Optimal Sensing for Opportunistic Spectrum Access in Cognitive Radio

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Abstract

One of the most difficult thing but important problem when designing an OSA (Opportunistic Spectrum Access) MAC protocol is how the unlicensed users decide when and which channel they should sense and access without conflicting the communications among PUs. To solve this problem, the unlicensed users should have the ability of adaptively and dynamically seeking and exploiting opportunities in both licensed and unlicensed spectrum and along both of the time and the frequency dimensions. Secondary Users (SUs) as unlicensed users are required to sense radio frequency band, and when PU are detected, they must vacate the channel immediately within certain amount of time. Due to hardware and energy constraints, full spectrum availability cannot be sensed as well as they do not monitor when there is no data to be transmitted. In this paper, we study MAC protocol design and optimal sensing for OSA in Cognitive Radio (CR) ad hoc network under Partially Observable Markov Decision Process (POMDP) algorithm that maximizes achievable throughput for SUs with sufficient protection to PUs. The bandwith effect to number of bit transmitted in one slot and tractable greedy algorithm to reduce the complexity of POMDP calculation was studied as well. The derivation of greedy approach proves that sensing problem can be solved either optimally or approximate the optimal solution. Computer simulation is used to evaluate the performances both of optimal and sub optimal strategy.

Keywords: Dynamic Spectrum Access, Opportunistic Spectrum Access, POMDP, Greedy Algorithm, Cognitive Radio

1. INTRODUCTION

Dynamic Spectrum Access (DSA) systems are one of the most promising technologies available to increase the range and efficiency of spectrum dependent services [1]. DSA systems locate unused spectrum, and organize their users to operate within the spectrum they have identified. DSA systems ensure that no interferences to other users by scanning and sensing the spectrum environment, as the Defense Advanced Research Projects Agency NeXt Generation (DARPA XG) spectrum sharing field tests have established, or through pre-existing knowledge, such as the geolocation database proposed for unlicensed access to TV band white space, or a combination of both.[2]. Shortly, DSA affords the benefits to spectrum allocation problems such as providing the increased density, better system management, and inherent in-channel and co-site interference resolution as well as it enables opportunistic access to the spectrum for uncoordinated sharing of spectrum on a non-interference basis. In addition, the other projects related to DSA and CR networks that have been developed are DIMSUMnet project [3], DRiVE/overdrive project [4], E2R and E3 [5]. These projects aim to resolve the current inefficient usage of spectrum band and make the radio has the ability to intelligently recognize the status of radio spectrum environment and adaptively change its transmission parameter such as transmission frequency and bandwidth, power efficiency, and modulation scheme, etc.

According to the hierarchical access model, licensed spectrum is opened to SUs under the condition that it does not interfere with PUs beyond a certain probability of collision [6][7]. Spectrum underlay and overlay are two strategies allowing the coexistence of primary and secondary users. Underlay refers to the approach where the transmission power of SUs is limited to be less than the noise floor of PUs, whereas overlay does not limit the transmit power of SUs but imposes restriction on when and where SUs can transmit [8]. The hierarchical access model is likely the most compatible with the current spectrum management policies and provides better spectrum efficiency in the licensed bands.

OSA itself is referred to as DSA, and often included as part of the larger concept of cognitive radios. It has emerged as a way to dramatically improve spectrum utilization. The basic idea is to allow SUs to identify available spectrum and characterize the presence of PUs. According to that information, the unlicensed devices identify communication opportunities (spectrum holes) in frequency, time, or even code, and transmit using those opportunities in a manner that limits the interference perceived by PUs. Furthermore, the design of OSA MAC protocols imposes new challenges that are not considered in the conventional wireless networks. One of the most difficult but important problem in designing an OSA MAC protocol is how the unlicensed users decide when and which channel they should sense and access without conflicting the communication to PUs.

According to the network architecture, CR networks can be classified into the infrastructure based and ad hoc networks [9]. The infrastructure-based CR network has a central coordinator such as base station in cellular network or an access point in WLANs. The observations performed by each CR user feed to the CR base station and CR base station decides which channel CR user can access. Then, CR user reconfigures its communication parameter, i.e. power, type of modulation, etc. On the other hand, CR ad hoc network does not have any infrastructure backbone. Hence, CR users communicate with others through the ad hoc connection on both licensed and unlicensed spectrum bands.

