

Secondary User Sensing Time Optimization in Sensing-Transmission Scheduling for Dynamic Spectrum Access in Cognitive Radio

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Article history

Received: 13-02-2014

Revised: 13-07-2015

Accepted: 6-10-2015

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Abstract: The constraint of limited frequency spectrum for wireless communication is very daunting. The radio spectrum licensed to permanent users is wasted at times when not used continuously. Cognitive radio technology involves a change in regulation of radio spectrum. In cognitive radio networks a secondary user network is designed for efficiently using gaps in spectrum and not causing at the same time harmful interference to license holding primary users. Opportunistic spectrum access involves the sensing of white spaces in the transmissions of Primary Users and their utilization by Secondary Users. There is a continuous tradeoff between the opposing goals of Primary User transmission protection and Secondary User throughput maximization. For a Secondary User, sensing is important so as to avoid collisions, hence packet loss. At the same time being too cautious and having long sensing periods can be costly. This paper presents optimization of Secondary User sensing time in sensing-transmission scheduling for dynamically accessing the spectrum in cognitive radios. The need to maximize the Secondary User access is achieved by optimizing its sensing time with respect to collision cost in a threshold based sensing-transmission structure using simulations. The results are presented in the form of traces of thresholds for different sensing times and collision costs. This scheme optimizes Secondary User throughput while safeguarding Primary User interests. This defines a standard to give an insight into the design of sensing-transmission scheduling in cognitive radio networks.

Keywords: Cognitive Radio, Threshold, Secondary User Sensing Time, Collision Cost, Sensing-Transmission Scheduling

Introduction

Today, spectrum is like real estate. It is a commodity which is fixed but the demand for it is increasing exponentially each day. Access to radio spectrum is difficult as it is controlled by a radio regulatory regime. Large parts of the radio spectrum are allocated to licensed radio services in a command-and-control way. Open access to most of the radio spectrum is not permitted. Only some small fractions of the radio spectrum, the unlicensed frequency bands, are openly available. The demand for additional spectrum is growing faster than the speed at which technology is able to increase spectrum efficiency and

capacity in radio communications. Cognitive radio is not only a new radio technology; it also includes a revolutionary change in how the radio spectrum is regulated. Cognitive radios are designed for efficiently using shared spectrum and not causing at the same time harmful interference to incumbent (primary, license holding) radio systems (Fette, 2009; Berlemann and Mangold, 2009).

Secondary users have to cognitively use the gaps in spectrum, which keep on changing dynamically. In this technology the protection of primary user's transmission is very important. PU is not expected to change its access policy or co-operate with SU. Hence the Listen Before Talk (LBT) policy has been studied extensively

by researchers. The SU listening is known as sensing and SU talk is called transmission. Though SU transmission is the only process which has to be maximized, it cannot be done without constraints. These are PU collisions and SU sensing durations because both these scenarios have to be restricted within limits.

Periodic sensing has been assumed in the IEEE 802.22, with both fast sensing and fine sensing. Prior works have considered per packet sensing, so the SU senses the PU channel at the beginning of each packet's transmission (Lai *et al.*, 2007; Zhao *et al.*, 2007; Liang *et al.*, 2008; Wang *et al.*, 2007). This type of sensing simplifies the design of the Physical and MAC layer but does not optimize the sensing-transmission scheduling. In many practical scenarios sensing is time consuming, for instance in IEEE 802.22 it is 10ms for cordless microphone signals (Chen *et al.*, 2008). This duration is 25ms for field-sync detection of a standard Digital TV system (Cordeiro *et al.*, 2006). This sensing time is not negligible compared to typical millisecond duration of a packet. Sensing overhead has to be tolerated because transmission without sensing would cause more collisions with PU. Thus in this study both benefit and penalty has been considered when designing sensing-transmissions schemes of SUs.

The effect of feedback from SU receiver has not been well studied as well. The SU transmitter cannot sense PU signals in the licensed band while transmitting, but the data received by the SU receiver can be affected by this PU interference. The SU receiver can be made to send an acknowledgement indicating successful reception of a packet when PU is not active. Similarly SU receiver can indicate failure of packet reception by sending a negative acknowledgement. This type of feedback can be used for taking better decisions by SU transmitters.

Related Works

The earlier models (Lai *et al.*, 2007; Zhao *et al.*, 2007; Liang *et al.*, 2008; Wang *et al.*, 2007) in this field have considered only periodic or per-packet sensing, which means that the SU senses the PU channel once before each packet is transmitted.

Liang *et al.* (2008; Wang *et al.*, 2007), the authors have derived an optimal tradeoff between throughput and the false-alarm probability of a SU, by choosing a suitable sensing time. This work also assumes periodic sensing. In comparison, we have achieved a balance between minimizing the PU interruption and maximizing the SU transmission time based on collision cost, sensing result and feedback. Also general sensing-transmission structure has been considered in this study.

Kim and Shin (2008), the authors have proposed a scheme that optimizes both the probing period and the sensing sequence to maximize the detection of spectrum

white spaces in multiple channels. They have assumed MAC-layer sensing scheduling for general PU idle/busy time distributions and not emphasized the inter-dependence of PU protection and SU performance which is integral to our research.

