA) where multiple PUs and SUs are coexisting [12].

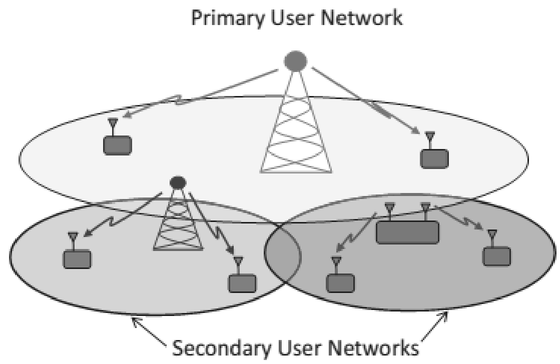

Figure 3. Coexistence of multiple primary and secondary user networks
(homogeneous or heterogeneous)

This is a technique by which a radio system adapts to available spectrum holes with limited spectrum use rights dynamically, in response to changing circumstances and objectives: the created interference changes the radio's state in environmental constraints [13]. The main task of DSA is to overcome two types of interference: i) harmful interference caused by device malfunctioning and ii) harmful interference caused by malicious user [9].

There are three main functions in Dynamic Spectrum Access [12]: i) spectrum awareness, ii) cognitive processing, and iii) spectrum access.

Spectrum awareness creates awareness about the Radio Frequency environment when spectrum access provides the ways to use the available spectrum opportunities for reuse efficiently. *Cognitive processing* is the intelligence and decision making function that performs several subtasks like learning of the radio environment, designing sensing efficient, and access policies which manages interference for coexistence of the SU networks with the PU networks.

3. DIFFERENT MODELS AND SCHEMES OF DSA

Based on the fixed allocation of the radio resources and little sharing of radio spectrum which causes in spectrum shortages, the current spectrum management policy is made. In comparison to the static spectrum access, dynamic spectrum access (DSA) is widely used in cognitive network and having various approaches and applications [14].

3.1. Different Approaches of DSA Models

As shown in Figure 4 dynamic spectrum access strategies can be classified as dynamic exclusive-use, open sharing model, and hierarchical access model.

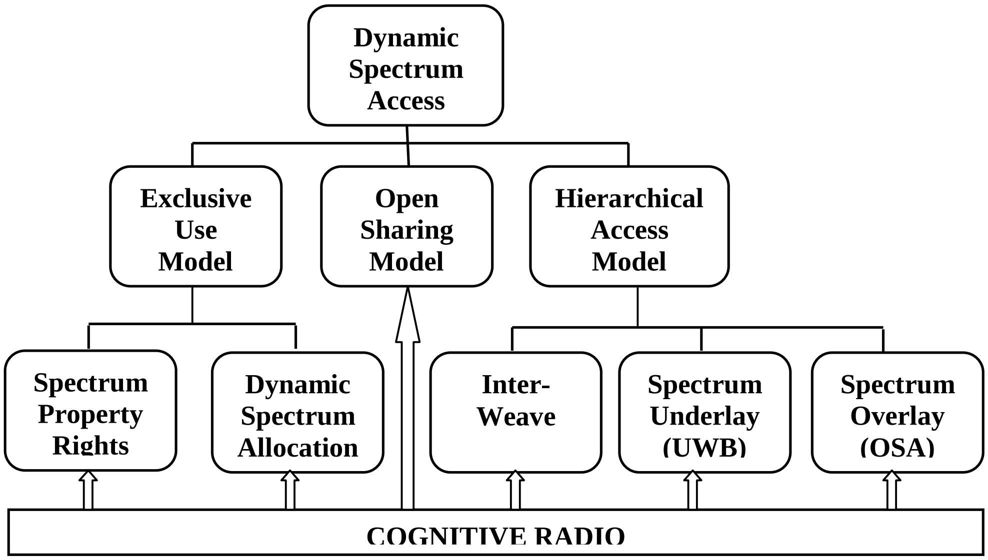

Figure 4. Dynamic Spectrum Access Models

3.1.1. Dynamic Exclusive Use model

The basic structure of the current spectrum regulation policy are maintained in this model: Spectrum bands are licensed to services for exclusive use. The main concept is to improve spectrum efficiency by introducing flexibility. Two approaches have been considered under this model [5]: i) *Spectrum property rights* and ii) *dynamic spectrum allocation*. *Spectrum property rights* approach allows licensees to sell and trade spectrum and to choose technology freely. Therefore, economy and market will play a more important role with the most profitable use of this limited resource.