CR MAC protocol has responsibilities to coordinate channel access to licensed bands. It enables multiple CR users to share the spectrum resource by determining who will access the channel and when it will be performed. This protocol design is necessary to accomplish the Quality of Service (QoS) of data transmission. In [10], CR MAC protocol for ad hoc network is classified into three classes, which are random access, time slotted, and hybrid protocol. Random access protocol does not need time synchronization, and generally based on Carrier Sense Multiple Access Collision Avoidance (CSMA/CA) principle. CR user monitors the spectrum bands to detect whether there is transmission from the other CR users. Data packet is transmitted after back off duration. Time slotted protocol need network wide synchronization, where time is divided into slots for both the control channel and the data transmission. Meanwhile, hybrid protocol is combination of random access and time slotted protocol. This protocol uses a partially slotted transmission, in which the control signaling generally occurs over synchronized time slots and random channel access for data transmission. POMDP frameworks for CR was proposed in [11] as one of hybrid protocol model for CR MAC, where limited sensing capabilities of CR imply that only part of channel can be sensed at one time. The adopted approach integrates the design of spectrum access protocol at the MAC layer with spectrum sensing at the physical layer and traffic statistics determined by the application layer. A similar approach is used in the CR access scheme in [12].

Most of the previous works on the throughput of CR user focus on the fundamental tradeoff between sensing capability and achievable throughput. In [13] throughput of SU relating to sensing time in local and cooperative spectrum sensing was investigated under two distinct scenarios, Constant Primary User Protection (CPUP) and Constant Secondary User Spectrum Usability (CSUSU). Furthermore, the throughput enhancement by implementing cooperative sensing strategy was proposed in [14]. The presented simulation results show that the effectiveness of the proposed sensing strategy improves the throughput of CR users and decreases the interference to the PUs. The design of sensing slot duration to maximize the achievable throughput of SUs under the constraint that PU is sufficiently protected was studied in [15]. Using energy detector, the author presented the trade off between sensing time and achievable throughput of SU.

In this paper, we study optimal sensing strategy that maximizes bit transmitted of SUs based on POMDP model and under the constraint that PU is sufficiently protected. We focus on study of cognitive MAC protocol design for OSA where each SU must sense the channel intelligently by statistical traffic behavior and decide to transmit the data based on the sensing outcome. The rest of the paper is organized as follows. In section II, we give description of policy strategy for optimal and sub optimal in channel sensing and access. The detail system model is described in section III. The numerical results and discussion are presented along with some comparisons in section IV. Finally, conclusion and future works are presented in the following section.

2. POLICY STRATEGY

Decision-making is the cognitive process leading to the selection of action among variations. One-way to automate the decision making process is to provide a model of dynamics for the domain in which the machine will be making decisions. A reward structure can be used to motivate immediate decision that will maximize the future reward.

POMDP is an aid in the automated decision-making. POMDP policy informs CR users what action to be executed. It can be a function or a mapping and typically depends upon the channel states. In this section, we provide detail formulation of policy strategy either optimal and sub optimal based on greedy approach for sensing decision.

2.1 Optimal Strategy

Channel access based on POMDP is known as an optimal strategy which model the channel opportunity of network system as discrete time Markov chain with number of channel state and formulate as $M=2^N$ states, where N is number of channel. The state diagram for N=2 is described in figure 1 where $\bar{\alpha}_i = 1 - \alpha_i$ and state (0,1) indicates the first channel is available and the second channel is busy. The term of partially observable mean that CR user selects set of channels to be sensed and set of channels to be accessed based on sensing outcome. This objective is to maximize the throughput of SUs under the constraint of interference to PU by exploiting the sensing history and the spectrum occupancy statistics.

The design of OSA protocol that maximizes the throughput of SU can be formulated as POMDP over finite horizon. It is defined by tuple {S,A,P,Θ,,R}, where S denotes a finite set of states with state i denoted by s_i, A denotes a finite set of actions with action i denoted by a_i, P denotes the transition probabilities $p_{i,j}$ for each action in each state as function of $\{\alpha_i, \beta_i\}_{i=1}^{N}$ which describes the channel availability of PU networks, R denotes the reward structure $\left(r_{j,A_1,A_2}\right)$ which is defined as number of transmitted bits in one slot when CR user take an action, and Θ is observation where SUs observe the availability of channel at state j, $\Theta_{j,A_1} \in \{0,1\}^{|A_1|}$. The reward is proportional to its bandwidth and formulated as follows:

$$r_{j,A_1,A_2}(t) = \sum_{i \in A_2} S_i(t) B_i \tag{1}$$

Figure 2 shows Markov dynamics process model where observations are made after an action is taken. Equivalently, observation could have been taken before actions.