Chang and Liu (2007), the authors showed threshold-based structure of the optimal strategy for channel guessing, probing and transmission. Temporal independence of channel states in a slotted structure has been assumed by the authors and during each slot, the state of the channel remains unchanged. In comparison, the aim of our paper is to compute the optimal sensing time in one PU channel. Also general un-slotted PU idle time distributions have been assumed

Chen *et al.* (2008), the authors assumed slotted PU activities and limited PU collision probability. They proposed an optimal operating point for the spectrum sensor, its access decision and channel selection. The whole observation history was utilized to find the optimal spectrum access policy. Thus the joint optimization problem was separated and reduced to an unconstrained problem.

The authors in (Zhao and Liu, 2008) extended the results in (Chen *et al.*, 2008) to un-slotted PU activities. Zhao and Liu (2008) the authors assumed a per-packet sensing/transmission structure and the independence of PU state transition probability on time.

Huang *et al.* (2008) an optimal threshold-based policy has been derived for the exponential idle time distribution depending on its memory-less property by Huang *et al.* (2008). The approach cannot be applied to other idle time distributions because the PU state transition is dependent on time. Also, perfect sensing is critical in their study, but not in this study.

The models of (Huang *et al.*, 2009a; 2009b) have not considered the effect of variation in cost of collision and the length of SU sensing time on optimal threshold for sensing-transmission structure. These factors are the primary constraints in this study.

Mokhtar *et al.* (2009) non perfect reporting channel has been considered in co-operative spectrum sensing. They have reduced the reporting errors in sensing, but imperfect feedback from SU receiver has not been considered to determine the sensing transmission scheduling.

The authors (Zhang and Tsang, 2011) have considered reward-based scheduling schemes and their optimality, but it's not clear how these algorithms can be applied in practice and how the actual sensing performances are.

Liu *et al.* (2012) have considered periodic sensing that too sequential of an in-band channel. Their focus has been mainly on deducing the optimal sensing frequency during an SU's active transmission on a PU licensed channel. Where-as in our paper we have considered feedback from

SU receiver to check for PU transmission and other interferences during SU transmission.

In our earlier paper (Aulakh and Vig, 2014a) we have considered the effect of variation in reward of successful transmission and cost of collision on optimal threshold for sensing-transmission structure. The effect of Probability of false alarm and cost of collision has been considered in (Aulakh and Vig, 2014b). The effect of length of SU sensing time and cost of collision on optimal threshold for sensing-transmission structure has not been fine tuned. These are the primary constraints in this study.

Discussion on Related Works

In comparison with the earlier works, this paper is different in the following issues: Sensing-transmission structure of Secondary User is considered to be general with or without periodic/per packet sensing. PU idle time distribution has been assumed to be general and un-slotted. The interdependence of PU protection and SU performance has been considered. Many of the earlier works have assumed perfect sensing. Imperfect sensing has been considered in this study. Also the SU receiver feedback in the form of acknowledgement/ negative acknowledgement has been considered. Effect of collision cost and SU sensing time on the optimal threshold has been fine tuned under all the above constraints.

Methodology

Firstly a system model is developed based on the constraints. Then it is simulated using MATLAB and the traces are compared with earlier works and then analyzed for new implications.

In order to develop a system model for SU sensing and transmission, based on semi-markov renewal theory, PU idle and busy period distributions are assumed to be general with means specified. Then based on probability theory and considering parameters like probability of false alarm, probability of correct detection of PU being busy, SU sensing period, SU packet length, probability of negative acknowledgement due to PU collision and probability of negative acknowledgement due to channel noise and interference the expressions for instantaneous benefit for successful SU packet transmission and penalty for collision with PU are deduced. The instantaneous utility obtained by SU at any time both for sensing and transmission is found next. Threshold is then defined as that probability of finding PU idle at which transmission utility exceeds sensing utility. This threshold is found to be dependent on various parameters including the SU sensing period.

To analyze the effect of SU sensing period the model is simulated in MATLAB and the threshold traces are obtained for different collision costs and SU sensing periods. Analyses of these results lead to

determining the exact sensing-transmission scheduling for a given application.

Development of System Model

Assume a Secondary User transceiver pair is opportunistically accessing a PU channel. PU is unaware of SU activities hence transmits following an idle/busy pattern based on the semi-markov renewal theory. Thus its idle (I) and busy (B) timeperiods are independent, having distributions $f_I(\cdot)$ and $f_B(\cdot)$ with means \bar{i} and \bar{b} .

The two activities of a SU transceiver are - sensing and transmitting. SU uses a spectrum sensor of energy or feature to find if PU is busy or idle at any instant. In case of non ideal sensing, Let:

- Probability of false alarm i.e., finding PU not idle when it is idle be $Prob_f$ and
- Probability of finding PU busy when it actually is busy be $Prob_d$
- Let SU time unit be δ and for simplicity assume: $\delta=1$. Then we assume that
- SU has a fixed sensing period of: $T_{sense} \times \delta = T_{sense}$ also
- SU has a fixed transmitting packet length of: $T_{packet} \times \delta = T_{packet}$
- Sensing and Transmitting times are very less as compared to PU average idle and busy times
- *Benefit* for successful SU packet transmission is: $Reward \times T_{packet}$ per δ
- Penalty for collision with PU is: $Collcost$ per δ or 1 in this case.

