Sensing-Throughput Tradeoff in Spectrum Handoff-Based Cognitive Radio

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Abstract. In cognitive radio (CR), there is a tradeoff between spectrum sensing time and throughput of secondary user (SU). In order to improve the SU's throughput, a sensing-throughput tradeoff in spectrum-handoff based CR is proposed, which allows the SU to search and transfer to a new idle channel to continue communication, when the PU is present. An optimization problem is proposed to maximize the SU's throughput in the proposed scheme through jointly optimizing the sensing time, the searching time and the number of available channels subject to the detection probability to the PU. The simulation results show that there exist the optimal solutions to the proposed scheme and the proposed scheme outperforms the conventional scheme notably.

Keywords: Cognitive radio · Energy sensing · Throughput · Sampling frequency · Detection probability

1 Introduction

In order to improve the current spectrum utilization, CR allows the secondary user (SU) to dynamically access the idle spectrum that isn't temporarily used by the PU, providing that the SU will not disturb the normal communication of the PU [1–3]. To control interference to PU, the SU detects whether the PU exists in the channel depending on the spectrum sensing technology; if the absence of the PU is detected, the SU can transmit data in the channel, and otherwise it must stop communicating [4, 5].

Energy sensing, as an effective spectrum sensing technology, is frequently used in CR, which estimates the presence of the signal source through comparing the energy statistics of the received signal to a presettled threshold [6–8]. The SU often uses the PU's spectrum by the listen-before-transmit strategy. At the beginning of every frame, the SU firstly detects the absence of the PU in the sensing slot, and then forwards data in the transmission slot [9]. An optimization scheme of energy sensing-throughput tradeoff is proposed in [10–13], whose optimal solutions are theoretically proven to be existent; however, the authors assume that when the presence of the PU is detected, the SU must stop transmitting and wait until the new detection result is achieved in the following frame, therefore yielding the great loss of the SU's throughput.

In the proposed scheme, the SU is allowed to transfer to another idle channel to continue communication through spectrum searching, when the presence of the PU is detected. We have considered the spectrum handoff and proposed a joint optimization scheme of sensing time and searching time [14]. Through the joint optimization, the total sensing delay including local spectrum sensing and idle channel searching can be decreased and the achievable throughput of the SU in a specific frame can be maximized.

2   Sensing-Throughput Tradeoff Scheme

2.1   Energy Sensing

In energy sensing, according to the two different states: the absence of the PU (denoted by H_0) and the presence of the PU (denoted by H_1), the received sampling signal $y(m)$ is given by

$$y(m) = \begin{cases} h(m)s(m) + n(m), H_1 \\ n(m), H_0 \end{cases}, m = 1, 2, \ldots, M \tag{1}$$

where $s(m)$ is the PU's signal with the power of p_s, $n(m)$ is the Gaussian noise with the power of σ_n^2, $h(m)$ is the channel gain between the SU and the PU, and M is the number of the sampling nodes. By supposing that the sampling frequency is f_s and the spectrum sensing time is τ, M is given by

$$M = \tau f_s. \tag{2}$$

Energy sensing firstly calculates the energy statistics of the SU's received signal as follows

$$Z(y) = \frac{1}{M} \sum_{m=1}^{M} \|y(m)\|^2. \tag{3}$$

By comparing $Z(y)$ to a presettled threshold λ, the presence of the PU is decided by $Z(y) \geq \lambda$, while the absence of the PU is determined by $Z(y) < \lambda$. Hence, the false alarm probability P_f and the detection probability P_d are the functions related with the sensing time τ as follows

$$P_f(\tau) = Q\left(\left(\frac{\lambda}{\sigma_n^2} - 1\right)\sqrt{\tau f_s}\right); \quad P_d(\tau) = Q\left(\left(\frac{\lambda}{\sigma_n^2(1 + \gamma_p)} - 1\right)\sqrt{\tau f_s}\right) \tag{4}$$

where the SNR of the communication link between the PU and the SU is $\gamma_p = h^2 p_s / \sigma_n^2$ and the function $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{+\infty} \exp(-\frac{y^2}{2}) \, dy$. According to (4), P_f can be denoted by P_d as follows

$$P_f(\tau) = Q\left(Q^{-1}(P_d)(1 + \gamma_p) + \gamma_p \sqrt{\tau f_s}\right). \tag{5}$$

