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**RESEARCH ARTICLE**

# A NOVEL ENERGY EFFICIENT TECHNIQUE FOR COGNITIVE RADIO NETWORKS

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**Abstract**— We consider a cognitive radio system with one secondary user (SU) accessing multiple channels via periodic sensing and spectrum handoff. We propose an optimal spectrum sensing and access mechanism such that the average energy cost of the SU, which includes the energy consumed by spectrum sensing, channel switching, and data transmission, is minimized, whereas multiple constraints on the reliability of sensing, the throughput, and the delay of the secondary transmission are satisfied. Optimality is achieved by jointly considering two fundamental tradeoffs involved in energy minimization, i.e., the sensing/transmission tradeoff and the wait/switch tradeoff. An efficient convex optimization procedure is developed to solve for the optimal values of the sensing slot duration and the channel switching probability. The advantages of the proposed spectrum sensing and access mechanism are shown through simulations.

 

## I. INTRODUCTION

Cognitive radio is a paradigm that promises efficient use of the radio spectrum through spectrum sharing between primary and secondary transmissions. In some cognitive radio systems, spectrum sharing is facilitated through periodic sensing [1]. Typically, the secondary user (SU) cannot sense and access the channel at the same time, which leads to the fundamental problem of determining the optimal sensing/transmission tradeoff [1], [2]. To date, this problem has been investigated, where the sensing time is designed to maximize the throughput of the SU under different constraints on sensing reliability [1], [2]. However, most of the existing sensing strategies consider the scenario where either a single channel is available [1] or multiple channels are sequentially sensed and accessed [2]. As a result, the SU only transmits data or waits without transmitting, on the channel that is sensed in the same frame. In wideband cognitive radio networks with multiple narrowband channels available for sharing, the throughput of the SU can be significantly increased by performing a "spectrum handoff" [3], in which the SU can switch to another vacant channel and continue data transmission when the current channel is sensed as busy. In practice, however, such a spectrum handoff is not always preferred due to the high energy consumption that may occur. In some cognitive radio systems where energy is critical, e.g., in wireless cognitive sensor networks [4], it is important that spectrum handoff is not excessively used. Instead, the SU may sometimes choose to stop transmission and wait on the current channel for a period of time at the cost of an increased delay and a reduced average throughput.

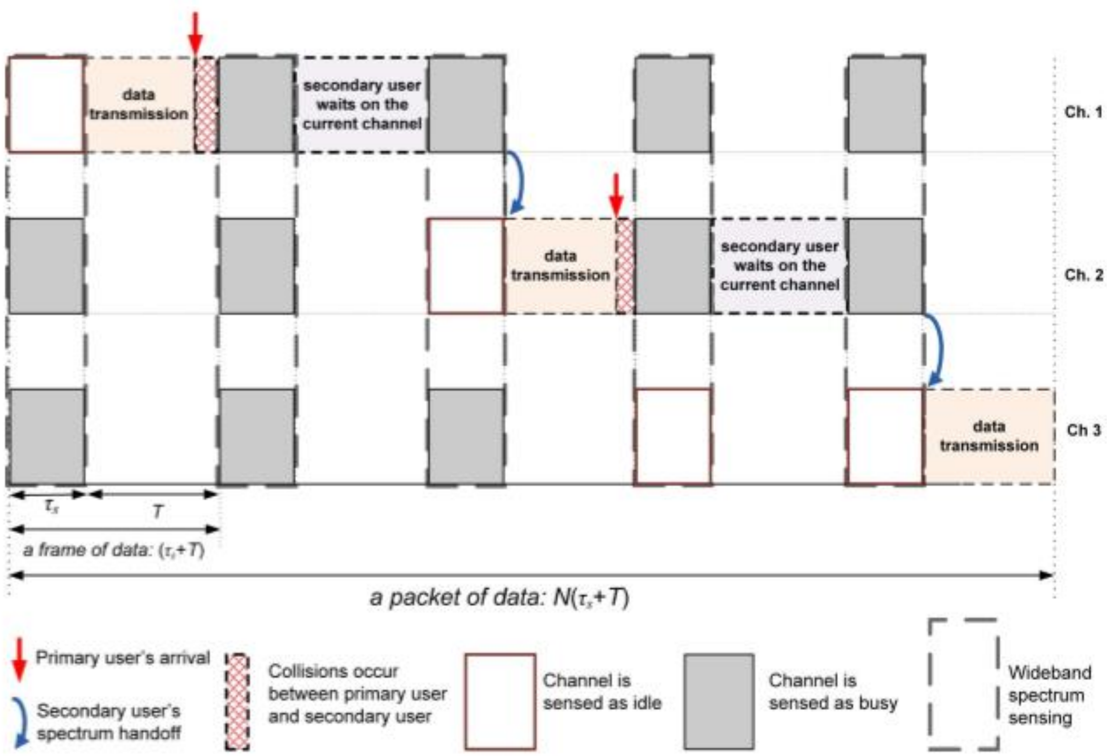


Fig. 1. SU's one-packet transmission including periodic sensing, data transmission, and spectrum handoff.