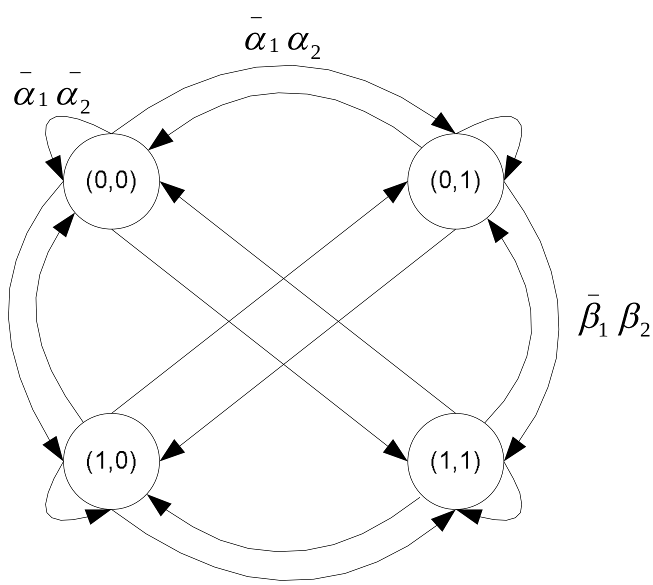

FIGURE 1: State diagram for N=2 as Markov process model

In POMDP model, the system state is not directly known, however CR users can observe to learn the most likely state. The observation yields the current system state. Then, the information state, also known as belief vector $\pi = (\pi_1, \ldots, \pi_M)$, aids in determining the most likely state of primary network by storing all previous actions and observations in a summary statistic. The belief vector is probability distribution over state of the channels.

Belief vector π is a sufficient statistic for the optimal policy and behaves as a discrete time continuous state Markov process. The users observe with distribution probability under system channel states. The information state is updated after each action and observation with the application of Bayes' rule as follows:

$$\pi'_j = \frac{\sum_{i=1}^{M} \pi_i \ p_{i,j} \ \Pr\left[\Theta_{j,a} = \theta\right]}{\sum_{i=1}^{M}\sum_{j=1}^{M} \pi_i \, p_{i,j} \ \Pr\left[\Theta_{j,a} = \theta\right]} \tag{2}$$

The resulting information state is vector of probabilities computed using the above formula and the information transformation function is given by

$$\pi' \cong \left[\pi'_1, ..., \pi'_M\right] \cong \tau\left(\pi | a, \theta\right) \tag{3}$$

In POMDP model, the policy maps the information states into action and maximizes the expected total reward. There are an infinite number of information states, since it is probability distribution over all states and stores the policy or value function in the form of tables. The maximum value function for all actions is given by the following formula:

$$V_t(\pi) = \max_{a=1,...,N} \left\{ \sum_{i=1}^{M} \pi_i \sum_{j=1}^{M} p_{i,j} \sum_{\theta=0}^{1} \Pr\left[\Theta_{j,a} = \theta\right]\left(\theta B_a + V_{t+1}\left(\tau\left(\pi | a, \theta\right)\right)\right) \right\} \tag{4}$$

Where $V_t(\pi)$ denotes the maximum expected reward that can be accrued in the remaining t decision intervals when the current information vector is π.

It is shown in [16] that $V_t(\pi)$ is piecewise linier and convex (PWLC) and can be written simply as

$$V_t(\pi) = \max_k \pi \gamma_k(t) \tag{5}$$

For some set of M dimensional column vectors $\{\gamma k(t)\}$. The set of γ-vectors represents one of linier pieces coefficient for piecewise linier function. These piecewise linier functions can represent the value functions for each step in the finite horizon POMDP problem. The value function drawn over the information state is shown in fig.3