Dynamic spectrum allocation approach aims to improve the efficiency of spectrum through dynamic spectrum assignment by using the spatial and temporal traffic statistics of different services i.e., spectrum is allocated to services for exclusive use in a given region and at a given time.

3.1.2. Open Sharing Model

Open sharing model is also called spectrum commons model. In spectrum commons model, every user has equal rights to use the spectrum. This is also known as open spectrum model, has been successfully applied for wireless services which operates in the unlicensed industrial scientific and medical (ISM) radio band (e.g., WLAN). Open sharing among users as the foundation for managing a spectral region used by this model [12]. There are three types of spectrum commons model [9]: i) Uncontrolled- commons, ii) Managed-commons and iii) Private-commons.

i) Uncontrolled-commons: When a spectrum band is managed and uses the uncontrolled commons model, no entity has exclusive license to the spectrum band.
ii) Managed-commons: Managed-commons represent an effort to avoid the tragedy of commons by imposing a limited form of structure of spectrum access. This is a resource which is owned or controlled by a group of individuals or entities and it is characterized by restrictions on when and how the resource is used.

iii) Private-commons: The concept of Private Commons was introduced by FCC in its Second Report on the elimination of barriers to development of Secondary markets for spectrum [14]. This concept grew on allowing use of advanced technologies which enable multiple users to access the spectrum.

3.1.3. Hierarchical Access Model

In hierarchical access model, SUs use the primary resources such that the interference to the PU is limited. There are three approaches under this model [15]: *Inter-weave, Underlay and Overlay.*

Inter-Weave: The inter-weave model is based on the idea of on opportunistic re-use the spectrum in the spatial domain i.e., the primary spectrum is utilized by CRs in the geographical areas where primary activity is absent. Exploitation of the so called "spatial spectrum holes" is attracting an interest, since many current licensed systems like, e.g., TV broadcasting and cellular systems. Figure 5 [15] shows where "CR 1" can ideally serve some of the SUs because no PU activity is present in its proximity.

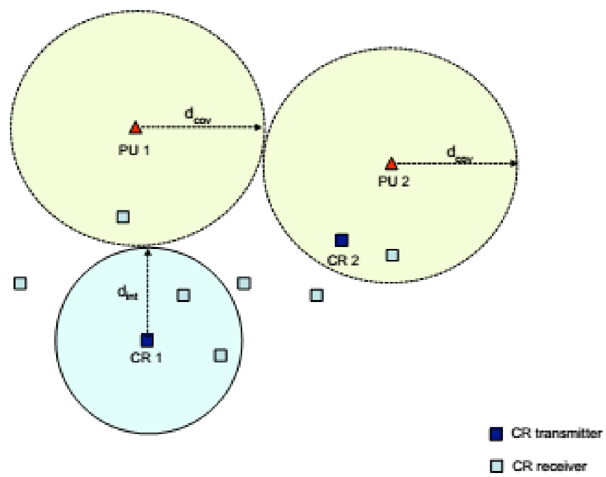

Figure 5. Exemplification of spectrum opportunities.

Underlay: Underlay technologies operate in the used spectrum at a very low power level for other licensed or license exempt uses but does not impair the users. Underlay use is not licensed [16]. Underlay access ideated CRs to operate below the noise floor of the PUs, involving an undercurrent of Cognitive Radio communications without PUs being aware of.

Overlay: An overlay approach allows higher powers that could result interference to existing users but overcomes this possibility by only permitting transmissions at times or areas where the spectrum is currently unused [16].

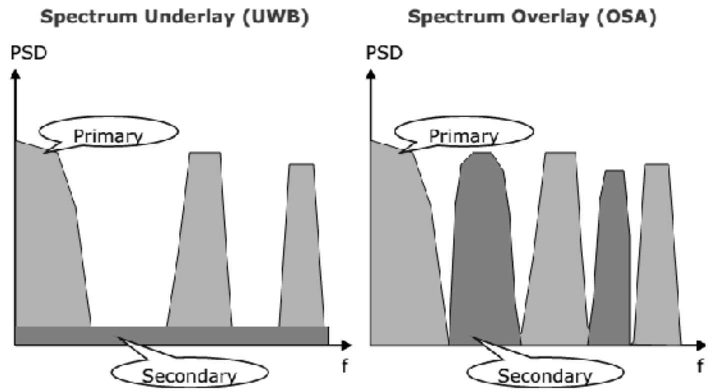

Figure 6. Spectrum overlay and underlay approaches

Secondary CR user can transmit with a high transmitting power to increase their rates for giving spectrum opportunities in spectrum overlay approach however they have to find the idle frequency bands which are unused by PUs. Similarly, in spectrum underlay approach, the SUs do not need to find the spectrum opportunities and can transmit at the same time coexisting with primary users however they are not permitted to transmit with high transmitting power even if the entire RF band is idle (entire RF is not used by primary users). Therefore overlay is known as interference model where underlay is known as interference avoidance model [9].