As a result, there exists an optimal wait/switch tradeoff in spectrum access when the energy consumption of the SU is considered. In the past, this tradeoff has been largely overlooked when the optimal spectrum access strategy is designed to maximize the throughput of the SU without considering the energy constraint [5]. Although energy efficiency in cognitive radio networks has gained more attention in the literature of late [6]–[8], the existing schemes focus on either the sensing/transmission tradeoff while neglecting spectrum handoff [6], [7] or the wait/switch tradeoff while ignoring sensing errors [8]. To the best of the authors' knowledge, no work that jointly considers spectrum sensing and handoff for energy-efficient cognitive radio networks has been carried out. In this paper, we propose an optimal spectrum sensing and access mechanism where the two fundamental tradeoffs in periodic sensing and spectrum handoff are jointly considered. The optimal sensing and access mechanism aims at minimizing the total energy cost of the SU, including that due to spectrum sensing, handoff, and data transmission, while, at the same time, satisfying multiple constraints on SU sensing reliability, average throughput, and delay. The rest of this paper is organized as follows: Section II describes the system model concerning the spectrum sensing and access mechanism. Section III formulates and solves the optimization problem. Simulation results and discussions are shown in Section IV, and Section V concludes this paper.

## II. SYSTEM MODEL

Consider a cognitive radio system with one secondary link and one primary link. Suppose that there are M channels that are shared between the primary user (PU) and the SU. At a given time instant, one of the M channels is allocated to the SU. Assume that the secondary transmission is slotted via periodic sensing, where each frame consists of a sensing slot of duration τs and a transmission slot of duration T. At the beginning of each transmission slot, the SU may choose to transmit data on the current channel, stay on the current channel without transmitting, or switch to another channel. Unlike the secondary transmission, the primary transmission is assumed to be continuous, and it follows an on–off traffic model [9], where the probability of the primary transmission being on (off) is the same for each channel. Fig. 1 shows the SU's activities in transmitting a packet of data. In the sensing slot, the SU performs wideband sensing to obtain the availability status of all the channels. Assume that energy detection is used to simultaneously sense the channels. Let the average received signal-to-noise ratio (SNR) of the PU's signal on each channel be γ, which is assumed to be the same for all channels during one packet of data transmission [10]. The detection probability and the false alarm probability, which are denoted as Pd and Pf, respectively, are given by [1]

$$P_d(\tau_s) = Q\left(\frac{1}{\sqrt{2\gamma+1}}\left(Q^{-1}(P_{f_t}) - \sqrt{\tau_s f_s}\gamma\right)\right) \quad (1)$$

$$P_f(\tau_s) = Q\left(\sqrt{2\gamma+1}Q^{-1}(P_{d_t}) + \sqrt{\tau_s f_s}\gamma\right) \quad (2)$$

where Q(x) is the Gaussian tail probability with inverse Q−1(·); fs is the sampling frequency in hertz; and Pdt and Pft are the target detection probability and false alarm probability, respectively, which are assumed to be the same for all channels. It is known that, for a fixed sampling frequency fs, there exists a minimum sensing time such that the target detection probability and false alarm probability are satisfied. Such a minimum required sensing time, which is denoted as τmin s , is given by [1]

$$\tau_s^{\min} = \frac{1}{\gamma^2 f_s}\left(Q^{-1}\left(P_{f_t}\right) - Q^{-1}\left(P_{d_t}\right)\sqrt{2\gamma+1}\right)^2. \quad (3)$$

When energy detection is used, the energy consumption due to sensing is determined by the length of the sensing time. Therefore, using τmin s as the sensing duration minimizes the energy cost of the SU due to spectrum sensing. However, such a τmin s is not necessarily the optimal in terms of minimizing the total energy cost of the SU, which is incurred from spectrum sensing, spectrum handoff, and data transmission. This is because increasing the sensing time may result in more accurate sensing results and smaller probability of switching to a channel that is falsely detected as idle, which, in turn, leads to lower energy consumption, given the throughput and delay constraints of the secondary transmission. Therefore, there exists an optimal τs when the total energy consumption of the SU is concerned. After obtaining information of the availability of all channels through sensing, the SU will make a decision prior to transmission on whether to switch to another vacant channel or stay on the current channel. We assume that, if the SU switches to another channel, it must perform transmission for a time duration of T until the next sensing slot arrives. However, if it stays on the current channel, it may choose to perform data transmission for a time duration of T or simply refrain from transmitting until the next sensing slot arrives. We assume that the delay due to spectrum handoff is small enough that it is negligible. In addition, when the SU waits on the current channel with power off, we assume that the energy consumption during this transmission slot is negligible. A flowchart of the SU's spectrum access process is given in Fig. 2. Such a switch-wait model is designed considering the tradeoff between energy savings and the performance of the secondary transmission in terms of throughput and delay. For example, when the current channel is sensed as idle, the SU should stay on the current channel and continue data transmission because there is no benefit to the SU in terms of both energy savings and throughput increment by switching to another channel. Similarly, when all M channels are sensed as busy, the SU should wait on the current channel and power off for a duration of T seconds, because attempting to switch or transmit on any of the channels will simply increase power consumption without improving the throughput and delay of the secondary transmission. In the case where the current channel is sensed as busy and there is at least one other channel that is sensed as idle, the SU needs to decide whether to wait on the current channel with power off to save energy at the cost of an increased delay and a reduced throughput, or to spend energy to switch to a vacant channel such that the secondary link transmission can continue. In such a case, we assume that the SU waits on the current channel and stops transmission with a probability of Ps, or switches to another vacant channel with a probability of 1−Ps. The design of the spectrum access strategy to minimize the total energy cost requires determining Ps, which relies on the accuracy of the sensing results and, therefore, is an implicit function of τs. Next, we formulate the optimization problem that jointly optimizes τs and Ps such that the energy consumption of the SU to transmit a packet of data is minimized, whereas constraints on the sensing accuracy and the throughput, and the delay of the secondary trans- mission are satisfied.