2.2   System Model

By supposing that the length of the SU's transmission frame is T, the conventional sensing-throughput tradeoff scheme is shown in Fig. 1. In the conventional scheme, every frame of the SU includes one sensing slot and one transmission slot. In the sensing slot, the SU firstly senses the PU, and if the absence of the PU is detected, the SU then forwards data in the transmission slot, otherwise it stops transmitting any data in this frame and waits to redetect the absence of the PU in the following frame [11]. In the conventional scheme, when the presence of the PU is detected, the SU cannot continue communication, which yields the great throughput loss and even interrupts the normal communication of the PU.
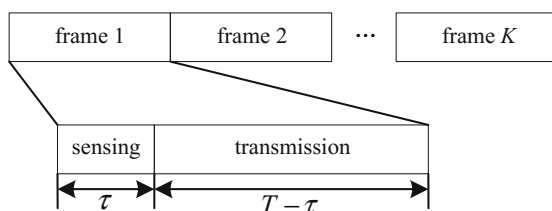

Fig. 1. Conventional sensing-throughput tradeoff scheme

The proposed spectrum handoff-based sensing-throughput tradeoff scheme is shown in Fig. 2, wherein one searching slot is added following the sensing slot, if the presence of the PU is detected in the sensing slot. By supposing that the frequency band available for the SU includes L channels, the SU will detect the left L-1 channels one by one for choosing a new idle channel in the searching slot, and then transfer to this idle channel to continue communication in the following transmission slot. In this figure, we assume that the time for searching one channel is ξ.
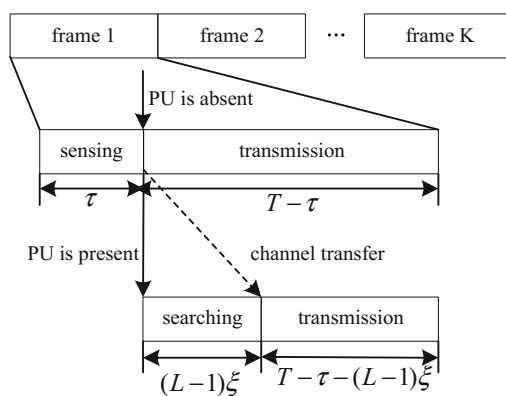

Fig. 2. Spectrum handoff-based sensing-throughput tradeoff scheme

We suppose that the communication rates of the SU at the absence and presence of the PU are C_0 and C_1, respectively, and $P(H_1)$ and $P(H_0)$ are the present and absent probabilities of the PU, respectively. Then we have

$$P(H_1) + P(H_0) = 1. \tag{6}$$

In the conventional scheme of Fig. 1, the SU may forward data in the transmission slot with the time of $T - \tau$, when the absence of the PU is detected. Hence, the SU's throughput in the unit bandwidth is given by

$$R_0(\tau) = (T - \tau) \ (P(H_0)C_0(1 - P_f(\tau)) + P(H_1)C_1(1 - P_d(\tau))) \tag{7}$$

When the SU detects the presence of the PU, it stops communicating in the transmission slot with the probability of

$$P_u(\tau) = P(H_0)P_f(\tau) + P(H_1)P_d(\tau). \tag{8}$$

In the proposed scheme of Fig. 2, when the SU detects the presence of the PU, it may choose and transfer to a new idle channel to continue communication, providing that there exists one idle channel among the left L–1 channels. The existent probability of one idle channel is given as follows

$$P_v(L) = 1 - P(H_1)^{L-1}. \tag{9}$$

After transferring to a new idle channel, the SU will forward data in the transmission slot of this channel with the time of $T - \tau - (L - 1)\xi$. As in (9), the SU's throughput in the unit bandwidth of the new channel is given by

$$\begin{aligned} R_1(\tau, \xi, L) = (T - \tau - (L - 1)\xi)P_u(\tau)P_v(L) \times \\ (P(H_0)C_0(1 - P_f(\xi)) + P(H_1)C_1(1 - P_d(\xi))) \end{aligned}. \tag{10}$$

Hence, the aggregate throughput of the SU in the proposed scheme is given by

$$R(\tau, \xi, L) = R_0(\tau) + R_1(\tau, \xi, L). \tag{11}$$

2.3   Scheme Optimization

With the fixed frame length, the transmission time available for the SU decreases with the increasing of the spectrum sensing time, yielding the great throughput loss; on the other hand, since $Q(x)$ is a monotone decreasing function, according to (5), with the fixed detection probability, the false alarm probability decreases with the increasing of the spectrum sensing time, yielding the great increasing of the spectrum access opportunity of the SU. Hence, there exists a tradeoff between the spectrum sensing time and the SU's throughput, and the achieved throughput can be improved through reasonably optimizing the sensing time.