4. Methods Of Dynamic Spectrum Access

There are many methods of DSA which work based on these models and discussed below.

4.1. Game Theoretic Approach

Game Theory can be explained as a mathematical framework consisting models and techniques used to analyze the iterative decisions behavior of individual's interest about their own benefit. This is a mathematical tool that is analyzed and planned the interaction among the multiple decision makers. Three major components are there in the following form
G=<N, A, { u_i } > [17].

i. **Decision Makers (N):** Each game is considered to have a finite number of decision makers or players N.

ii. **Action Space (A):** Every player 'i' has its own action space (Ai) which is the set of actions including all possible actions that player can choose. The total action space 'A' is calculated by multiplying all action sets [17].

$$A = A_1 \times A_2 \times A_3 \times \ldots. \times A_N \quad (4.1.1)$$

iii. **Utility Set (U):** this is a set consisting utility or payoff functions for all players [17].

$$U = \{ U_1, U_2, U_2, \ldots\ldots U_N \} \quad (4.1.2)$$

The games are generally divided into two types, cooperative games and competitive games [5],

1) Cooperative Games: all players are interested about all the overall benefits, not very worried about their own personal benefit. Few recent works in Cognitive Radio uses cooperative game theory to reduce transmitting power of SUs to avoid generating interference to PU transmissions. The well known property of game-theoretical approaches is called Nash Equilibrium (NE). In NE, each player is considered to know the equilibrium strategies of the other players, and none has anything to gain by changing strategy [10]. Each rational network users only cares about own benefit and chooses the optimal strategy which can maximize his/her pay off function and such outcome is termed as *Nash Equilibrium* in non-cooperative spectrum sharing game [9].

2) Competitive Games: Each user is mainly concerned about his personal payoff, therefore all decisions are made competitively and selfishly. These concepts have been extensively used in spectrum allocations for Cognitive Radio networks where the Primary User and Secondary User participating in a game. To choose strategies that maximize their individual payoffs they behave rationally [10].

4.2. A Measurement-based Model for Dynamic Spectrum Access

In [18], A Measurement-based model is considered a Semi-Markov model which captures the behavior of WLAN so good enough to be used for obtaining optimal control strategies within a decision frame work and it is based on actual measurements in the 2.4GHZ ISM band using a vector signal analyzer to get complex base band data. A setup is shown figure 7 [9].

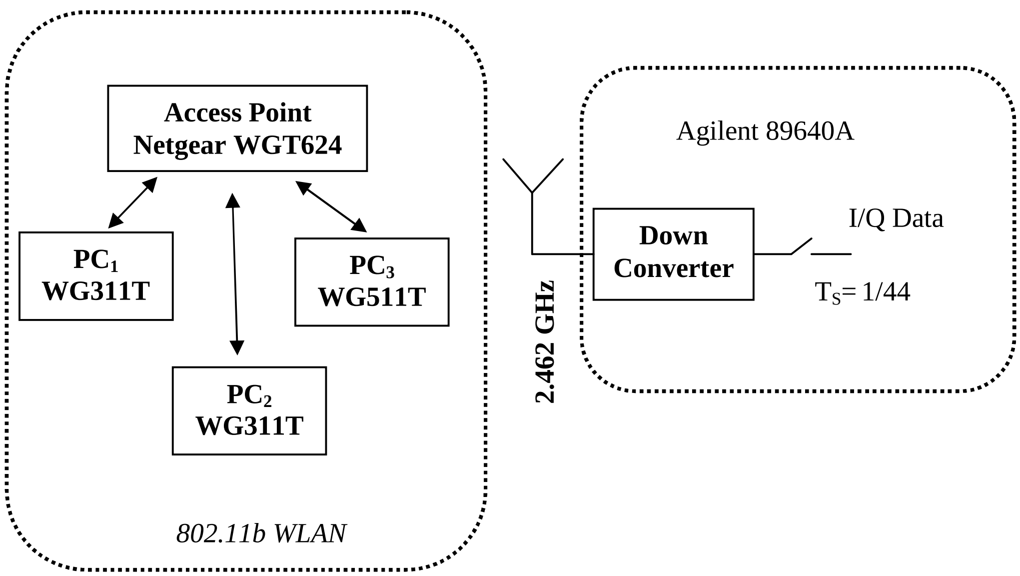

Figure 7. Measurement Setup

Different from existing publication a commercial WLAN adapter card is used to obtain packet trace but here a vector signal analyzer (VSA) is used to capture the raw complex baseband data. These data have to identify busy and idle periods of the channel.