 

## III. OPTIMIZATION PROBLEM

The optimization problem is formulated as

$$\begin{array}{ll} \min\limits_{\tau_s, P_s} & J(\tau_s, P_s) \\ \text{subject to} & P_d(\tau_s) \geq P_{d_t} \\ & P_f(\tau_s) \leq P_{f_t} \\ & R(\tau_s, P_s) \geq \mathcal{R} \\ & D(\tau_s, P_s) \leq \mathcal{D} \end{array} \qquad (4)$$

where S is the time required for the SU to transmit a packet of data, J is the total average energy consumption required to finish transmitting one packet of data, R is the average throughput, D is the average delay, and R and D are the thresholds for the average throughput and delay of the secondary transmission, respectively. Recall that Pd and Pf are the probabilities of detection and false alarm, respectively, and Pdt and Pft are the corresponding target probabilities of detection and false alarm, respectively. To solve the optimization problem, we need to derive the expressions for J, R, andD, which are functions of τs and Ps.

### A. Preliminaries

We first introduce some probability calculations that will be used later. Let Xi = 0 andXi = 1 be the events that the status of the ith channel is idle and busy, respectively, and ˜ Xi = 0 and ˜ Xi = 1 be the events that the ith channel is sensed as idle and busy, respectively. The probability of detection and the probability of false alarm, which are defined as Pd = P( ˜ Xi = 1|Xi = 1) and Pf = P( ˜ Xi = 1|Xi = 0), are both functions of τs. Denote the probability of a channel being busy as ρ, which is assumed to be known for a given primary system [9]. The probabilities that the ith channel is correctly sensed as idle, falsely sensed as idle, correctly sensed as busy, and falsely sensed as busy are given by Pc1 = P( ˜ Xi = 0|Xi = 0)P(Xi = 0)=( 1−Pf) (1−ρ), Pc2 = P( ˜ Xi = 0|Xi = 1)P(Xi = 1)=( 1−Pd)ρ, Pc3 = P( ˜ Xi = 1|Xi = 1)P(Xi = 1)=Pdρ, andPc4 = P( ˜ Xi = 1|Xi = 0)P(Xi = 0)=Pf(1−ρ), respectively. Note that Pc1, Pc2, Pc3 and Pc4 are all functions of τs because Pd and Pf are functions of τs. We assume throughout this paper that all M channels are statistically independent.

### B. Derivation of J(τs,Ps)

The average time required for the SU to finish transmitting one packet of data with a time duration of S is given by Ts = S/Pt, where Pt is the probability of transmission. One has

N(τs,Ps)=[S/(PtT)] (5)

where [.] is the ceiling operator. The probability that the current channel is sensed as idle (Event-1 in Fig. 2), which is denoted as P1, is

P1(τs)=Pc1 + Pc2 =( 1−ρ)(1−Pf)+ρ(1−Pd) (6)

Similarly, the probability that all other M −1 channels are sensed as busy, which is denoted as Pb, is given by

$$P_b(\tau_s)=(P_{c3} + P_{c4})^{M-1} =(P_d\rho + P_f(1-\rho))^{M-1} \quad (7)$$

which follows from the independence of the channels. When the current channel is sensed as busy and at least one of the other channels is sensed as idle, the SU may choose to switch to a vacant channel to continue data transmission with a probability of 1−Ps. Such an event, which is denoted as Event-3 in Fig. 2, has a probability of

