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PERFORMANCE OF OPPORTUNISTIC SPECTRUM ACCESS WITH SENSING ERROR IN COGNITIVE RADIO AD HOC NETWORKS

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Abstract

Sensing in opportunistic spectrum access (OSA) has a responsibility to detect the available channel by performing binary hypothesis as busy or idle states. If channel is busy, secondary user (SU) cannot access and refrain from data transmission. SU is allowed to access when primary user (PU) does not use it (idle states). However, channel is sensed on imperfect communication link. Fading, noise and any obstacles existed can cause sensing errors in PU signal detection. False alarm detects idle states as a busy channel while miss-identification detects busy states as an idle channel. False detection makes SU refrain from transmission and reduces number of bits transmitted. On the other hand, miss-identification causes SU collide to PU transmission. This paper study the performance of OSA based on the greedy approach with sensing errors by the restriction of maximum collision probability allowed (collision threshold) by PU network. The throughput of SU and spectrum capacity metric is used to evaluate OSA performance and make comparisons to those ones without sensing error as function of number of slot based on the greedy approach. The relations between throughput and signal to noise ratio (SNR) with different collision probability as well as false detection with different SNR are presented. According to the obtained results show that CR users can gain the reward from the previous slot for both of with and without sensing errors. It is indicated by the throughput improvement as slot number increases. However, sensing on imperfect channel with sensing errors can degrade the throughput performance. Subsequently, the throughput of SU and spectrum capacity improves by increasing maximum collision probability allowed by PU network as well. Due to frequent collision with PU, the throughput of SU and spectrum capacity decreases at certain value of collision threshold. Computer simulation is used to evaluate and validate these works.

Keywords: Dynamic spectrum access, Opportunistic spectrum access, Partially observable Markov decision process, Cognitive radio, Ad hoc network.

Nomenclatures

a_*	Action
A_1	Sensing action
A_2	Access action
B	Channel bandwidth
H	Binary hypothesis
K	Acknowledgement
L	Number of sensed and accessed channel
N	Number of channel
$P_{i,j}$	Transition probability
P_r	Probability
r_j	Reward function, bits/slot
S	State of channel
V_t	Total reward function within T slot, bits/slot
W_t	Total reward function on sub-optimal Greedy, bits/slot

Greek Symbols

α	Probability from busy to idle state
β	Probability of keeping on idle state
δ	Probability of miss detection
ε	Probability of false alarm
Φ	Optimal access policy
γ	Column vector
π	Belief vector
π'	Updated belief vector
Θ	Sensing outcome
θ	State of sensing outcome, 0 or 1
τ	Transformation of belief vector
ω	Belief vector on Greedy approach
ζ	Maximum collision allowed by primary user (collision threshold)

Abbreviations

CR	Cognitive radio
CSMA	Carrier Sense Multiple Access
DSA	Dynamic spectrum access
MAC	Medium access control
OSA	Opportunistic spectrum access
PFA	Probability of false alarm
PM	Probability of miss detection
POMDP	Partially observable Markov decision process
PU/SU	Primary user/Secondary user
PWLC	Piecewise linier and convex
ROC	Receiver operative curve
SNR	Signal to noise ratio

1. Introduction

Recently spectrum utilization attracts many researchers to concern due to scarcity problem in the future wireless access. In order to address this critical problem, the FCC (Federal Communication Commission) has approved unlicensed devices to use license spectrum bands when it is unoccupied by PUs. Consequently, dynamic spectrum access (DSA) techniques are proposed to overcome this spectrum inefficiency allocation as well as develop cognitive radio (CR) networks to further improve spectrum efficiency. In CR networks, the unlicensed devices (CR users or SU) should vacate the band when the licensed device (PU) is detected.

Dynamic Spectrum Access (DSA) system was introduced as one of the most promising technologies available to increase the range and efficiency of spectrum dependent services [1]. DSA system map unused spectrum, and arrange SUs to operate within the spectrum they have identified. The implementation of DSA systems guarantee that no interference to the other users by observing and sensing the existing spectrum environment. To complete DSA system requirement, the Defense Advanced Research Projects Agency NeXt Generation (DARPA XG) spectrum sharing field tests and the geolocation database proposed for unlicensed access to TV band white space have established [2]. Shortly, implementation of DSA in wireless access can provide the increased density, better system management, and inherent in-channel and co-site interference resolution. 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 which have been developed and proposed to resolve inefficient spectrum band allocation are DIMSUMnet project [3], DRiVE/overdrive project [4], E2R and E3 [5], etc. These projects make the radio has the ability to intelligently recognize the condition of radio spectrum environment and adaptively adjust transmission frequency and bandwidth, power efficiency, modulation scheme, etc.