There is a wireless router (Netgear WGT624) and three computers with wireless adapter cards (two Netgear WG311T and one WG511T) in the WLAN [9].

After capturing the transmission of WLAN, vector signal analyzer collects the complex data base band samples and it internally down converts 2.462GHz to an internal Intermediate Frequency at a sample rate of 44MHZ. Continuous-time Semi-Markov process allows an arbitrary specification of temporary time distribution in each state. A Semi-Markov process is a stochastic process whose behavior of transition is characterized in two steps.

i) the transition between states follow a markov chain and defined by transition matrix in Equation 4.2.1, where P_{ij} denoted the probability that transition occurs from state 'i' to state 'j'.

$$\boldsymbol{P} = \begin{bmatrix} P_{11} & \cdots & P_{1n} \\ \vdots & \ddots & \vdots \\ P_{n1} & \cdots & P_{nn} \end{bmatrix} \qquad (4.2.1)$$

ii) given that the system is in state 'i' and will transition to state 'j', the sojourn time t in state 'i' is distributed according to cumulative distribution function Q_{ij} (t). The estimator in Equation 4.2.2

$$\boldsymbol{P_{ij}} = \frac{n_{ij}}{n_i} \qquad (4.2.2)$$

In which the transition count n_{ij} is the number of transitions 'i' → 'j' occurring in our observation Sequence. Similarly

$$n_i = \sum_k n_{ik} \qquad (4.2.3)$$

Where $\boldsymbol{n_i}$ the number of times that the system resides in state i.

The state sequences DATA→SIFS→ACK are deterministic (the corresponding transition probabilities are very close to one) in high SNR transmission between the nodes and no hidden terminals are there. Therefore, it is possible to make easy the model by putting these states together. While this model prevents occurrence of collisions, retain good accuracy because collisions are infrequent. The Markov model is as shown in Figure 8.

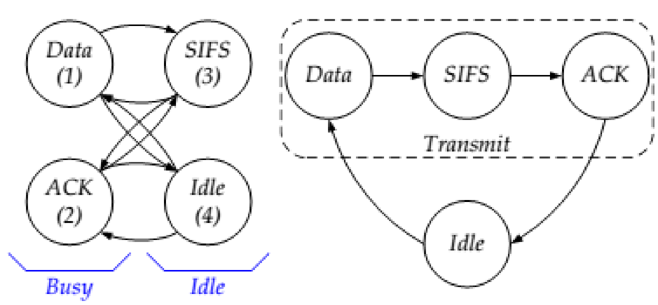

Figure 8. Proposed Markov model. The lumped model (with deterministic DATA→SIFS→ACK transitions is shown on the right).

In Figure 8 'transmit' state (a lumped version of DATA, SIFS, and ACK), and an idle state is shown. The transition probabilities of this simplified semi Markov model is not now worth considering, because an idle period Continuous time Semi-Markov model follows every transmit state and captures the idle periods remaining between the burst transmissions of the wireless LAN. This model exhibits a good compromise between accuracy and computation complexity.

4.3. Dynamic Spectrum Access Using a Network Coded Cognitive Control Channel

Network coding is introduced for data dissemination in wireless networks to increase throughput, robustness and decrease delay. Store, code and forward technique are provided in network coding where each node stores all the incoming packets in an internal buffer and successively sends their linear combinations, where combining is performed over some finite Galois Field. For example, n packets, a node must collect at least n independent combinations of the original packets. A high throughput gains in multicast or broadcast networks are provided in this way [19].

Dynamic Spectrum Access scheme allows the users opportunistically access the channels available for communications efficiently. There are four important aspects of opportunistic spectrum access: 1) implementation of the control channel, 2) multi-channel medium access control, 3) primary user detection, and 4) secondary reuse of spectrum unused by primary users [20]. All secondary users visit all channels in a pseudo random fashion and exchange control information whenever they come across in any channel.