$$P_3(\tau_s,P_s)=( 1-P_1)(1-P_b)(1-P_s) \quad (8)$$

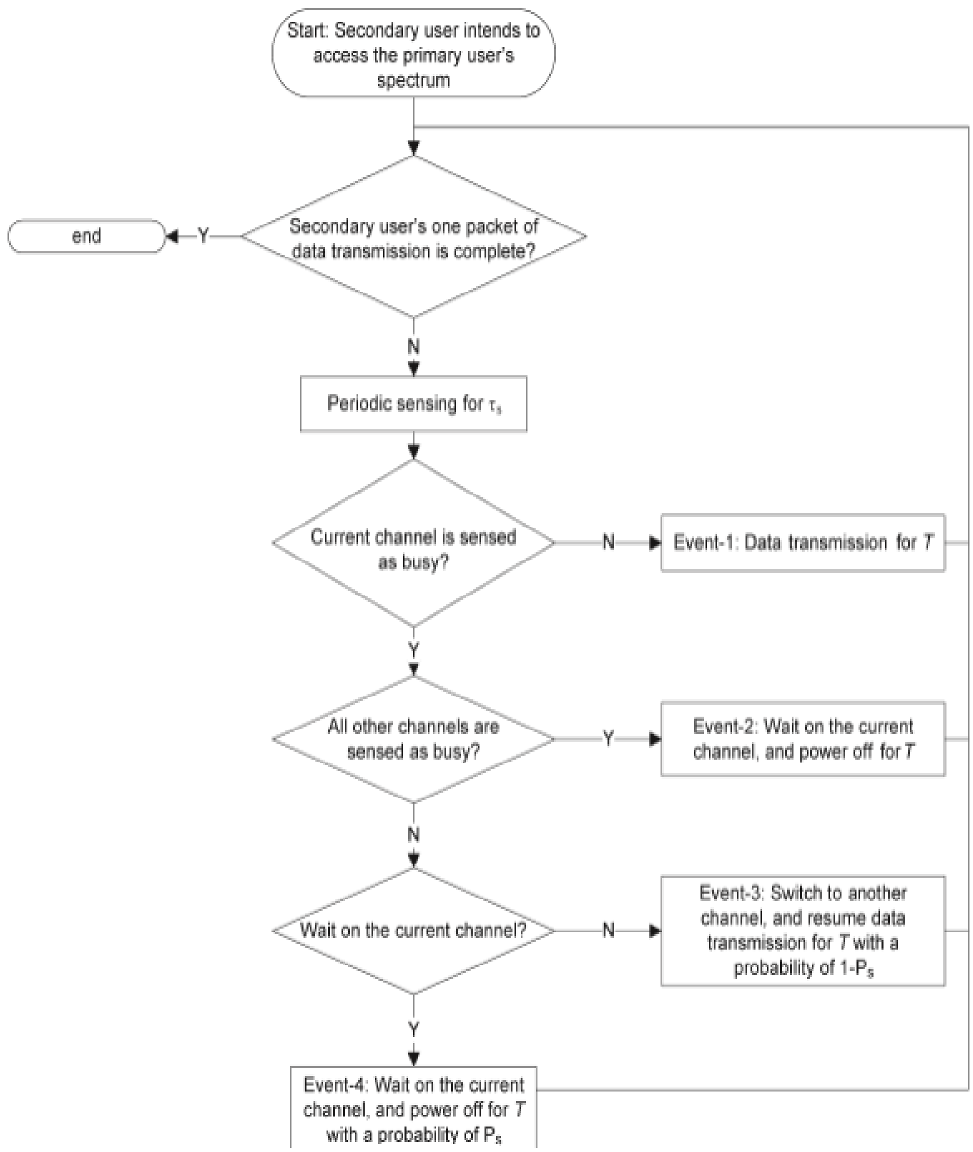


Fig. 2. Proposed energy-efficient spectrum sensing and access mechanism for the SU to transmit a packet of data

 

The probability that the SU performs data transmission is therefore given by

$Pt(\tau s,Ps)=P1 + P3 = P1 +(1-P1)(1-Pb)(1-Ps)$ (9)

The total average energy cost, including the energy consumption due to spectrum sensing, spectrum handoff, and data transmission, is given by

$$J(\tau_s, P_s) = \underbrace{N\tau_s E_s}_{\text{sensing}} + \underbrace{NP_3 J_{sw}}_{\text{switching}} + \underbrace{SE_t}_{\text{transmission}} \qquad (10)$$

where Es and Et are the power (energy cost per second) due to sensing and data transmission, respectively, both in the unit of watts; and Jsw is the energy cost for one channel switching, in the unit of joules. Assuming that Es, Et, andJsw are known for a given secondary system, the average total energy cost can be obtained by calcu- lating (10). Note that, in (10), we have assumed for simplicity that the same energy cost applies when the SU switches from the current channel to one of the other channels that are sensed as idle. In such a case, when the SU decides to switch, one of the idle channels is randomly selected without affecting the average energy cost. It is noted, however, that the energy cost due to each channel switching may be different, depending on, for example, whether the channel to switch to is located close to, or far from, the current channel in frequency. Having noticed that such a variation in the energy consumption due to channel switching does not affect the constraints given in (4) when the occupying state of each channel is the same, the SU may simply choose to switch to the channel that is the most adjacent to the current channel, thus costing the least energy due to switching.

### C. Derivation of R(τs,Ps)

Let C0 = log 2(1 + SNR) bits/s/Hz be the SU's data rate, where SNR is the received SNR at the secondary receiver. Without primary transmission, the bits that are successfully transmitted in one trans- mission period T is C0T. However, the primary transmission is not slotted, and it can arrive at any time during the transmission slot T, causing a collision between the primary and secondary transmissions. We assume that, during the time when a collision occurs, the SU's transmission rate is approximately zero [1]. In addition, we assume that, once a primary transmission arrives in one transmission slot, the primary transmission does not exit until the next sensing slot arrives [9]. Let β0 be the average duration of the PU being off in a given channel, which is usually known according to the traffic model of a given system [9]. The average time duration for the primary transmission to occur on an idle channel in a transmission slot T, which is denoted as ¯ t, is given by¯ t = T −β0(1−e−(T/β0)) [9], and the number of bits transmitted in one transmission slot T, which is denoted as BT , is given by BT =( 1−(¯t/T))C0T [9]. Following Fig. 2, there are two cases where collisions may occur. The two cases occur in Event-1 and Event-3 when the channel that the SU stays on or switches to is idle. For the first case, the average number of bits that are transmitted in a period of τs + T is given by

$B1 = Pc1BT$ (11)

For the second case, the average number of bits that are transmitted in a period of τs + T is given by

$B2 = P3(1-Pe)BT$ (12)

where Pe is the probability of the SU switching to a busy channel, which can be calculated as follows. Let Sb = 1 denotes the event that the SU switches to a busy channel. Suppose that, among the M −1 other channels (apart from the current channel), there are ω channels that have been sensed as idle. Let I denote the set of channels that are correctly sensed as idle and J denote the set of channels that are incorrectly sensed as idle. The probability of the SU switching to a busy channel is given by