Though the sensing period and packet length have been assumed to be fixed, the SU can sense and transmit multiple times in succession, thus enhancing SU utility as desired. The PU can regulate the *Collcost* to control the SU access aggressiveness because the Average Utility function is *Benefit* minus *Collcost*. In this way the desired balance between SU spectrum usage and PU collision protection can be achieved and spectrum sharing between PU and SU can also be implemented.

It has been assumed that SU is aware of PU idle time distribution. Extensive measurements (Willkomm *et al.*, 2008; Geirhofer *et al.*, 2006), using various methods (Azzalini, 1981; Kim and Shin, 2008) can estimate this idle time distribution function. This assumption is like assuming that PU idle time has exponential distribution with knowledge of its parameter, which has been done in earlier works.

In order to incorporate the feature of feedback in SU communication, the presence of acknowledgement and negative acknowledgement from the SU Receiver has been assumed. An acknowledgement validates packet transmission and its reception without collision. A

negative acknowledgement can be due to collision with PU or interference or fading within the SU channel. Probability of negative acknowledgement due to PU collision is defined as a_1 and Probability of negative acknowledgement due to any other reason is a_0 . Always: $a_1 > a_0$.

Formulation of Problem

In order to efficiently utilize the white spaces in PU spectrum, sensing and transmission has to be scheduled by a SU transceiver as in Fig. 1. The SU can either sense multiple times or transmit multiple packets at any instant. This is a partially observable decision process as the SU does not have complete knowledge about PU being idle or busy.

PU State Transition

The Primary User state transition is not dependent on Secondary User actions but depends on time instant. If t time has passed since PU's last transition from busy state to idle state and if it is assumed that the PU is still idle at time t , then probabilities that it will continue to remain idle are:

When SU is sensing:

$$Prob_t^{Sense} = \frac{1 - F_t(t + Tsense)}{1 - F_t(t)} \quad (1)$$

When SU is transmitting:

$$Prob_t^{Transmit} = \frac{1 - F_t(t + Tpacket)}{1 - F_t(t)} \quad (2)$$

where, $F_t(\cdot)$ is cumulative distribution function of PU idle time.

The two probabilities depend on the time elapsed, which is $t + Tsense$ when sensing and $t + Tpacket$ when transmitting.

Outcome State

The SU has two actions: Sense and Transmit. The outcome of SU sensing can either be that PU is idle or it is busy. The outcome of SU transmission can be an acknowledgement or a negative acknowledgement.

Let conditional probability of PU being idle at time t be denoted by Pr_t . Then the probability of PU remaining idle after sensing will be $Pr_{t+Tsense}$ and probability of PU remaining idle after transmitting will be $Pr_{t+Tpacket}$. These probabilities according to the Bayes' rule, will depend on the outcomes of each action and can be expressed as:

$$Pr_{t+Tsense} = \frac{Pr_t \times Prob_t^{Sense} \times (1 - Prob_f)}{Pr_t \times Prob_t^{Sense} \times (1 - Prob_f) + (1 - Pr_t \times Prob_t^{Sense}) \times (1 - Prob_d)} \quad (3)$$

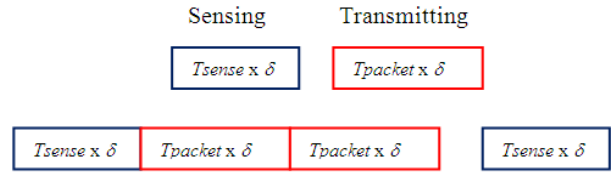


Fig. 1. Sensing-transmission scheduling

If outcome is PU idle:

$$Pr_{t+Tsense} = \frac{Pr_t \times Prob_t^{Sense} \times Prob_f}{Pr_t \times Prob_t^{Sense} \times Prob_f + (1 - Pr_t \times Prob_t^{Sense}) \times Prob_d} \quad (4)$$

If outcome is PU busy:

$$Pr_{t+Tpacket} = \frac{Pr_t \times Prob_t^{Transmit} \times (1 - a_0)}{Pr_t \times Prob_t^{Transmit} \times (1 - a_0) + (1 - Pr_t \times Prob_t^{Transmit}) \times (1 - a_1)} \quad (5)$$

If ack is received:

$$Pr_{t+Tpacket} = \frac{Pr_t \times Prob_t^{Transmit} \times a_0}{Pr_t \times Prob_t^{Transmit} \times a_0 + (1 - Pr_t \times Prob_t^{Transmit}) \times a_1} \quad (6)$$

If nack is received

As the assumption is that SU is aware of the beginning of PU idle time, hence we assume that PU is idle at $t=0$; Hence $Pr_0 = 1$.

Reward for Successful Transmission

As the current PU idle probability is Pr_t , then the probability that PU remains idle while SU is transmitting a packet ($Tpacket$) at time t will be $Pr_t \times Prob_t^{Transmit}$ and the probability that SU has successfully transmitted a packet by getting an acknowledgement is:

$$(1 - a_0) Pr_t \times Prob_t^{Transmit} + (1 - a_1) (1 - Pr_t \times Prob_t^{Transmit})$$

Then the expected instantaneous benefit will be:

$$B_t(Pr_t) = \left[\frac{Pr_t \times Prob_t^{Transmit} \times (1 - a_0) + (1 - Pr_t \times Prob_t^{Transmit})}{(1 - a_1)} \right] \times Reward \times Tpacket \quad (7)$$

And the expected instantaneous collision cost will be:

$$C_t(Pr_t) = (1 - Pr_t \times Prob_t^{Transmit}) \times Collcost \times Tpacket \quad (8)$$