A resource allocation algorithm run independently by each user, transmission opportunities only on free channels are assigned. This method is completely distributed and it does not need allocated spectrum resources for control purposes but rather leverages of the virtual control channel which is carrying out network coding techniques and exploit a cooperative detection strategy to identify unused spectrum. This results a degradation of the spreading performance of network coded cognitive control channel-DSA with respect to NC4-MAC.

The Most important aspects of the extended version NC4-DSA are the following [20]:

i. In each allocation period, primary user detects and tracks the varying pattern of primary user's activity over all channels.

ii. Each user gathers the detection information during an allocation period is to be sent to all users using the control channel.

iii. Cooperative detection is performed independently by each user using the same deterministic algorithm; so, all users will be able to infer the same set of free channels which are correctly decoded the control information.

iv. The resource allocation algorithm assigns transmission opportunities only on free channels which is run independently by each user and some users will still be instructed to switch to busy channels for primary user detection purposes.

The performance evaluation of NC4-DSA with respect to primary user detection, interference performance, the spectrum reuse efficiency of the secondary users and good put in dynamic spectrum access are shown in Figure 9, Figure 10, Figure 11, and Figure12.

In figure 9 the value of the signal to noise ratio of the primary user is $\gamma \in \{0,5\}$ dB. The normal probability scale is used for both axes; cooperative detection strategy allows to achieve significant improvements in the achievable tradeoff between primary user detection and false alarm probability. The detection improves with increasing Ns and S.

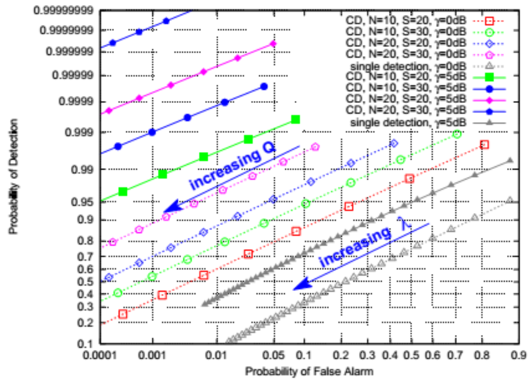

Figure 9. Primary user detection (λ - energy threshold parameter, Q- detection count threshold)

In [19] the performance for secondary spectrum access is shown by the "CD" curves in Figure 10 and Figure 11, where we plot respectively P_{interf} and P_{reuse} as a function of the mean activity duration $\ell_1 = 1/\beta$ and inactivity duration $\ell_0 = 1/\alpha$ of the PU respectively, for a example with C = 10, $\pi_1 = 0.7$ and $\lambda_{CD} = 5$ dB. For each combination of N and γ a value of the threshold count parameter Q was chosen to yield a good tradeoff between P_{cd} and P_{cf} ; the chosen value is seen in the figure

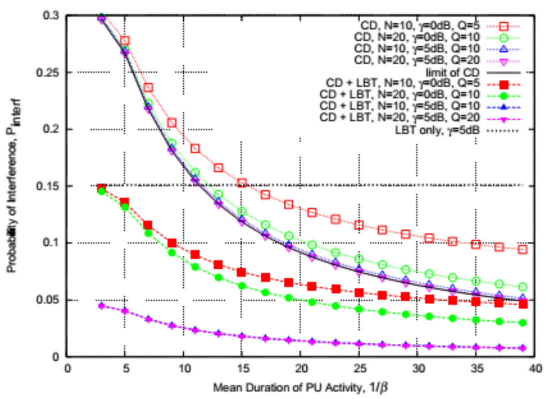

Figure 10. Probability of interference to the PU caused by CRs.

Figure 10 shows that P_{interf} decreases when ℓ_1 increases, since the longer activation period of the PU allows CRs to detect it and avoid interfering with it and for most values of N and γ, the performance obtained by the cooperative secondary spectrum access scheme is very close to the limit performance of P_{interf} and P_{reuse}.

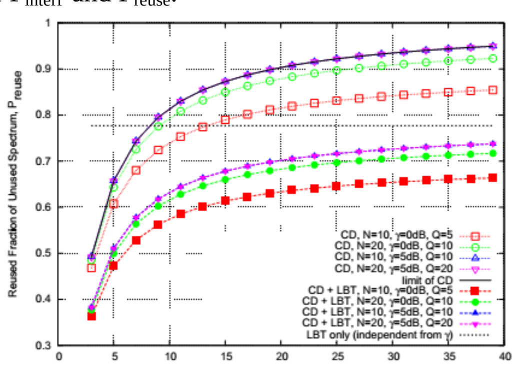

Figure 11. Efficiency of secondary reuse of spectrum unused by the PUs.