Pe(τs)=P(Sb = 1)

$$= \sum_{\omega=1}^{M-1} \sum_{j=1}^{\omega} P\left(S_b = 1, |\mathcal{I}| + |\mathcal{J}| = \omega, |\mathcal{J}| = j\right) \qquad (13)$$

where

$$P\left(S_b = 1, |\mathcal{I}| + |\mathcal{J}| = \omega, |\mathcal{J}| = j\right) = \frac{j}{\omega}\binom{\omega}{j} P_{c_1}^{\omega-j} P_{c_2}^{j} = \binom{\omega-1}{j-1} P_{c_1}^{\omega-j} P_{c_2}^{j} \qquad (14)$$

which is a function of τs, because Pc1 and Pc2 are functions of τs. The average throughput of the secondary transmission is given by

$$R(\tau_s, P_s) = \frac{B_1 + B_2}{\tau_s + T} = \frac{P_{c_1} + P_3(1 - P_e)}{\tau_s + T} B_T \qquad (15)$$

where R is a function of τs and Ps, asPc1 and Pe are functions of τs, and P3 is a function of τs and Ps.

**D. Derivation of D(τs,Ps)**

Recall that the delay due to channel switching can be neglected. The delay in a secondary transmission is therefore caused by spectrum sensing and the SU waiting on the current channel without transmit- ting. The delay due to spectrum sensing is Nτs, whereN is given by (5). There are two cases where the SU waits on the current channel: 1) when all channels are sensed as busy (Event-2 in Fig. 2) and 2) when there is at least one other vacant channel but the SU chooses not to switch with a probability of Ps (Event-4 in Fig. 2). The probability that the SU waits on the current channel is given by

Pwt(τs,Ps)=P2 + P4 =( 1−P1)Pb +(1−P1)(1−Pb)Ps (16)

where P1 and Pb are given in Section III-B. The average delay for the SU to finish transmitting a packet of data is given by

D(τs,Ps)=Nτs + NTPwt (17)

E**. Solving the Optimization Problem**

It is noted from the derivations given in (15) and (17) that, for a given τs, R is monotonically decreasing with Ps, whereas D is monotonically increasing with Ps. This is intuitively correct because the more the SU waits on the current channel without transmitting (with a larger Ps), the less data it can deliver within a given time period. We also note from (4) that the optimal Ps is determined by the last two constraints. In addition, it can be verified that, for a given τs, J(Ps) is monotonically decreasing with Ps when Jsw > Esτs/P1(τs). One can confirm that this condition can be easily satisfied with the parameters given in practical systems. As a result, the optimal Ps is simply the maximum allowable Ps that satisfies both constraints. In another word, the optimal Ps that solves (4) is given by

Popt s (τs) = min{α(τs),β(τs)} (18)

where α(τs) and β(τs) are obtained by letting R(Ps,τs)=R and D(Ps,τs)=D, and solving for Ps, respectively. Specifically, we have

$$\alpha(\tau_s) = 1 - \frac{(\tau_s + T)\mathcal{R} - P_{e_1} B_T}{B_T(1-P_1)(1-P_e)(1-P_b)} \qquad (19)$$

$$\beta(\tau_s) = \frac{\eta T - (1-\eta)\tau_s}{T(1-P_1)(1-P_b)} - \frac{P_b}{1-P_b} \qquad (20)$$

where η = D/(D+ S). Note that, in order for the optimal Ps to exist, thresholds R and D need to be defined such that min{α(τs),β(τs)}∈ [0,1]. Having obtained (18) as a function of τs, (4) becomes an optimization problem with a single variable τs. One can confirm that, with parameters considered in practical cases, e.g., for a reasonably low received primary SNR of γ<2 dB [1], [2] or considering the actual sensing time τs to be in a range reasonably close to τmin s (τmin s ≤ τs ≤ 2τmin s ), both J and D are convex functions of τs, and R is a concave function of τs. In addition, having noticed that the first two constraints in (4) effectively defines that τs ≥ τmin s , which is an affine function of τs, the optimization problem given in (4) is therefore a convex optimization problem with a single variable τs, and the optimal τs can be obtained by using existing numerical techniques.

## IV. SIMULATIONS AND DISCUSSIONS

We show the optimality of the proposed spectrum sensing and access mechanism and compare the performance of the secondary transmission in terms of throughput and delay to that using the same transmission structure without spectrum handoff. In all simulations, we assumed that there are M = 3 channels available for spectrum sharing between the PU and the SU. In addition, we assume that the duration of a packet of data is S = 6 s, the duration of each transmission slot is T = 0.5 s, and the power required for spectrum sensing and transmission are Es = 40 mW and Et = 69.5 mW, respectively [4]. We considered two cases for the energy cost due to each channel switching, where Jsw = 40 mJ and Jsw = 2 mJ, corresponding to practical scenarios where the frequency channel to which the SU switches is located far from, or relatively close to, the current channel. The results in all figures are obtained by letting the received SNR of the PU's signal be γ = −10 dB, the probability of a channel being busy be ρ = 0.35, and the target probability of detection and false alarm be Pdt = 0.9 and Pft = 0.1. The throughput and delay thresholds are defined asR = μR0 and D = λS, whereμ ∈ [0,1] and λ ∈ [0,1], andR0 =( 1−ρ)C0 is the average throughput of SU with PU transmission at SNR = 10 dB. Having noticed that only one of the throughput and delay constrains can be active in the optimization procedure, in the following figures, we study the effects that the constraints have on energy consumption separately. In all the figures, the curves for each pair of Ps and τs are plotted to a point where the constraint is satisfied. In another words, the missing tail part in some curves indicates that the corresponding constraint can no longer be satisfied when such τs and Ps are used.