2.2 Sub Optimal Strategy based on Greedy Approach

Due to the complexity of optimal policy computation when number of slot and channel increase, Q.Zhao et al in [11] proposes sub optimal protocol based on a greedy approach. They reduced the dimension of states from exponential to linear by regarding to N, i.e. from $M=2^N$ to N state. The recursive equation to maximize the expected reward is formulated as follows:

$$\begin{aligned} W_t(\Omega) &= \left(\omega_{a_*}\beta_{a_*} + \left(1-\omega_{a_*}\right)\alpha_{a_*}\right)B_{a_*} + \sum_{\theta=0}^{1} \Pr\left[\Theta_{a_*} = \theta | \Omega, a_*\right] W_{t+1}\left(\tau\left(\Omega | a_*, \theta\right)\right) \\ &= \left(\omega_{a_*}\beta_{a_*} + \left(1-\omega_{a_*}\right)\alpha_{a_*}\right)B_{a_*} + \left[\omega_{a_*}\left(1-\beta_{a_*}\right) + \left(1-\omega_{a_*}\right)\left(1-\alpha_{a_*}\right)\right] W_{t+1}\left(\tau\left(\Omega | a_*, 0\right)\right) + \\ &\left[\omega_{a_*}\beta_{a_*} + \left(1-\omega_{a_*}\right)\alpha_{a_*}\right] W_{t+1}\left(\tau\left(\Omega | a_*, 1\right)\right) \end{aligned} \tag{6}$$

where $W_t(\Omega)$ denotes the expected remaining reward starting from slot t achieved by greedy approach, $\tau\left(\Omega | a_*, \theta\right)$ denotes the updated information on channel availability given the observation θ under action a, and $\left(\omega_{a_*}\beta_{a_*} + \left(1-\omega_{a_*}\right)\alpha_{a_*}\right)$ denotes the probability of availability for channel a in slot t. The notation of a_* is the chosen action in slot t to maximize the expected immediate reward and given by

$$a_*(t) = \arg\max_{a=1,...,N} \left(\omega_a(t)\beta_a + \left(1-\omega_a(t)\right)\alpha_a\right)B_a \tag{7}$$