OSA is included as part of the larger concept of cognitive radios. It has emerged as a method to dramatically improve spectrum utilization. The basic concept of OSA is to allow SU to identify available spectrum and characterize the presence of PU. According to that information, the unlicensed devices identify communication opportunities by observing and sensing the existing spectrum in frequency, time, or even code. CR users transmit using those opportunities in a manner that limits the interference perceived by PU.

Cognitive radio is one possible and promising technology to be implemented in OSA system. It works on overlay system with restriction of no interference to license user activity. Thus, CR MAC protocol has responsibilities to coordinate channel access to licensed bands. The design of OSA MAC protocols imposes new challenges that are not considered in the conventional wireless networks. One of the main issue and challenging 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 PU. The OSA MAC design must consider that number of collision to licensed users is bounded below the threshold. Therefore, this protocol design becomes too crucial to accomplish the Quality of Service (QoS) of data transmission.

CR MAC protocol for ad hoc network is classified into three classes, which are random access, time slotted, and hybrid protocol [6-8]. Random access protocol does not need time synchronization, and are generally based on Carrier Sense Multiple Access Collision Avoidance (CSMA/CA) principle. CR user monitors the spectrum bands to detect whether any 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. 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 [9] 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. This 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 [10]. A similar approach is used in the CR access scheme in [11].

Most of the previous works on the throughput of CR focus on the fundamental tradeoff between sensing capability and achievable throughput. In [12] throughput of SU relating to sensing time in local and cooperative spectrum sensing was investigated under 2 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 [13]. The presented simulation shows 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 [14]. Using energy detector, the author presented the tradeoff between sensing time and achievable throughput of SU.

However, most of the existing works assumes that SU have a full band sensing ability. In fact, the cost to achieve wide band spectrum sensing by a single SU is quite high. It should be realistic to assume that SU has a capability to sense a limited bandwidth of spectrum during a certain amount of time. To our knowledge so far, Zhao et al. and Chen et al. [9-10] were among the earliest researchers who investigated the limited sensing ability of each SU in cognitive radio system under POMDP frameworks. They presented a cross layer design approach to implement partial sensing results to optimise spectrum access.

In this paper, we study the performance of OSA with partial sensing where SU independently sense on imperfect channel under POMDP framework. The license channel is modelled as Markov discrete process, where "0" and "1" are assumed as idle and busy channel. SU senses and accesses channel independently as well as it behaves like an ad hoc network. We adopted greedy approach strategy that maximizes bit transmitted within T slot transmission under the constraint that PU is sufficiently protected. SU must vacate the band soon when PU returns to access its channel back. In addition, by using this framework, each SU must sense the channel intelligently by statistical traffic behaviour and make a decision based on the sensing outcome. The rest of the paper is organized as follows. In section II, we give description of POMDP formulation for both of optimal and sub optimal based on greedy approach 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 is presented in the following section.

2. POMDP Formulation

Decision-making is the cognitive process leading to the selection of action among variations. One technique to automate the decision making process is to create a dynamics model. A reward structure is possibly to be implemented in this model to motivate immediate decision that will maximize the throughput.

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 and formulate policy strategy both optimal and sub optimal based on greedy approach for sensing decision which firstly introduced and proposed by Zhao et al. [9].

2.1. Optimal strategy

Channel access based on POMDP is known as an optimal sensing 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 Fig. 1, where $\overline{\alpha}_i = 1-\alpha_i$ 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.

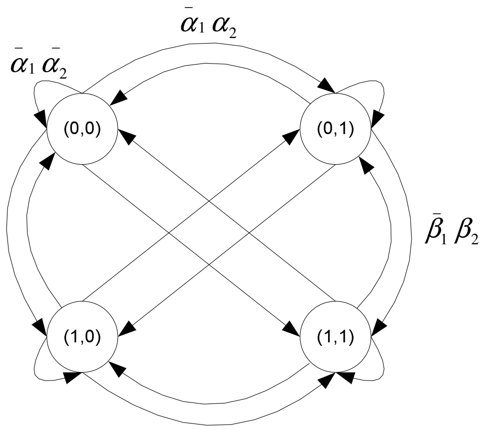

Fig. 1. State Diagram for *N*=2 as Markov Process Model.