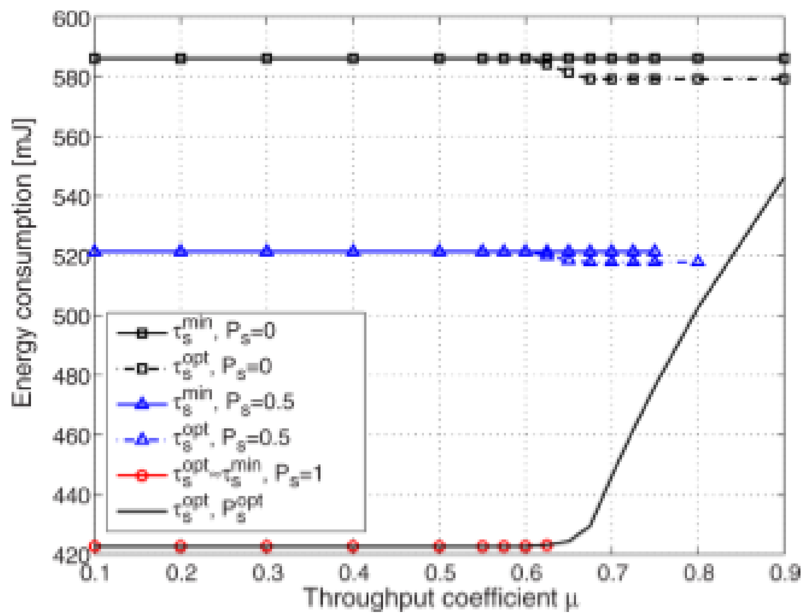


Fig. 3. Energy consumption as a function of the throughput constraint $\mathcal{R} = \mu R_0$ and $J_{sw} = 40$ mJ.

Fig. 3 plots the energy consumption of the SU as a function of the throughput coefficient μ for Jsw = 40 mJ. It is observed from Fig. 3 that, regardless of the value of Ps, when the throughput constraint is less stringent (with a smaller μ), the minimum energy consumption is achieved when the optimal τs is equivalent to τmin s given in (3). This is because, for a given Ps, whenμ is small, it is likely that the throughput constraint will be satisfied as long as τs is sufficiently small. As a result, the optimal sensing time is only determined by the sensing reliability. Interestingly, for a given Ps such as Ps = 0 and 0.5, it is observed that a larger sensing duration (τopt s >τmin s ) is desired for a more stringent throughput constraint, i.e., with an increasing μ. This is because a longer sensing duration indicates more accurate sensing results, thus increasing the possibility of correctly transmitting on an idle channel. In addition, although increasing the sensing duration increases the energy consumption due to spectrum sensing, the overall energy consumption is essentially decreased since more successful transmissions can be guaranteed. It is also shown in the figure that the minimum energy can be achieved when the SU always chooses to wait at the current channel without transmitting (Ps = 1). However, such an access scheme can only meet the through- put constraint with a coefficient of about μ<0.65 when τmin s is used. Using the optimal τs and Ps obtained in Section III, however, always yield the lowest energy consumption while satisfying the throughput constraint. Fig. 4 plots the energy consumption of the SU as a function of the delay coefficient λ for Jsw = 40 mJ, where a smaller λ indicates a more stringent delay constraint. Again, it is observed from the figure that, with the same τs, more stringent delay constraint can be satisfied when the probability of waiting on the current channel without transmitting decreases, i.e., when a smaller Ps is used. However, a higher energy consumption occurs when a smaller Ps is used. The optimal τs and Ps pair yields the minimum energy consumption while satisfying the required delay constraint. A similar figure with Jsw = 2 mJ is also plotted in Fig. 5, where it shows that, when the energy for channel switching is small, the optimal τs is essentially τmin s given in (3).

In such a case, the optimization procedure can be considerably simplified where the optimal Ps is obtained by first obtaining τmin s and then computing (18). It is observed from the figure that jointly optimizing τs and Ps yields the lowest energy cost and satisfies both constraints while that using a non-optimal Ps always results in higher energy consumption and may not necessarily satisfy a stringent delay constraint, e.g., λ<0.65 when Ps = 1.

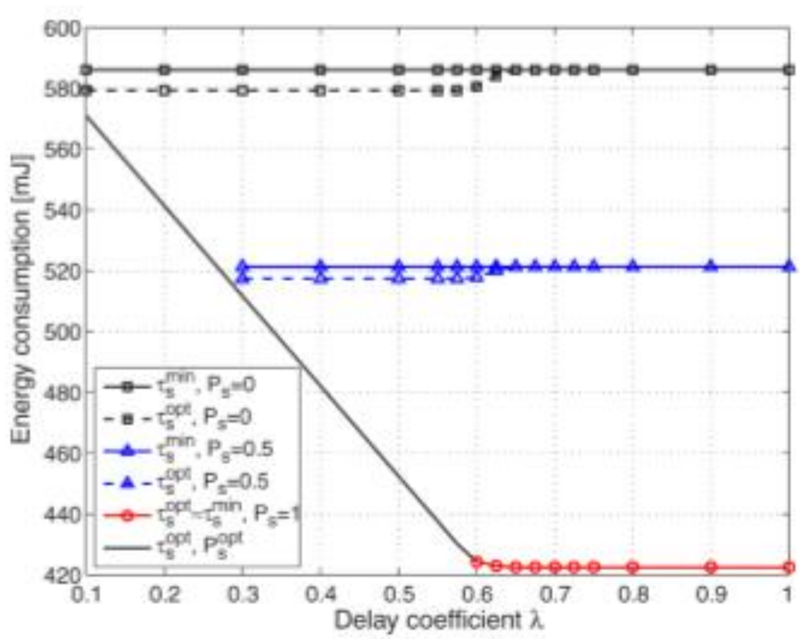


Fig. 4. Energy consumption as a function of the delay constraint $\mathcal{D} = \lambda S$ and $J_{sw} = 40$ mJ.