Thus the instantaneous utility obtained by SU at time t is $U_i(Pr_i, sense) = 0$ in sensing and $U_i(Pr_i, transmit) = B_i(Pr_i) - C_i(Pr_i)$ in transmitting:

$$U_i(Pr_i, transmit) = \left[\begin{array}{c} Pr_i Prob_i^{Transmit} (1 - a_0) + (1 - Pr_i \times Prob_i^{Transmit}) \\ (1 - a_1) \end{array} \right] \left[\begin{array}{c} Reward \times Tpacket - (1 - Pr_i \times Prob_i^{Transmit}) \\ Collcost \times Tpacket \end{array} \right]$$

$$U_i(Pr_i, transmit) = \left[\begin{array}{c} Pr_i Prob_i^{Transmit} (1 - a_0) Reward + \\ (1 - Pr_i \times Prob_i^{Transmit}) \\ \{(1 - a_1) Reward - Collcost\} \end{array} \right] Tpacket \quad (9)$$

Criterion for Optimality

The purpose is to determine a sensing transmission scheduling strategy that achieves the maximum the expected average utility per time unit.

To maximize:

$$\lim_{L \rightarrow \infty} \frac{(\sum_{l=1}^L \sum_{t=0}^{M_l} U_i(Pr_i, action_t)) / L}{(\sum_{l=1}^L (I_l + B_l)) / L}$$

Here: $action_t$ is SU action at time t which can be sensing or transmitting, M_l is the number of actions taken in the l th idle-busy period, I_l is length of l th idle period and B_l is length of l th busy period. Since L is very large this reduces to maximizing of

$$V(t, Pr_i) = \frac{E \left[\sum_{t=0}^{M_l} U_i(Pr_i, action_t) \right]}{\bar{i} + \bar{b}} \text{ for an access policy of}$$

SU which defines a mapping of SU belief of PU being idle or busy to SU action of sensing or transmission. Since $\bar{i} + \bar{b}$ is fixed. The problem reduces to maximizing the numerator.

The maximum expected utility obtained by SU at time t is then:

$$V(t, Pr_i) = \max_{\{sense, transmit\}} \{Sense(t, Pr_i), Transmit(t, Pr_i)\} \quad (10)$$

$Transmit(t, Pr_i)$ and $Sense(t, Pr_i)$ are instantaneous expected utilities of SU by transmitting the packet and sensing the channel respectively.

From Equation (9):

$$Sense(t, Pr_i) = \sum_{i=\substack{idle \\ busy}} Pr \left[outcome_{t+Tsense}^{sense} = i \right] \quad (11)$$

$$V(t + Tsense, Pr_{t+Tsense}(i))$$

$$Transmit(t, Pr_i) = \sum_{j=\substack{ack \\ nack}} Pr \left[outcome_{t+Tpacket}^{transmit} = j \right] \quad (12)$$

$$V(t + Tpacket, Pr_{t+Tpacket}(j)) + U_i(Pr_i, transmit)$$

Pr_i is conditional probability of PU being idle at time t . The value of Pr_i at which the expected utility of transmission, $Transmit(t, Pr_i)$ exceeds that of sensing, $Sense(t, Pr_i)$, gives the optimal threshold: Pr_i^* .

$Sense(t, Pr_i)$ and $Transmit(t, Pr_i)$ intersect at $Pr_i = Pr_i^*$. So Pr_i^* is that value of Pr_i at which SU should start transmission as instantaneous transmitting utility exceeds instantaneous sensing utility. Thus Pr_i^* defines the threshold of sensing-transmission structure, when the SU should start transmission.

Lower the values of Pr_i^* better for SU, since it can transmit even when probability of PU being idle is lower. But to protect the PU interests, cost of collision has to be introduced and increased from unity.

Simulation Results

Results for five cases of collision cost (3 to 7) have been derived. Collision cost is high in cases where PU carries critical data, which cannot afford collisions. The PU idle time is uniformly distributed in [100,1000]. SU transmission packet length is kept constant at 30. Probability of detection and Probability of false alarm are 0.99 and 0.01 respectively. $Reward$ is taken as 1. Probability of nack due to collision with PU is taken as 0.9 and due to any other reason is then 0.1. Thus both imperfect sensing and feedback scenarios are taken into consideration. For each case of collision cost, the SU sensing time is varied from 7 to 11 in steps of 1.

Collision Cost is 3

It is evident from the graph in Fig. 2 and 3 that the threshold value increases with decrease in SU sensing time. It can be seen Table 1 that at the instant of time index of 100 the values of threshold for SU sensing times of 11, 10, 9, 8 and 7 are 0.9204, 0.9272, 0.9336, 0.9402 and 0.9469. There is an increase of almost 3% in the threshold value as sensing time is decreased from 11 to 7.

Collision Cost is 4

In this case also, the threshold value increases with decrease in SU sensing time as seen in Fig. 4. At the instant when time index is 100 the values of threshold for SU sensing times 11, 10, 9, 8 and 7 are 0.9421, 0.9472, 0.9519, 0.9567 and 0.962 from Table 2. There is an increase of over 2% in the threshold value as sensing time is decreased from 11 to 7. The increase is less than in case cost of collision is 3. The threshold is

also higher at every time instant for the same length of sensing time in case cost of collision is increased.