The design of OSA protocol that maximizes the throughput of SU with limited sensing capability can be formulated as POMDP over finite horizon. It is defined by 5 main parameters $\{S, A, P, \Theta, R\}$. S denotes a finite set of states with state $i(s_i)$, A denotes a finite set of actions with action $i(a_i)$, P denotes the transition probabilities $(p_{i,j})$ which describes the channel availability of PU networks for each action in each state $\{\alpha_i, \beta_i\}_{i=1}^{N}$, 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 SU 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.

In POMDP model, the network 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 $\pi = (\pi_1, ..., \pi_M)$, 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.

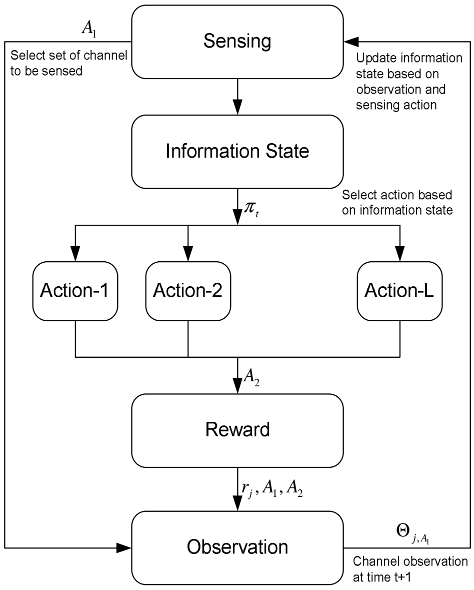

Fig. 2. POMDP Dynamic Model for OSA.

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:

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

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

$$\pi' \equiv [\pi'_1,...,\pi'_M] \cong \tau(\pi|a,\theta) \quad (3)$$

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:

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

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

$$V_t(\pi) = \max_k \pi\gamma_k(t) \quad (5)$$

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.

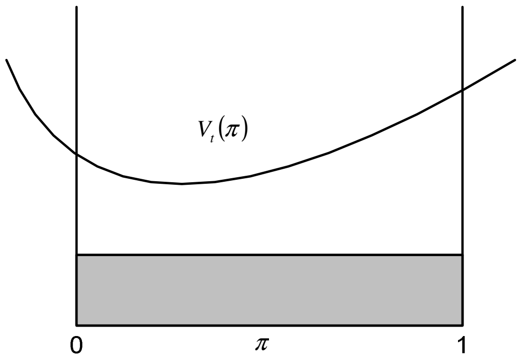

Fig. 3. Value Function Drawn over Information Space.

2.2. Sub-optimal strategy based on Greedy approach

Due to the complexity of optimal policy computation when number of slot and channel increase, Zhao et al. [9] proposed 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 as well as presented that the performance of greedy approach match and relatively close to optimal strategy. The recursive equation to maximize the expected reward is formulated as follows:

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

where $W_t(\Omega)$ denotes the expected remaining reward starting from slot t achieved by greedy approach, $\tau(\Omega|a_*,\theta)$ denotes the updated information on channel availability given the observation θ under action a. The notation of a_* is the selected action in slot t to maximize the expected immediate reward and given by

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

and information update of belief vector becomes

$$\Omega(t+1) = \left[\omega_1(t+1),\ldots,\omega_N(t+1) \cong \tau\left(\Omega(t) \middle| a_*(t), \Theta_{a_*}(t)\right)\right]$$

$$\omega_i(t+1) = \begin{cases} 1, & \text{if } a_*(t) = i, \Theta a_*(t) = 1 \\ 0, & \text{if } a_*(t) = i, \Theta a_*(t) = 0 \\ \omega_i(t)\beta_i + (1-\omega_i(t))\alpha_i, & \text{if } a_*(t) \neq i \end{cases} \tag{8}$$

2.3. Spectrum sensing and access with error

Fading, noise, and any obstacles cannot be ignored in wireless communication link. These imperfect conditions can cause some errors in PU signal detection and spectrum sensing. False detection senses idle states as a busy channel and SU refrain to transmit data. On the other hand, miss-identification senses busy states as an idle channel and cause SU collide to PU transmission.