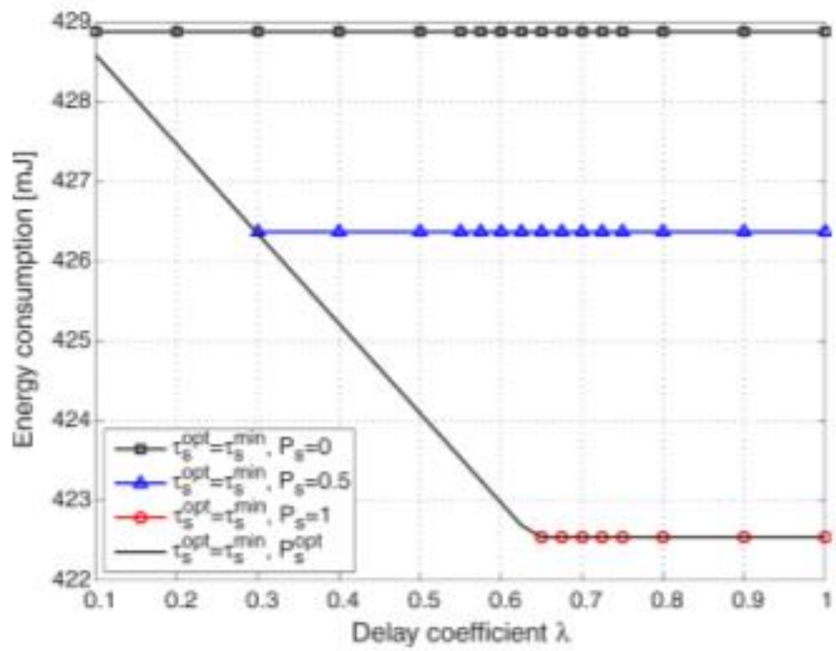


**Fig. 5. Energy consumption as a function of the delay constraint $\mathcal{D} = \lambda S$ and $J_{sw} = 2$ mJ.**

In Figs. 6 and 7, we compare the proposed spectrum sensing and access scheme with that given in [1], in which only the sensing/ throughput tradeoff was considered to design the optimal τs. It is shown in Figs. 6 and 7 that, when either the throughput constraint or the delay constraint is considered, for both cases where Jsw = 40 mJ and Jsw = 2 mJ, the τs that only optimizes the sensing/throughput tradeoff (as is given in [1]) is not necessarily optimal in terms of minimizing the total energy cost, where it yields an equivalent or higher energy consumption compared with the case when τopt s is used. Note that τopt s is designed when both the sensing/throughput and wait/switch tradeoffs are jointly considered. In particular, when no spectrum handoff is considered (Ps = 1), usingτs as defined in [1] cannot meet a throughput constraint for about μ>0.65 or a delay constraint for λ<0.6.

 

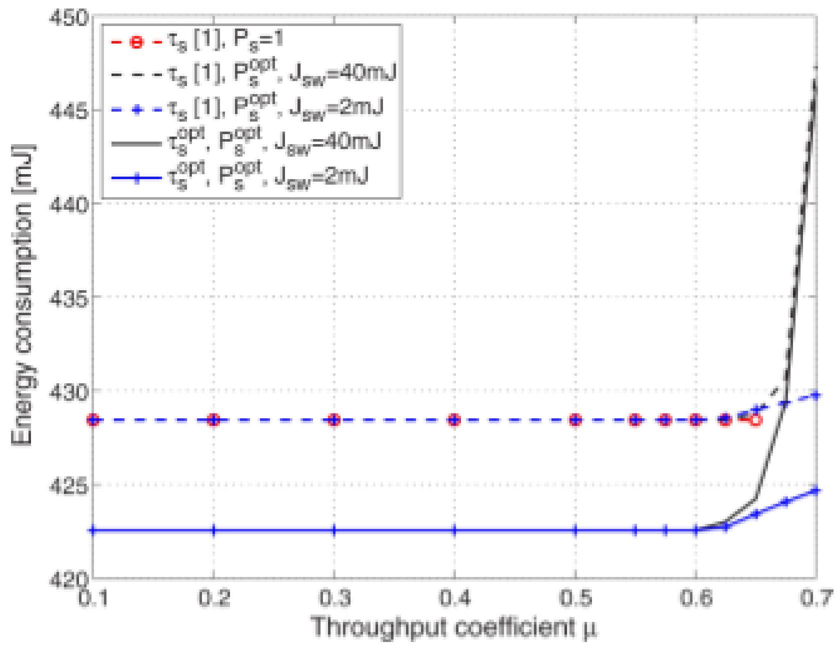


Fig. 6. Energy consumption using the optimal $\tau_s$ and $P_s$, compared with that using the $\tau_s$, where only the sensing/throughput tradeoff is considered, when the throughput constraint is considered.