Figure 12 shows that also the probability of successfully reusing unused spectrum depends on the mean duration of the inactive period of the PU. Secondary spectrum access scheme is more successful when the PU stays idle for longer periods. Again, the performance is best possible when γ = 5 dB, and is in general rather close to the performance limit, with the exception of the case N = 10 and γ = 0 dB which suffers from weak performance of both single detection and CD. Therefore, both P_{interf} and P_{reuse} have a very weak dependence on the steady state activation probability π_1 of the Primary User.

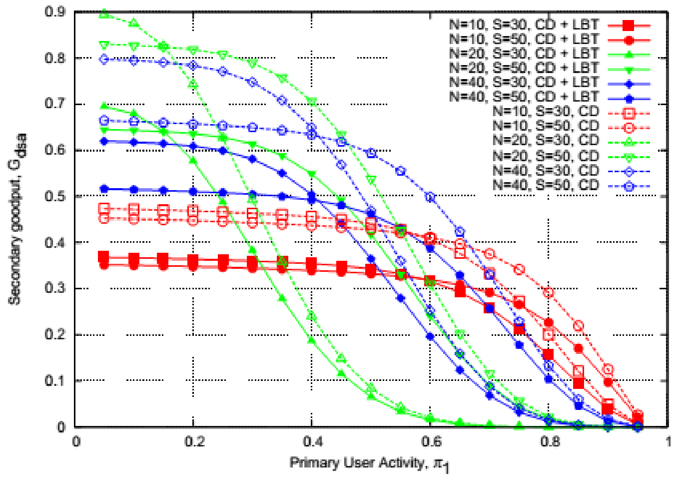

Figure 12. Goodput for secondary spectrum access

The Good put performance of NC4-DSA for both the original "cooperative detection only" version and the "cooperative + LBT" variant. The performance is shown in Figure 11, function of the primary user activity π_1 for C = 10, γ= 5 dB, λ_{CD}= 5 dB, ℓ_1= 35, T_{all}/T_{ctrl}= 600, and λ_{LBT} =3 dB (when LBT is used). The effect on the detection of the PUs and the reuse efficiency of unused spectrum on the overall good put is limited, since detection works almost perfectly with the value of S (slot) that is practical for the dissemination of control information in the primary / secondary description; this effect does not increase in π_1[9].

4.4. Fuzzy Logic Based System

Fuzzy logic provides a way to get the solution to a problem based on inaccurate, noisy, and incomplete information. Fuzzy logic uses a set of fuzzy membership functions and indirect rules to obtain the solution that meets objectives desirable. There are three important parts in a system of control of fuzzy logic: 1) fuzzifier, 2) fuzzy logic processor and 3) defuzzifier. The fuzzifier is used to plot the actual inputs by making them fuzzy, the fuzzy logic processor provides an inference engine to get a solution based on sets of predefined rules, and the defuzzifier is applied to convert the solution to real output [10].

Fuzzy logic is a multi-valued logic. Many input parameters are used to take the decision. Here distance, signal strength, velocity and spectrum efficiency are known as input parameters. The chance of taking decision is increased if the channel (offered by PU) signal is high and distance between PU and SU is low. If the distance is small, the velocity increases the chance of the spectrum accessing is more [9].

4.5. Spatio-Temporal Spectrum Management Model

Spectrum scarcity problem is due to the inflexibility of spectrum allocation regime, a more suitable spectrum allocation is adapted to the spatio-temporal bandwidth demand which will increase the spectrum availability, solving the (inexistent) spectrum scarcity problem. Figure 13 shows Spatio-temporal dynamic spectrum access model. In this model [8], the service area is divided into multiple regions. In the region 'k', network service provider 'i' provides wireless services to users, and spectrum demand for this service provider is denoted by D_{ik}. The spectrum of a given region is owned by RSB (Regional Spectrum Broker) which grants short time licenses for the requesters [21].

In TDSA (Temporal Dynamic Spectrum Allocation) method, the demands for spectrum to RSB are sent by the service providers of the region. The RSB allocates continuous spectrum blocks to the requesters and the blocks are separated by guard bands.