Collision Cost is 5, 6 and 7

The threshold value continues to increase with decrease in SU sensing time and further increase in cost of collision as is shown in Fig. 5 to 8. At the instant of

time index 100, the value of threshold for costs of collision 5, 6 and 7 (SU sensing time is 7) is 0.9711, 0.977 and 0.9815 from Table 3 to 5. There is an increase of 3.6% in the threshold value as cost of collision is decreased from 7 to 3 (SU sensing time is 7). The increase is 5.6% when length of SU sensing time is 11.

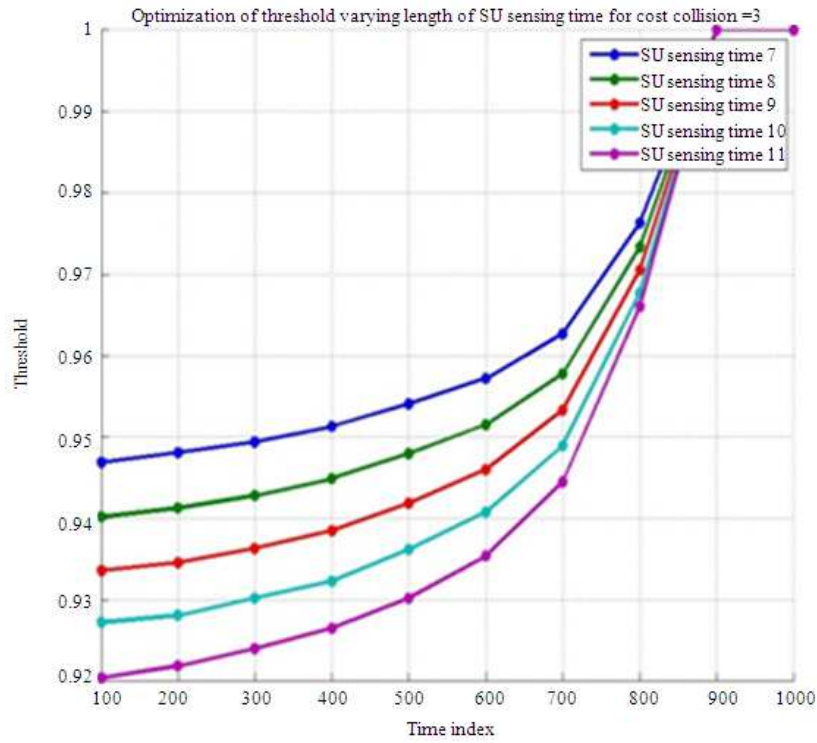


Fig. 2. Threshold V/s time index (SU sensing time = 7 to11)(Collcost = 3)

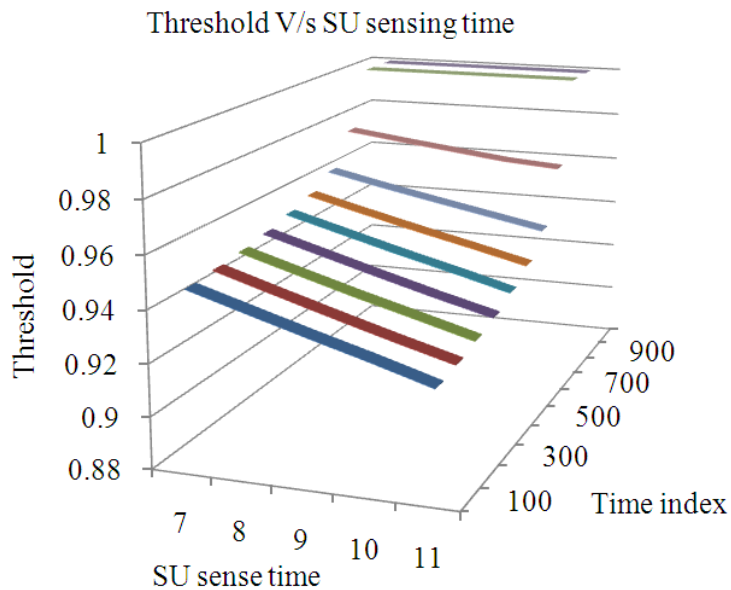


Fig. 3. Threshold V/s SU sensing time (Time index=100-1000)(Collcost = 3)