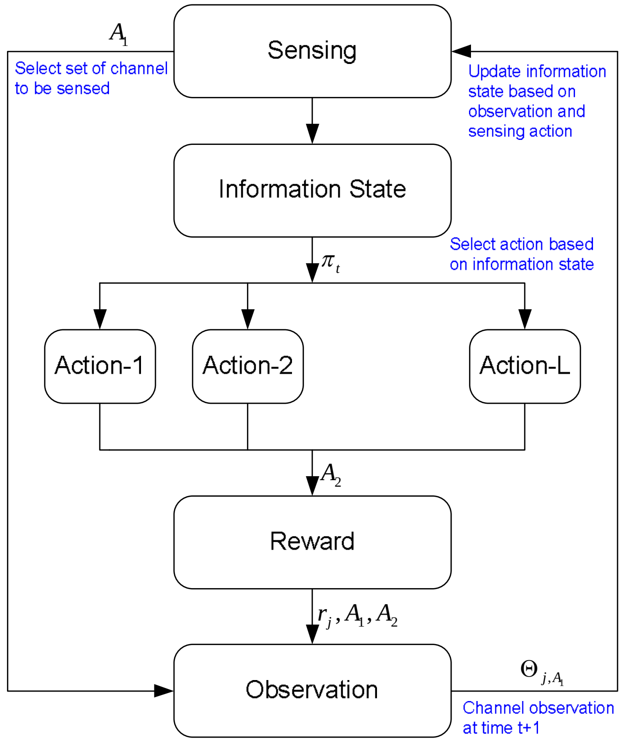

FIGURE 2: POMDP dynamic model

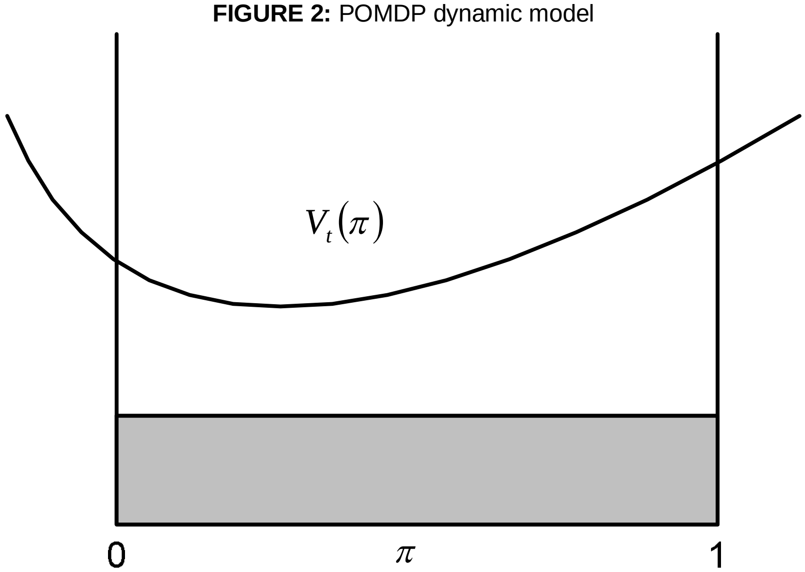

FIGURE 3: Value function drawn over information space

3. SYSTEM MODEL

The spectrum contains number of channel is licensed to PUs and have an authority to use it. However, when channel is not used, SUs can access the channel with prior to observe whether channel is available to avoid interference to PUs. We consider group of SUs sense and monitor primary channels which change depends on the time step and switch from occupied and unoccupied according to Markov chain. The existed channels are shared among PUs and a large of number SUs.

There are number of channels considered in this study and state of these channels change independently. Each channel has the bandwidth Bi (i=1,…,N). The state diagram and a sample path of the state evolution for N=3 are illustrated in fig.4. The state of channel $S_n(T)=\{1,0\}$ indicates that channel is busy and idle. In the system, transmission time is divided into slots of equal length T, where slot k refers to the discrete time period [kT, (k+1)T]. The structure of the each slot is described in fig.5. At the beginning of each slot, SUs sense set of the channels (L_1). Based on the sensing outcome, SUs will decide which channel to be accessed (L_2), where $L_2 \leq L_1 \leq N$. At the end of the slot, SU will send the acknowledgement signal that indicates successful transmission. The traffic statistics of the primary network follows a discrete time Markov process with number of states. Furthermore, secondary network is seeking spectrum opportunity in these N channels. Ad hoc network is assumed in which SUs sense and access the spectrum channel independently without exchanging local information.

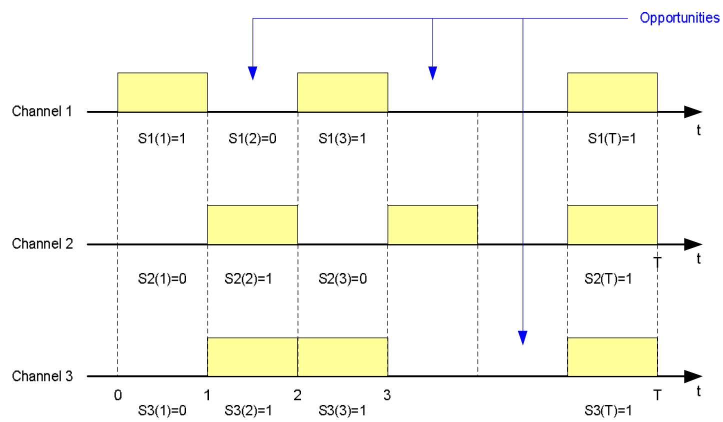

FIGURE 4: Spectrum occupancy for N=3

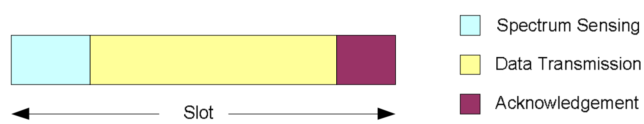

FIGURE 5: The slot structure

4. NUMERICAL RESULTS AND DISCUSSION

In this section, computer simulation results are presented to evaluate the performance of optimal and sub optimal based on the greedy approach with throughput metric as a function of slot number.

4.1 Optimal Cognitive MAC Protocol

This sub section presents the performance of optimal cognitive MAC based on POMDP model. We assumed that sensing errors is ignored in this simulation. Three channels are considered with the same bandwidth B=1 and number of slots (T) is 25. We have two cases with different transition probabilities (α,β). In case 1, probability of channel transition from idle (0) to busy (1) is 0.3, whereas channel remain unchanged from idle state is 0.7. Case 2 is the opposite of case 1, where the probability of channel remains unchanged (β=0.3) is lower than probability of channel transition (α=0.7).

As shown in fig.6 that throughput of SU increases over time in both cases. Due to the probability of channel remains unchanged in case 1 greater than case 2, hence the throughput of SU in case 1 is higher than case 2. Higher probability of channel remain unchanged cause case 1 has more time of data transmission than case 2 without interruption by transition of channel state. In fig.7, 8, and 9, we set the value of channel bandwidth (B) to 5, 10, and 20 respectively, and then keep the other parameters constant. The result shows that by increasing the value of channel bandwidth cause number of transmitted bit of SU over channel increases significantly.