Channel detection can be modeled as the following formulas. Suppose that number of channel is sensed and SU perform binary hypothesis as follows:

$H_0 = S_n(t) = 0\,(idle)$

$H_1 = S_n(t) = 1\,(busy)$

Let $\Theta_n(t) \in \{0$ (idle), 1 (busy)$\}$ denote the sensing outcome of binary hypothesis. The performance of spectrum sensing is characterized by probability of false alarm (PFA) $\varepsilon_n(t)$, and probability of miss-detection (PM) $\delta_n(t)$ [16]. The channel a_* selected by greedy approach is thus given by

$$a_*(t) = \arg\max_{a=1,\ldots,N}\left(\omega_a(t)\beta_a + (1-\omega_a(t))\alpha_a\right)(1-\varepsilon)B_a \tag{9}$$

The belief vector should be updated both at transmitter and receiver. Information at the transmitter in one slot included the decision $\{a_*, \Phi_{a_*}\}$ and the observation $\{\Theta_{a_*}, K_{a_*}\}$ where $K_{a_*} \in \{0,1\}$ denotes an acknowledgement in the end of the slot. However, information at the receiver only covers a_* and K_{a_*} since the receiver does not have the sensing outcome Θ_{a_*} and cannot distinguish an unsuccessful transmission from no access decision $\Phi_{a_*} = 0$. Then, modification of update belief vector in Eq. (8) is as follows:

$$\begin{aligned}\Omega(t+1) &\equiv \left[\omega_1(t+1),\ldots,\omega_N(t+1) = \tau\left(\Omega(t)\middle| a_*, K_{a_*}\right)\right] \\ \omega_i(t+1) &\equiv \Pr\left[S_i(t)=1\middle|\Omega(t), a_*, K_{a*}\right]\end{aligned} \tag{10}$$

where $K_{a_*} = \Theta a_*(t)$

3. Cognitive Radio System Model

The existing spectrum contains number of channel that is licensed to PUs and they have an authority to use it. Channel state can be considered as Markov discrete process, which follows 0 and 1 for idle and busy channel. When channel is unoccupied, 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 $B_i(i=1,\ldots, N)$. 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.

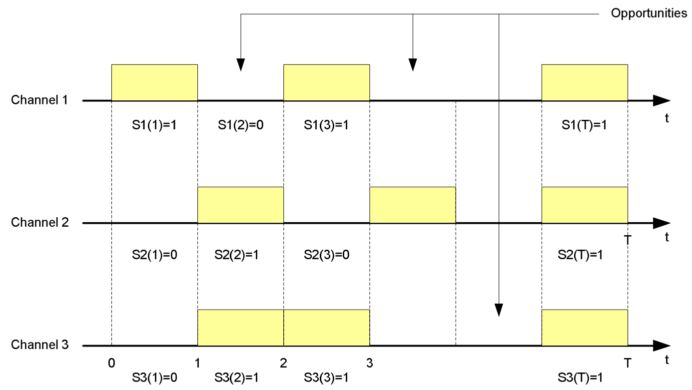

Fig. 4. Spectrum Occupancy for *N*=3.

In cognitive MAC, the general structure of communication is divided into slots of equal length T, where slot k refers to the discrete time period $[kT, (k+1)T]$ and constructed into sensing, transmission, and acknowledgement sub-slot. 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) at certain period of time. Based on the sensing outcome, SUs will decide which channel to be accessed (L_2), where $L_2 \leq L_1 \leq N$. In the period of data transmission sub-slot, SUs start to send data packet to SUs receiver. Finally, at the end of slot, SU will send the acknowledgement signal that indicates for 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 considered, where SUs sense and access the spectrum channel independently without exchanging local information.

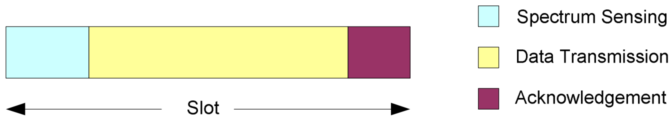

Fig. 5. The Slot Structure of Cognitive MAC.