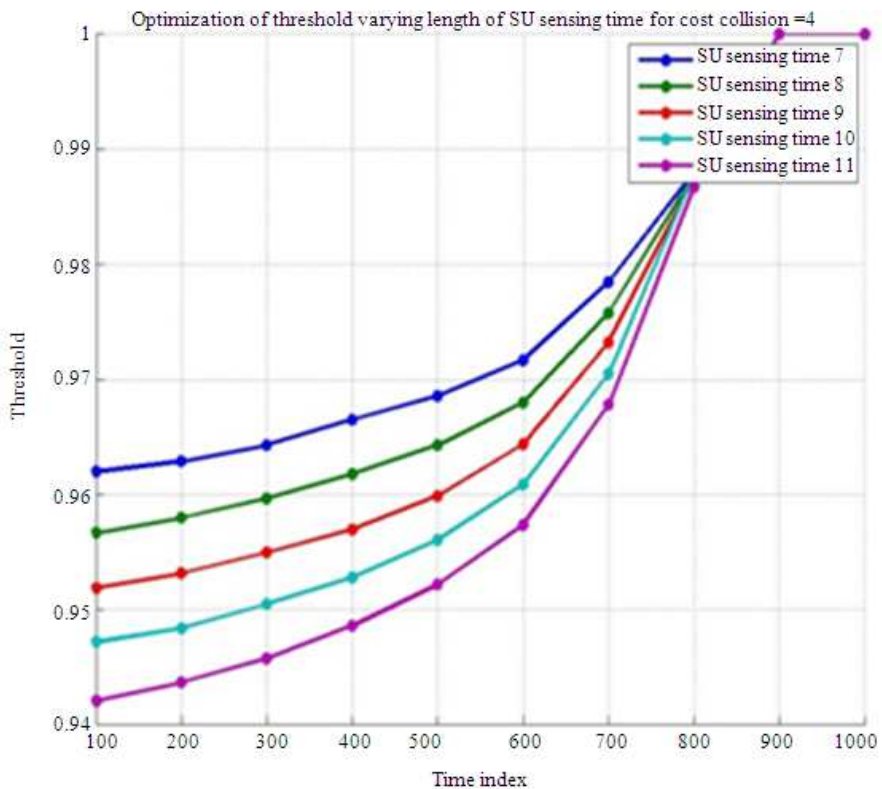


Fig. 4. Threshold V/s time index (SU sensing time = 7 to11)(Collcost = 4)

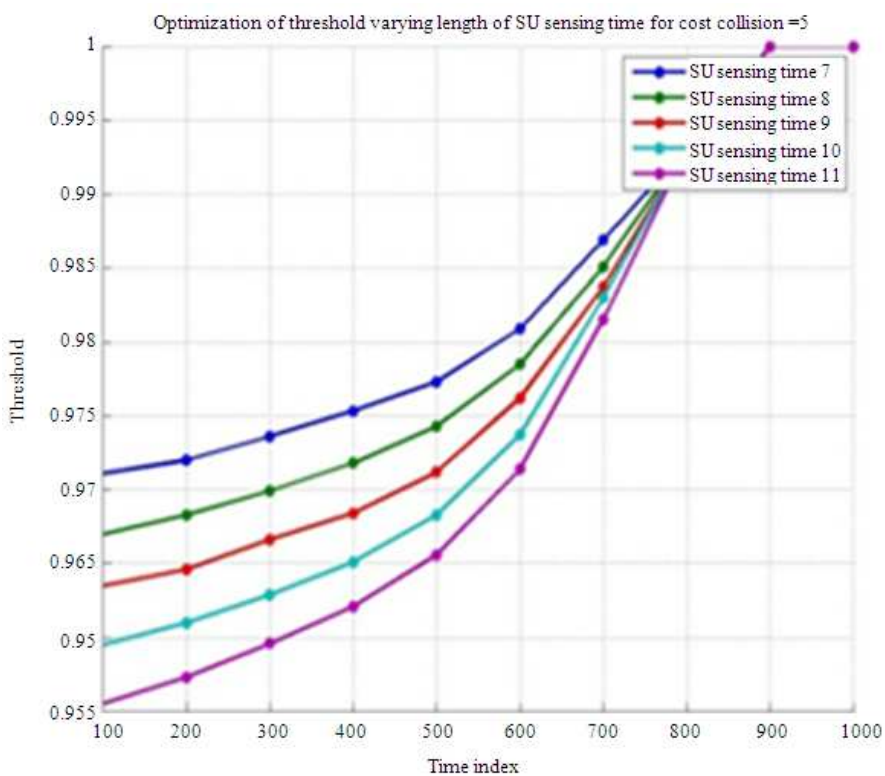


Fig. 5. Threshold V/s time index (SU sensing time = 7to11)(Collcost = 5)