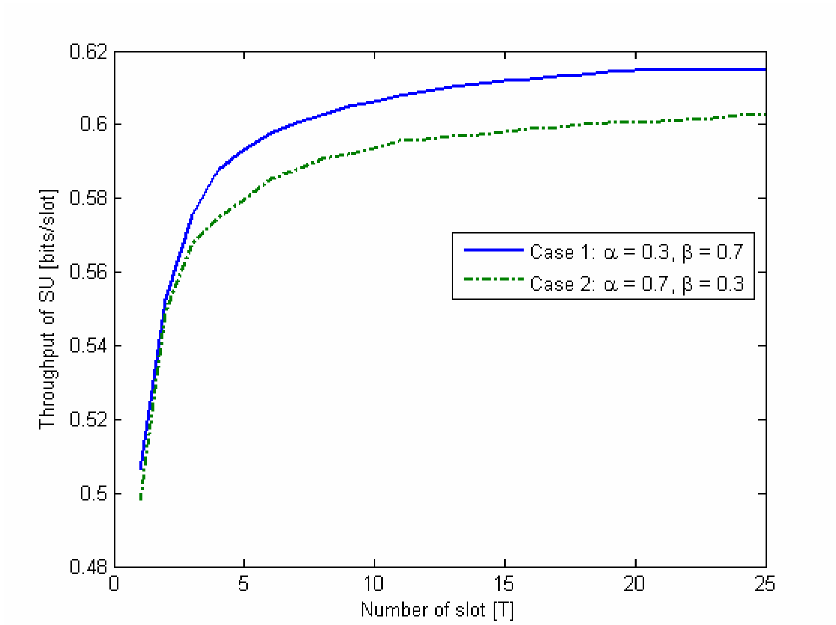

FIGURE 6: Achievable throughput of SU with parameter setup B=1, N=3, T=25

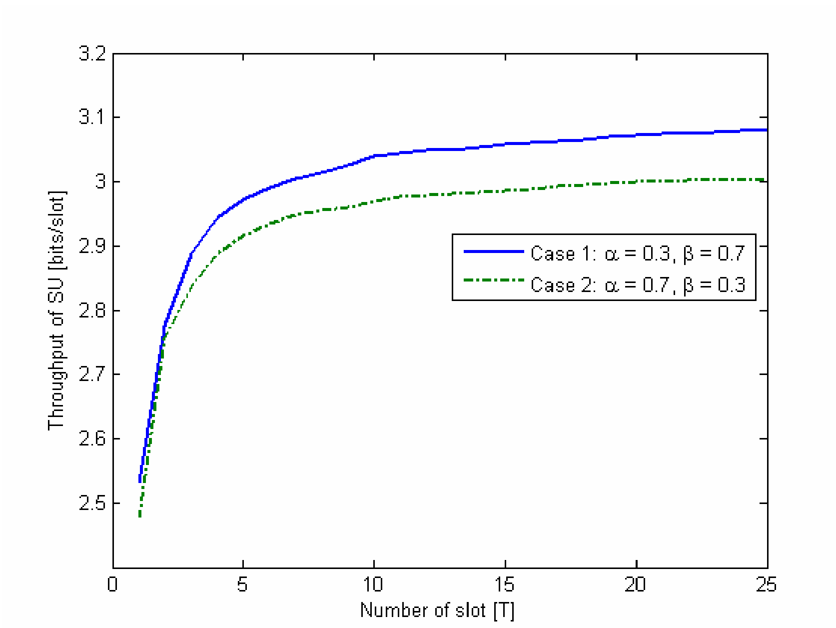

FIGURE 7: Achievable throughput of SU with parameter setup B=5, N=3, T=25

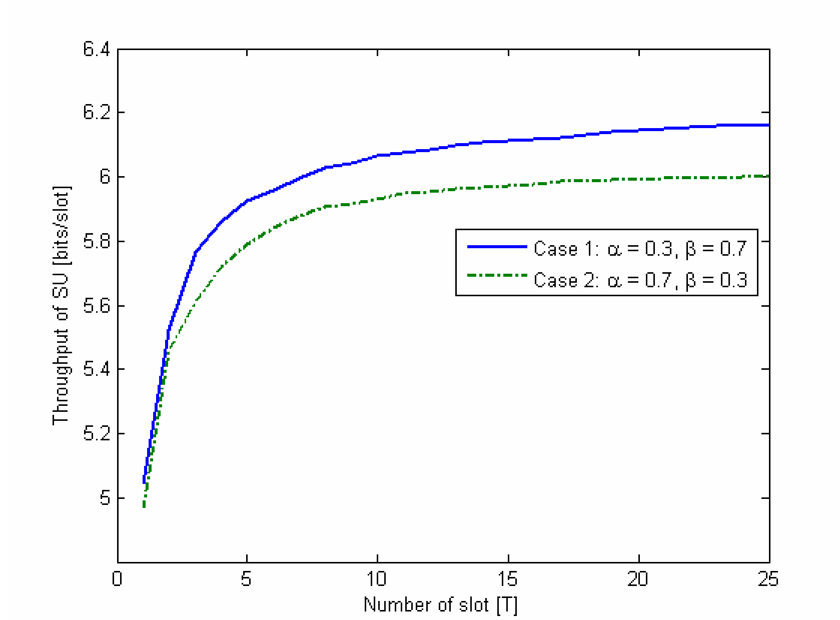

FIGURE 8: Achievable throughput of SU with parameter setup B=10, N=3, T=25

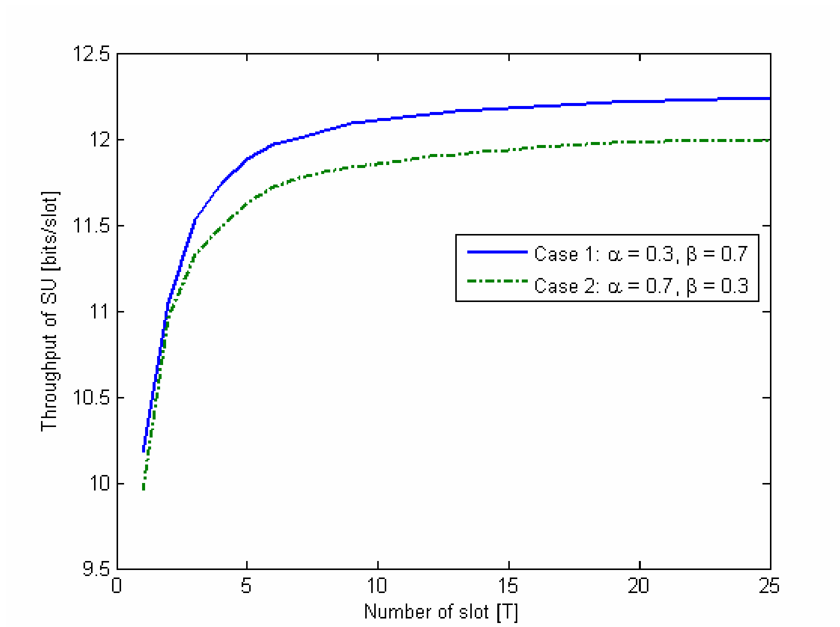

FIGURE 9: Achievable throughput of SU with parameter setup B=20, N=3, T=25

4.2 Sub-optimal Cognitive MAC Protocol

This sub section presents the performance of sub optimal strategy based on greedy approach as compared to the optimal strategy. The same as aforementioned parameters above that sensing error was ignored in this simulation. Three channels (N=3) is considered with the same bandwidth B=1, number of slots (T) is 25. Transition probabilities (α,β) were set to (0.2,0.8). According to fig.10, this simulation parameter setup yields the throughput of SU for greedy approach relatively match and nearly equal to optimal strategy. However, when setup is converted to multiple bandwidths B=[0.75,1,1.5] with different transition probabilities α_i=[0.8,0.6,0.4] and β_i=[0.6,0.4,0.2] as described in fig.11, the greedy approach has the performance loss.