4. Numerical Results and Discussion

In this section, computer simulation results are presented to evaluate the performance of OSA with sensing errors compared to without sensing error based on the greedy approach. We used MATLAB software as a simulation tool to model spectrum opportunities in CR networks and derived the results. At the beginning of the slot, SUs take L number of channel samples to be sensed with the same value of SNR (signal to noise ratio). Collision to PUs occurred when SUs senses busy state as idle channel. The throughput of SUs obtains optimal value when collision probability equal to miss-detection probability ($\zeta=\delta$).

Figure 6 shows that the throughput of SUs with different SNR 0dB, 1dB, and 2dB, as a function of collision threshold (ζ). We set number of channel, N=3, slot number, T=25, and transition probabilities α=3, β=5. As described in the figure, the throughput of SUs improves when ζ increases. Collision threshold is defined as maximum collision allowed by PU user. The value of ζ has an impact to the probability of false detection as described in Fig. 7. Increasing ζ makes probability of false alarm becomes small and lead to increase the throughput performance. On the other hand, at low value of ζ, the derived false detection is high. This condition degrades the throughput performance.

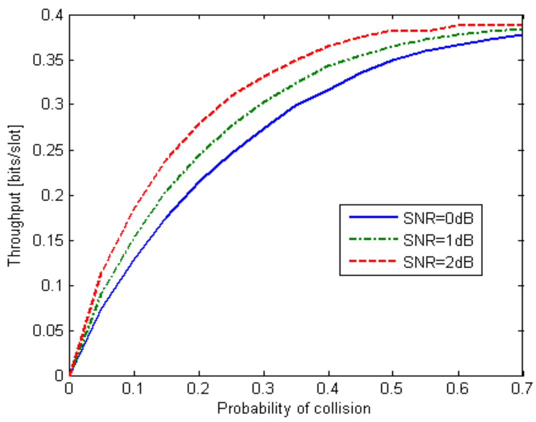

Fig. 6. The Throughput of SUs with Sensing Errors Based on Greedy Approach with Parameter Setting B=1, N=3, T=25, α=0.3 and β=0.5.

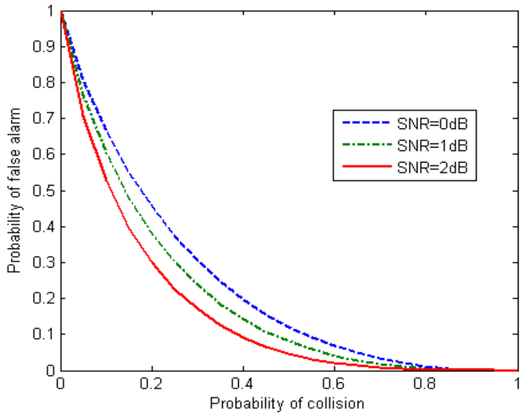

Fig. 7. ROC Curve between Collision Threshold Probability and False Alarm Probability with SNR=[0dB, 1dB, and 2dB].

Furthermore, we make a comparison with the achieved throughput performance on perfect channel sensing (without sensing errors). Figure 8 shows that increasing number of slot can improve the throughput performance on both perfect and imperfect channel sensing. It means that SU can gain the reward within T slot transmission. This achieved result confirms that sensing on imperfect channel can degrade the throughput performance. Figure 9 describes the throughput of SUs as function of SNR with different collision threshold probability ζ=[0.1, 0.15, 0.2]. Increasing SNR can improve the throughput of SU. The throughput of SU with ζ=0.2 has the highest value. However, when SNR greater than 10dB, the throughput of SU is relatively equal. It means that SNR with the values greater than 10dB can reduces false detection.

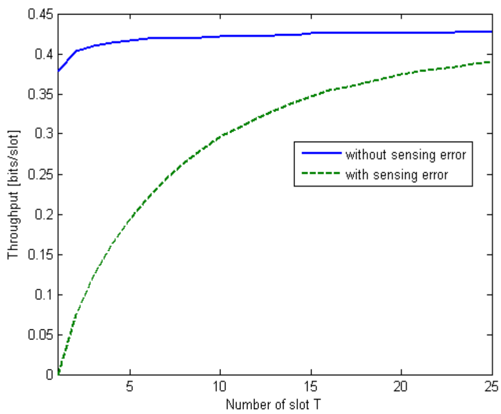

Fig. 8. The Throughput of SUs with Sensing Errors Based on Greedy Approach with Parameter Setting B=1, N=3, T=25, α=0.3 and β=0.7.