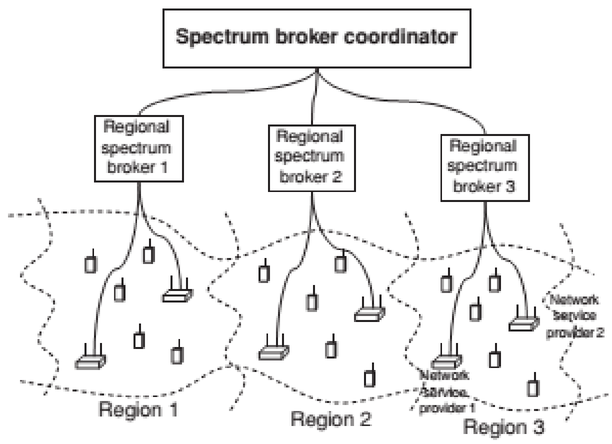

Figure 13. Spatio-temporal dynamic spectrum access model.

The Spectrum Dynamic Spectrum Allocation (SDSA) deals with spectrum demands coming at the same time in different regions. The main objective of the SDSA is adjusting the different demands within different regions on the way, where the least interference occurs in the overlapping regions. Figure 14 and Figure 15 [9] shows the simulation results. In region 1 the demand of NSP_1 is larger than that of the region NSP_2 and in region 2, it is just opposite way. The numbers of carriers which are used by the providers in both regions as a function of time. The excess spectrum is required to satisfy the demands in the case of overhearing, which is denoted by a darker tone shown in the Figures.

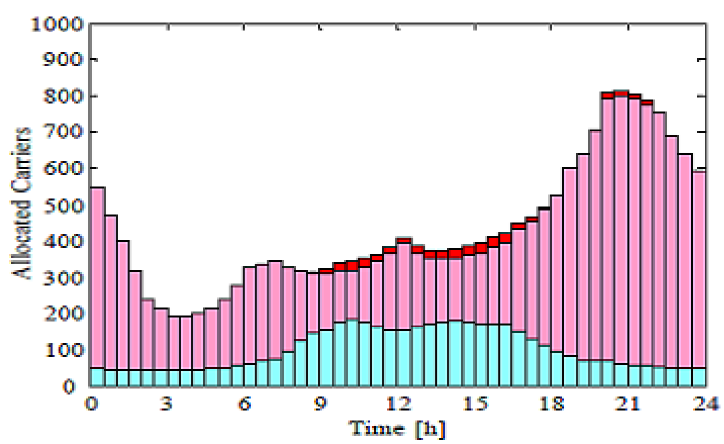

Figure 14. Allocated spectrum sizes for both providers in region 1.

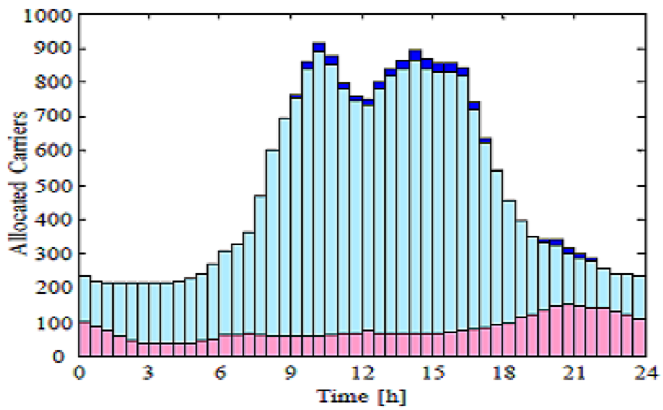

Figure 15. Allocated spectrum sizes for both providers in region 2

4.6. Markovian Queuing Model for Dynamic Spectrum Allocation

Centralized architecture is used in Markovian Queuing model for dynamic spectrum allocation. In centralized network the central controller of an ad-hoc network allocates bandwidth to intended users. This CR ad-hoc network assumes to coexist with the network of licensed users where the controller of licensed user is updated with the CR coordinating engine. A centralized network eliminates hidden terminal problem, obtains complete database of unoccupied frequencies and provide better coverage and efficiency spectrum handover technique. Each SU consists of two transceivers, one is dedicated to control and another is software defined radio based. The SDR based transceivers scan the availability of spectra in its area and forward the information of these spectrum holes to the central controller in case Secondary User form an infrastructure less network or to the Base Station in case of infrastructure based network. Figure16 [22] shows the equivalent model of network queues.