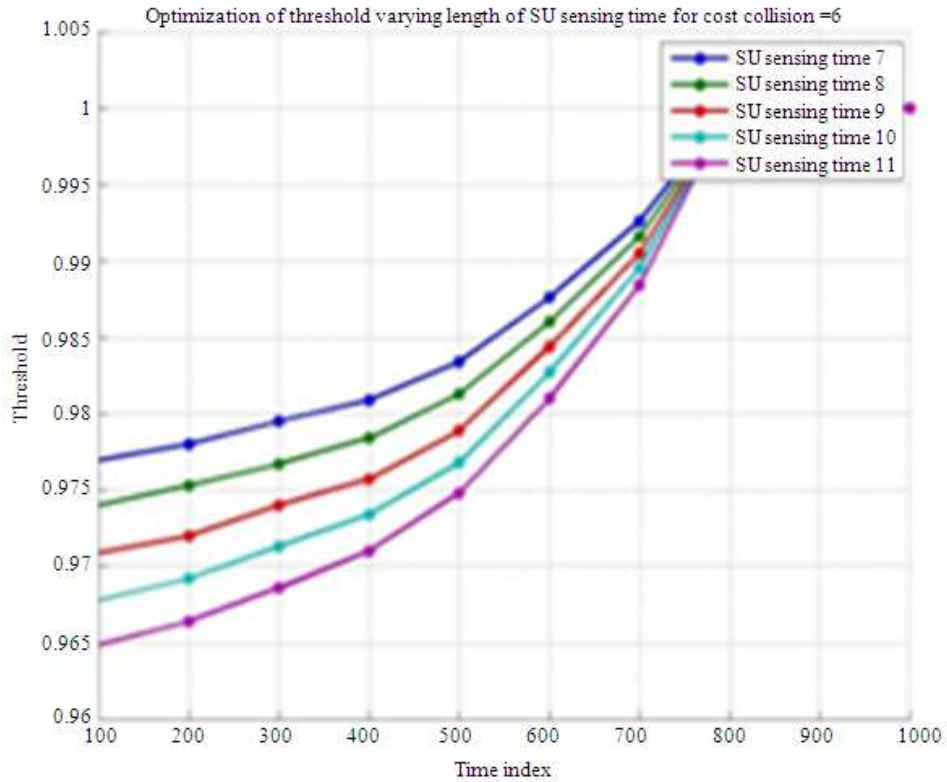


Fig. 6. Threshold V/s time index (SU sensing time = 7 to11)(Collcost = 6)

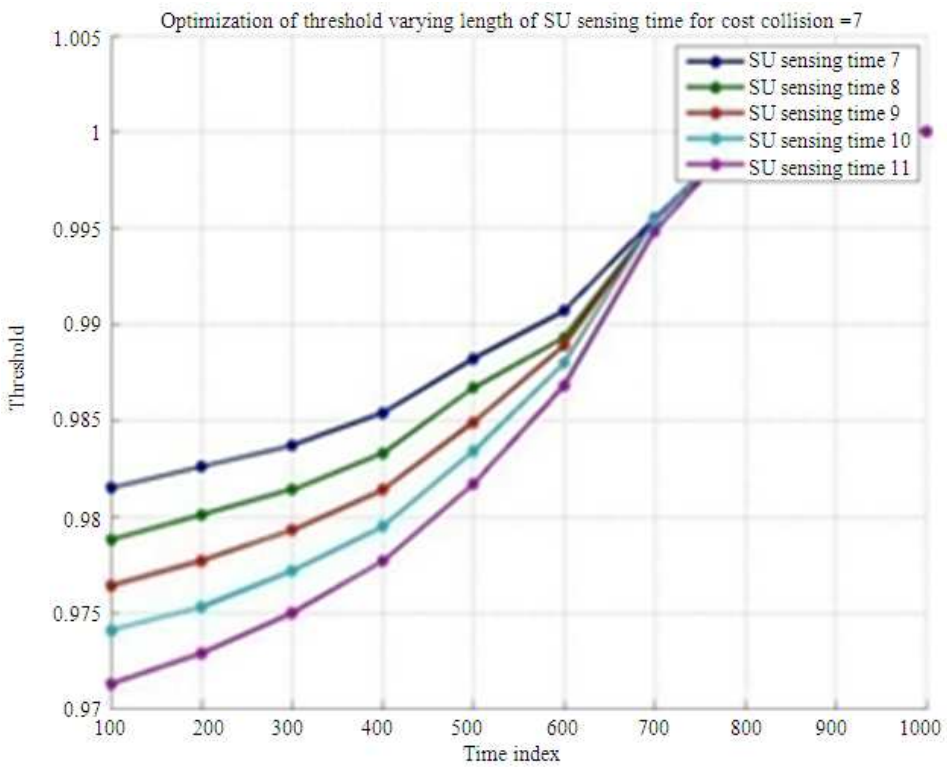


Fig. 7. Threshold V/s time index (SU sensing time = 7to11)(Collcost = 7)

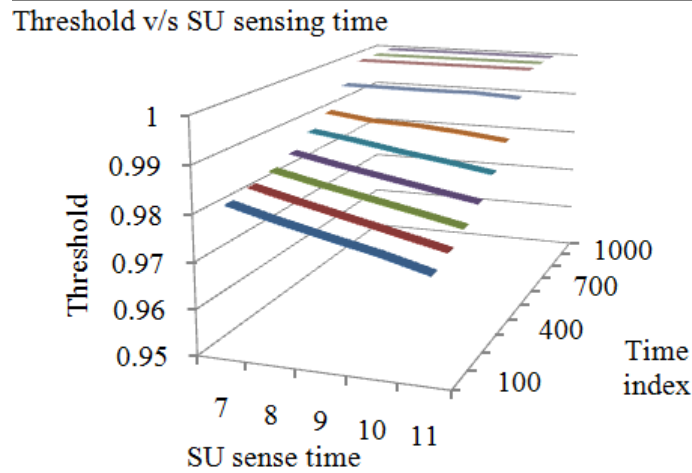


Fig. 8. Threshold V/s SU sensing time (time index=100-1000)(Collcost = 7)

Table 1. Threshold V/s time (SU sensing time=7 to 11)(Collcost = 3)

Threshold values for varying lengths of SU sensing times for Collcost = 3					
Time index	Tsense =7	8	9	10	11
100	0.9469	0.9402	0.9336	0.9272	0.9204
200	0.9481	0.9413	0.9346	0.9281	0.9219
300	0.9494	0.9428	0.9363	0.9302	0.9240
400	0.9513	0.9449	0.9385	0.9323	0.9265
500	0.9541	0.9480	0.9419	0.9362	0.9302
600	0.9572	0.9515	0.9460	0.9408	0.9354
700	0.9627	0.9578	0.9533	0.9489	0.9445
800	0.9763	0.9733	0.9705	0.9677	0.9660
900	1.0000	1.0000	1.0000	1.0000	1.0000
1000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 2. Threshold V/s time (SU sensing time = 7 to 11)(Collcost =4)