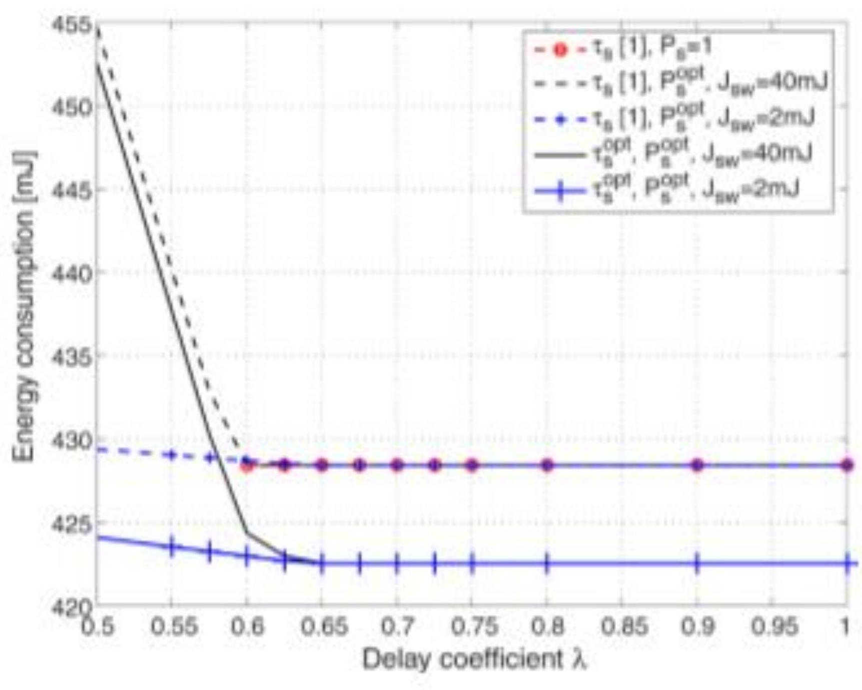


Fig. 7. Energy consumption using the optimal $\tau_s$ and $P_s$, compared with that using the $\tau_s$ where only the sensing/throughput tradeoff is considered, when the delay constraint is considered.

## V. CONCLUSION

In this paper, a spectrum sensing and access mechanism with spectrum handoff has been proposed. The proposed mechanism has jointly considered the sensing/throughput tradeoff in terms of the duration of sensing time τs, as well as the wait/switch tradeoff in terms of the probability of channel switching 1−Ps. An optimization problem has been formulated and has been efficiently solved such that τs and Ps are jointly optimized to minimize the energy consumption of the SU in transmitting a packet of data while, at the same time, satisfying multiple constraints on the sensing reliability and performance of the secondary transmission in terms of throughput and delay. Simulation results showed the optimality of the proposed mechanism and the benefit of performing spectrum handoff where more stringent throughput and delay constraints on the secondary transmission can be satisfied while providing the minimum energy cost.

## REFERENCES

[1] Y.-C. Liang, Y. Zeng, E. C. Peh, and A. T. Hoang, “Sensing-throughput tradeoff for cognitive radio networks,” IEEE Trans. Wireless Commun., vol. 7, no. 4, pp. 1326–1337, Apr. 2008.

[2] X. Li, Q. Zhao, X. Guan, and L. Tong, “Sensing and communication tradeoff for cognitive access of continues-time Markov channels,” in Proc. IEEE WCNC, Apr. 2010, pp. 1–6.

[3] C.-W. Wang, L.-C. Wang, and F. Adachi, “Modeling and analysis for reactive-decision spectrum handoff in cognitive radio networks,” in Proc. IEEE Globecom, Dec 2010, pp. 1–6.

[4] S. Maleki, A. Pandharipande, and G. Leus, “Energy-efficient distributed spectrum sensing for cogntive sensor netowrks,” IEEE Sens. J., vol. 11, no. 3, pp. 565–573, Mar. 2011.

[5] Q. Zhao, S. Geirhofer, L. Tong, and B. M. Sadler, “Opportunistic spec- trum access via periodic channel sensing,” IEEE Trans. Signal Process., vol. 56, no. 2, pp. 785–796, Feb. 2008.

[6] A. T. Hoang, Y.-C. Liang, D. T. C. Wong, Y. Zeng, and R. Zhang, “Opportunistic spectrum access for energy-constrained cognitive ra- dios,” IEEE Trans. Wireless Commun., vol. 8, no. 3, pp. 1206–1211, Mar. 2009.

[7] H. Su and X. Zhang, “Power-efficient periodic spectrum sensing for cogn- tive MAC in dynamic spectrum access networks,” in Proc. IEEE WCNC, Apr. 2010, pp. 1–6.

[8] Y. Chen, Q. Zhao, and A. Swami, “Distributed spectrum sensing and access in cognitive radio networks with energy constraint,” IEEE Trans. Signal Process., vol. 57, no. 2, pp. 783–797, Feb. 2009.

[9] Y. Pei, A. T. Hoang, and Y.-C. Liang, “Sensing-throughput tradeoff in cognitive radio networks: How frequently should spectrum sensing be carried out?,” in Proc. IEEE Int. Symp. PIMRC, Sep. 2007, pp. 1–5.

[10] C.-W. Wang and L.-C. Wang, “Modeling and analysis for proactive- decision spectrum handoff in cognitive radio networks,” in Proc. IEEE ICC, Jun. 2009, pp. 1–6.

 