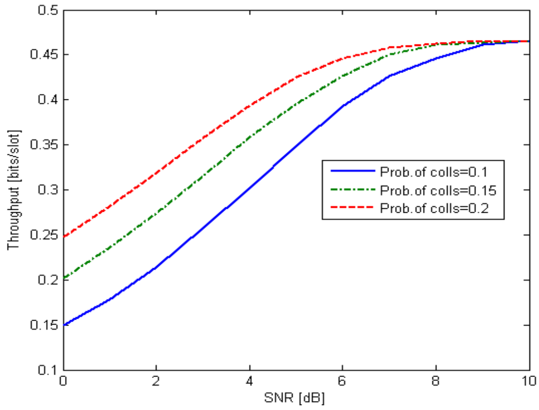

Fig. 9. The Throughput of SUs as a Function of SNR with Different Collision Threshold Probability and Parameter Setting *B*=1, *N*=3, *T*=25, α=0.3 and β=0.5.

Furthermore, false detection wastes the opportunity to access unoccupied channel. Idle channel is sensed as a busy one, so that SU refrain from data transmission. Figure 10 shows the throughput performance as a function of false detection probability. The achieved throughput improves when false detection is low. On the other hand, it decreases when probability of false detection is getting high.

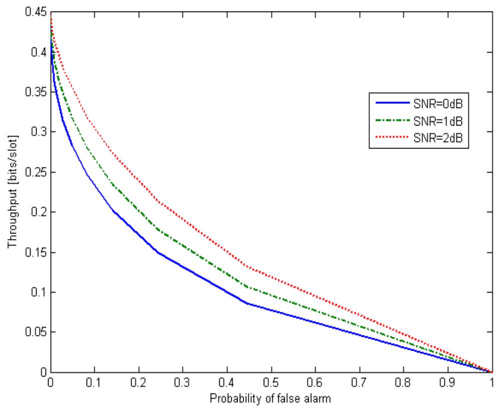

Fig. 10. The Throughput of SU with Sensing Errors Based on Greedy Approach as a Function of False Detection Probability with Different SNR Values and Parameter Setting *B*=1, *N*=3, *T*=25, α=0.3 and β=0.5.

The spectrum capacity as function of collision threshold is shown in Fig. 11. The frequent collision can decrease overall spectrum capacity for primary and secondary users. It reaches the optimum value at certain collision threshold. According to the derived result, the best spectrum capacity, 0.713 bits/slot/Hz is obtained when collision threshold, ζ=0.15. Subsequently, Fig. 12 shows the overall spectrum capacity with different SNR values [0dB, 1dB, 2dB]. Spectrum capacity achieves the optimum values at ζ=0.35, 0.3 and 0.25 for SNR values 0 dB, 1 dB, and 2 dB respectively.

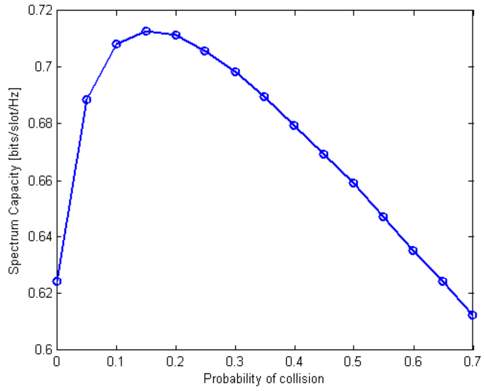

Fig. 11. The Spectrum Capacity as a Function of Collision Threshold with Sensing Error and Parameter Setting B=1, N=3, T=25, SNR=5dB, α=0.3 and β=0.5.

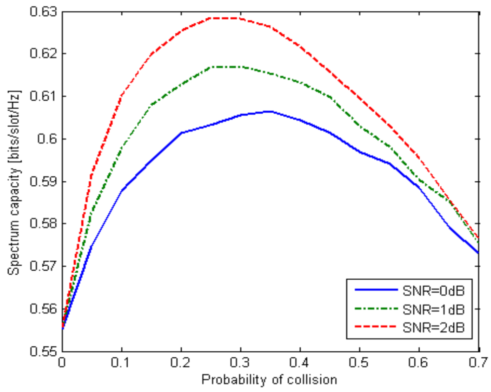

Fig. 12. The Spectrum Capacity as a Function of Collision Threshold with Sensing Errors and Parameter Setting B=1, N=3, T=25, α=0.3 and β=0.5.