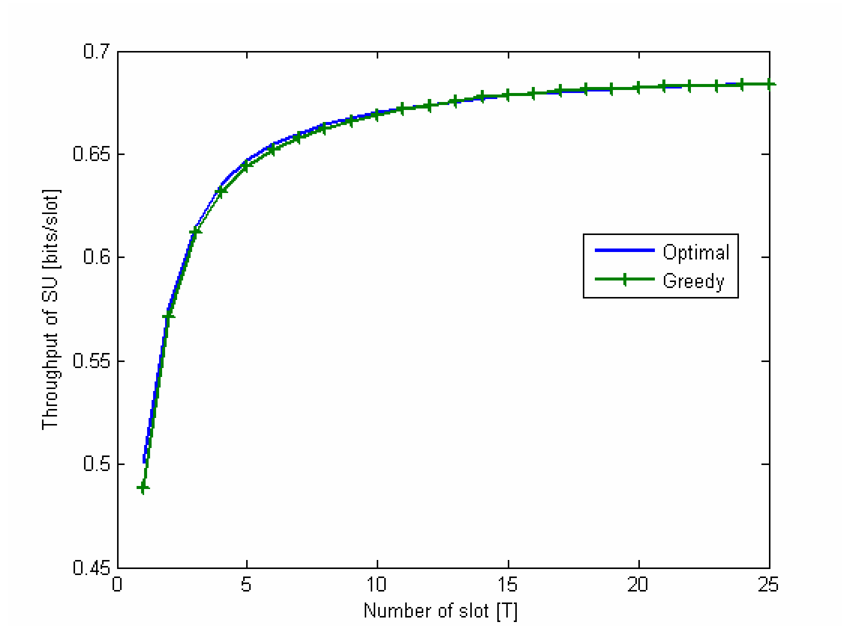

FIGURE 10: Performance comparison between optimal and greedy approach with parameter setup B=1, N=3, T=25, α=0.2 and β=0.8

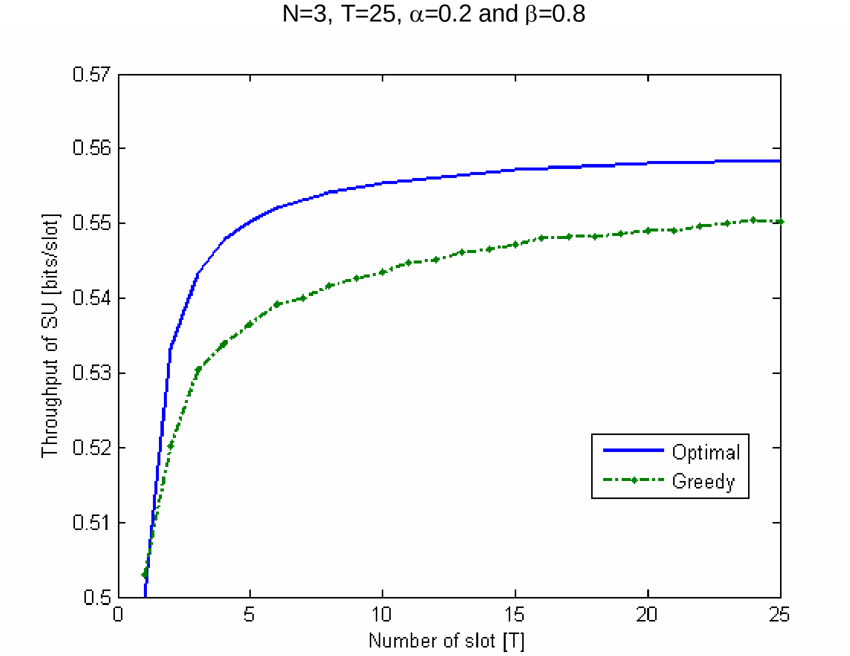

FIGURE 11: Performance comparison between optimal and greedy approach with multiple bandwidths [0.75, 1, 1.5] and transition probabilities α_i=[0.8, 0.6, 0.4] and β_i=[0.6, 0.4, 0.2]

5. CONCLUSION AND FUTURE WORKS

The performance of OSA in CR ad hoc network by considering SUs interest was studied. POMDP model was implemented to evaluate the throughput as function of slot number. The results show that the optimal strategy maximizes the average number of bits transmitted by the SU in T slots. Furthermore, increasing channel bandwidth cause number of bit transmitted in one slot increase significantly. Due to the complexity of POMDP model when channel increases, greedy approach as a sub optimal strategy was studied. It yields the throughput of CR user match and nearly close to optimal strategy. However, sensing errors are ignored in this study. Hence, in the future works, we will consider false detection and miss-detection in PU signal sensing. Then, cooperative signal detection technique will be implemented. Cooperative technique can improve probability of detection with less sensing errors where each CR users cooperatively sense primary channels. Furthermore, trade off between sensing action and throughput as well as kind of application such as multimedia application over CR networks will be further investigated.

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