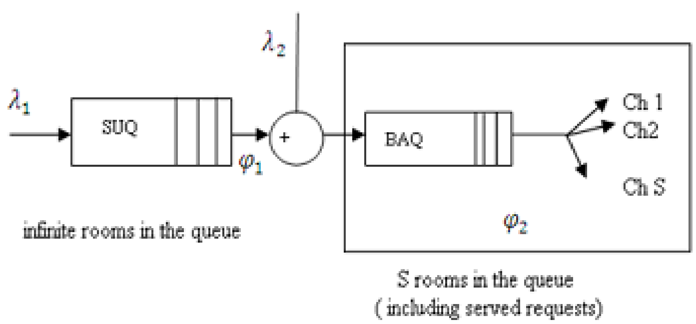

Figure 16. Queuing Model for DSA in Cognitive Radio

These queues are in the special case of stochastic processes, characterized by the arrival process of service requests, waiting list of requests which are to be processed. The queue stacking all the entries of SUs is referred to SUQ and the entire request entering this queue are served on the first come first serve basis. At any time when bandwidth needs to be allocated to the Secondary User, the head considers both the request from the SU and the PU, who needs it licensed channel. Therefore while distributing a number of frequencies for Primary User and Secondary User; the arrival rates of both the users are added to access the frequencies with the head. This queue so formed is known as bandwidth allocation queue (BAQ). Markov process is used to study the Queuing model. The blocking probability P_B (the probability that an SU request denied) for the bandwidth request made by Cognitive Radio that finds all the channels with head as occupied is given by Erlang-B formula

$$P_B \equiv P_S = \frac{\rho_2^s}{S! \sum_{i=0}^{s} \frac{\rho_2^i}{i!}} \qquad (4.6.1)$$

Figure17 [9] shows the Blocking Probability. Variation in P_B with change in number of available channels in the system as 2, 5, 7, 10, 13, and 15. Blocking probability increases with the increase in SU traffic in the network.

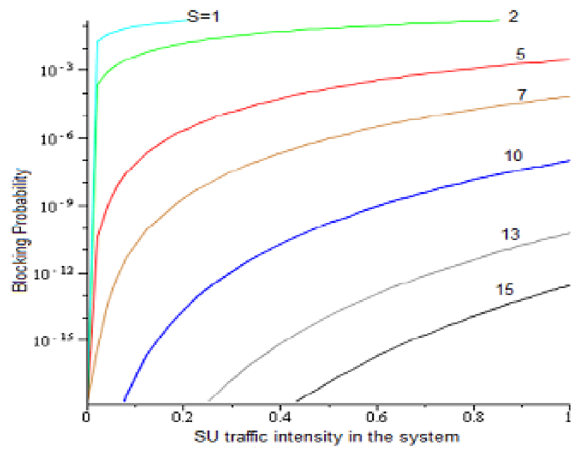

Figure 17. Blocking probabilities (P_B) Against SU utilization in the system (ρ_1). The Variation in P_B is depicted with different numbers of channels (S), available with the system.

5. CONCLUSIONS

Cognitive radio is a paradigm for wireless communication where transmission or reception parameters are changed by a network or a wireless node to communicate efficiently and avoid interference with licensed or unlicensed users. Here different dynamic spectrum access models are discussed. Game theoretic approach is an important and one of the most authentic approaches in studying, modelling and analyzing the Cognitive interaction process. It has been used to a large degree for spectrum sharing and become an interesting field of research for spectrum management in the context of Cognitive Radio. Game theory is the most acceptable technique to obtain the equilibrium solution to the problem of the spectrum sharing, as obvious from the discussions earlier in the paper.

A Measurement based model uses the continuous time semi Markov model which captures the idle periods remaining between the bursty transmissions of a wireless LAN. This model provides a good compromise between accuracy and computation complexity. In the Markovian queuing model a centralized architecture coexisting with licensed users is proposed for bandwidth allocation and to find blocking probability. The sensing is taken into account to be decentralized to overcome hidden terminal problem and to get a complete database of unoccupied frequencies. The delay performance of threshold policies is to minimize the delay of Secondary User subject to a Primary User collision probability constraint. Spatio-Temporal spectrum management model simplifies the problem of spectrum allocation and described architecture that splits up the complex problems into temporal and spatial parts (TDSA and SDSA). Problem of interference in the overlapping regions can be handled based on the information of Regional

Service Broker. This model gives a solution to find an optimal spatio-temporal allocation. It can be concluded that Game theoretic approach is the most acceptable tool for CR systems. Further study can also be done for if any model can be derived using Game theory and Measurement model which may provide more accurate and realistic results.

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