5. Conclusions

We have studied the performance of OSA with sensing errors in CR ad hoc network. In this case, SU senses license channel over imperfect condition with false detection and miss identification. Such errors cause some mistakes on PU signal detection and have a significant impact to the achieved throughput performance.

Moreover, the throughput performance and spectrum capacity can improve by increasing maximum collision probability allowed by PU network. However, due to frequent collision with PU, spectrum capacity can decrease at certain value of collision probability threshold. The tradeoff between throughput performance and collision threshold is achieved as the derived results as well. Subsequently, the throughput performance improves when SNR value is getting higher. SNR with the values greater than 10 dB can be considered as spectrum sensing with less noise and fading (error).

References

1. Zhao, Q.; and Sadler, B.M. (2007). A survey of dynamic spectrum access. *IEEE Signal Processing Magazine*, 2(3), 79-89.
2. DARPA: The next generation (XG) program. http://www.darpa.mil/ato/programs/xg/index.htm.
3. Buddhikot, M.; Kolodzy, P.; Miller, S.; Ryan, K.; and Evans, J. (2005). DIMSUMnet: New directions in wireless networking using coordinated dynamic spectrum access. *In Proceedings of World of Wireless Mobile and Multimedia Networks*, *IEEE WoWMoM Conference*, 78-85.
4. Xu, L.; Tonjes, R.; Paila, T.; Hansmann, W.; Fank, M.; and Albrecht, M. (2000). DRiVE-ing to the internet: Dynamic radio for IP services in vehicular environments. In *25th Annual IEEE Conference Proceedings on Local Computer Networks*, 2000. LCN 2000, USA, 281-289.
5. E3 Project, http://ict-e3.eu.
6. Akyildiz, I.F.; Lee, W.Y.; and Chowdury, K.R. (2009). CRAHNs: Cognitive radio Ad Hoc networks. *Journal of Ad Hoc Networks*, 7(5), 810-836.
7. Wang, H.; Qin, H.; and Zhu, L. (2008). A survey on MAC protocols for opportunistic spectrum access in cognitive radio networks. *In Proceedings of International Conference on Computer Science and Software Engineering*, 1, 214-218.
8. Cormio, C.; and Chowdury K.R. (2009). A survey on MAC protocols for cognitive radio networks. *Journal of Ad Hoc Networks*, 7(7), 1315-1329.
9. Zhao, Q.; Tong, L.; Swami, A.; and Chen, Y. (2007). Decentralized cognitive MAC for opportunistic spectrum access in Ad Hoc network: A POMDP framework. *IEEE Journal Selected Areas Communication*, 25(3), 589-600.
10. Chen,Y.; Zhao, Q.; and Swami, A. (2008). Joint design and separation principle for opportunistic spectrum access in the presence of sensing errors. *IEEE Transactions on Information Theory*, 54(5), 2053-2071
11. Geirhofer, S.; Tong, L.; and Sadler, B.M. (2008). Cognitive medium access: Constraining interference based on experimental models. *IEEE Journal Selected Areas Communications*, 26(1), 95-105.
12. El-Saleh, A.A.; Ismail, M.; Ali, M.A.M.; and Alnuaimy, A.N.H. (2009). Capacity optimization for local and cooperative spectrum sensing in cognitive radio networks. *International Journal of Electronics*, *Circuits and Systems*, 3(3), 69-75.
13. Lee, K.; and Yener, A. (2007). Throughput enhancing cooperative spectrum sensing strategies for cognitive radios. *In Proceedings of Asilomar Conference on Signals, Systems and Computers*, 2045-2049.
14. Liang, Y.C.; Zeng, Y.; Peh, E.; and Hoang A.T. (2008). Sensing-throughput tradeoff for cognitive radio networks. *IEEE Transaction on Wireless Communication*, 7(4), 1326-1337.
15. Smallwood, R.; and Sondik, E. (1971). The optimal control of partially observable Markov processes over finite horizon. *Operation Research*, 21(5), 1071-1088.
16. Trees, H.L.V. (2001). *Detection, estimation, and modulation theory*, *Part I.* Wiley-Interscience.