Threshold values for varying lengths of SU sensing times for Collcost = 4					
Time index	Tsense =7	8	9	10	11
100	0.962	0.9567	0.9519	0.9472	0.9421
200	0.9629	0.9580	0.9532	0.9484	0.9437
300	0.9643	0.9597	0.9550	0.9505	0.9458
400	0.9665	0.9618	0.9570	0.9528	0.9486
500	0.9686	0.9643	0.9599	0.9561	0.9522
600	0.9717	0.9680	0.9644	0.9609	0.9574
700	0.9785	0.9758	0.9732	0.9705	0.9678
800	0.9880	0.9878	0.9875	0.9879	0.9867
900	1.0000	1.0000	1.0000	1.0000	1.0000
1000	1.0000	1.0000	1.0000	1.0000	1.0000

Inferences and Explanation

Firstly optimal threshold increases with decrease in SU sensing time. This implies that SU senses more often when SU sensing time is less. Higher threshold also implies that SU throughput drops as its sensing utility is more than transmitting utility. Thus SU needs higher probability of PU being idle to start transmission. The Pr_i^* increase with decrease in $Tsense$ is more at $Collcost = 3$ than at $Collcost = 7$, hence at lower collision cost SU

sensing time has more impact on optimal threshold than at higher collision cost.

Secondly optimal threshold increases with increase in cost of collision. Thus depending upon the criticality of PU data, an optimum cost of collision has to be defined. Increase in Pr_i^* with increase in $Collcost$ is less at $Tsense = 7$ and more at $Tsense = 11$, hence cost of collision has higher impact on optimal threshold at higher SU sensing times than at lower SU sensing times.

Table 3. Threshold V/s time (SU sensing time = 7 to 11)(Collcost =5)

Threshold values for varying lengths of SU sensing times for Collcost = 5					
Time index	$T_{sense}=7$	8	9	10	11
100	0.9711	0.9670	0.9635	0.9595	0.9555
200	0.9720	0.9683	0.9646	0.9610	0.9573
300	0.9736	0.9699	0.9666	0.9629	0.9596
400	0.9753	0.9718	0.9684	0.9651	0.9621
500	0.9773	0.9743	0.9712	0.9683	0.9656
600	0.9809	0.9785	0.9762	0.9737	0.9714
700	0.9869	0.9851	0.9837	0.9830	0.9815
800	0.9931	0.9931	0.9931	0.9931	0.9931
900	1.0000	1.0000	1.0000	1.0000	1.0000
1000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 4. Threshold V/s time (SU sensing time = 7 to 11)(Collcost =6)

Threshold values for varying lengths of SU sensing times for Collcost = 6					
Time index	$T_{sense}=7$	8	9	10	11
100	0.9770	0.9740	0.9709	0.9678	0.9649
200	0.9780	0.9753	0.9720	0.9692	0.9664
300	0.9795	0.9767	0.9740	0.9713	0.9686
400	0.9809	0.9784	0.9757	0.9734	0.9710
500	0.9834	0.9813	0.9789	0.9768	0.9748
600	0.9876	0.9860	0.9844	0.9827	0.9810
700	0.9926	0.9916	0.9905	0.9895	0.9884
800	1.0000	1.0000	1.0000	1.0000	1.0000
900	1.0000	1.0000	1.0000	1.0000	1.0000
1000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 5. Threshold V/s time (SU sensing time = 7 to 11)(Collcost =7)

Threshold values for varying lengths of SU sensing times for Collcost = 7					
Time index	$T_{sense}=7$	8	9	10	11
100	0.9815	0.9788	0.9764	0.9741	0.9713
200	0.9826	0.9801	0.9777	0.9753	0.9729
300	0.9837	0.9814	0.9793	0.9772	0.9750
400	0.9854	0.9833	0.9814	0.9795	0.9777
500	0.9882	0.9867	0.9849	0.9834	0.9817
600	0.9907	0.9893	0.9889	0.9880	0.9868
700	0.9955	0.9954	0.9953	0.9954	0.9948
800	1.0000	1.0000	1.0000	1.0000	1.0000
900	1.0000	1.0000	1.0000	1.0000	1.0000
1000	1.0000	1.0000	1.0000	1.0000	1.0000

Conclusion and Future Scope

The present work has lead to traces of optimal threshold (Pr_t^*) value against variations in length of SU sensing time (T_{sense}). These traces lead to determination of the optimal balance between SU aggressiveness and PU contention. With this fine tuning it will be possible to maximize the average utility. This will go on to increase the spectrum utilization efficiency. The results would lead to better and more available spectrum. They will provide an insight for the design of sensing-transmission control in cognitive networks.

This work can be extended to study the effect on optimal threshold (Pr_t^*) for variations in parameters like

probability of detection ($Probd$) i.e., recognizing busy PU as busy, average idle time of PU, average busy time of PU and length of SU packet (T_{packet}).

Funding Information

The authors have no support or funding to report.

Author's Contributions

Inderdeep Kaur Aulakh: After undertaking an extensive study on the topic of sensing-transmission scheduling in cognitive radio networks she developed the system model, based on the constraints. Then simulated it

in Matlab and compared the results with earlier works and also analyzed them for new implications.

Renu Vig: Designed the research plan, organized and supervised the study.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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