Our goal to optimize the proposed scheme is to maximize the SU's throughput R through jointly optimizing the sensing time τ, the searching time ξ and the number of available channels L, providing that the detection probability to the PU is guaranteed. The optimization problem is described as follows

$$
\begin{aligned}
&\max_{\tau,\xi,L} R(\tau,\xi,L) \\
&\text{s.t.}\, P_d(\tau) \geq \bar{P}_d \\
&\qquad P_d(\xi) \geq \bar{P}_d \\
&\qquad \tau + (L-1)\xi \leq T \\
&\qquad \tau \geq 0, \ \xi \geq 0 \\
&\qquad L \geq 1
\end{aligned}
\tag{12}
$$

Since L is an integer, it is not computationally expensive to search L one by one. Hence, by fixing L, (12) is a double-variable optimization problem of τ and ξ, which can be solved by adopting alternating direction optimization, i.e., we formulate two sub-optimization problems about one of the two parameters, respectively, by fixing the other parameter with an initial value, and then obtain the joint optimal solutions by repeating to optimize these two sub-optimization problems iteratively. We initialize $\tau = \tau_0$ where $\tau_0 \in [0, T]$ and satisfies $P_d(\tau_0) \geq \bar{P}_d$, and therefore $R_0(\tau_0)$ is a constant that can be ignored in the optimization process. We can calculate the approximate solution by using the half searching algorithm as shown in Table 1. The time complexity of the half searching algorithm is related with the computation accuracy δ, which is denoted by $O(log_2\frac{1}{\delta})$.

Table 1. Half searching algorithm

(1) initialize $\xi_{min} = 0$, $\xi_{max} = T'$ and $\delta = 10^{-3}$;
(2) let $\xi = (\xi_{min} + \xi_{max})/2$;
(3) if $\nabla R_1(\xi) \geq 0$, let $\xi_{min} = \xi$; otherwise let $\xi_{max} = \xi$;
(4) repeat to implement (2) and (3) until $\left|\xi_{max} - \xi_{min}\right| < \delta$;
(5) let $\xi^{\#} = (\xi_{min} + \xi_{max})/2$.

Then fixing $\xi = \xi^{\#}$ and substituting it into (11), we have

$$
\begin{aligned}
R(\tau,\xi^{\#}) = {}& (T - \tau)(P(H_0)C_0(1 - P_f(\tau)) + P(H_1)C_1(1 - P_d(\tau))) + \\
& P_v(L)G(\xi^{\#})(T - \tau - (L-1)\xi^{\#})(P(H_0)P_f(\tau) + P(H_1)P_d(\tau))
\end{aligned}
\tag{13}
$$

where $G(\xi^{\#}) = P(H_0)C_0(1 - P_f(\xi^{\#})) + P(H_1)C_1(1 - P_d(\xi^{\#}))$. Obviously $G(\xi^{\#}) < C_0$, and thus $1 - G(\xi^{\#})/C_0 > 0$. There is also an optimal $\tau^{\#} \in [0, T'']$ that makes

$\bar{R}(\tau^{\#})$ achieve the maximum, and $\tau^{\#}$ can also be obtained through the half searching algorithm. By supposing that k is the number of the iterations, the joint optimization algorithm of τ and ξ is shown in Table 2.

Table 2. Joint optimization algorithm

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(1) initialize $k=1$, $\tau^{(k)} = \tau_0$, $\xi^{(k)} = 0$ and $\delta = 10^{-3}$;

(2) with the given $\tau^{(k)}$, calculate the optimal $\xi^{\#}$ by using the half searching algorithm;

(3) let $\xi^{(k+1)} = \xi^{\#}$, calculate the optimal $\tau^{\#}$ by using the half searching algorithm;

(4) let $\tau^{(k+1)} = \tau^{\#}$ and $k=k+1$;

(5) repeat to implement (2)~(4) until $\left| \tau^{(k)} - \tau^{(k-1)} \right| < \delta$ and $\left| \xi^{(k)} - \xi^{(k-1)} \right| < \delta$;

(6) output the optimal solutions $\tau^* = \tau^{(k)}$ and $\xi^* = \xi^{(k)}$.

The iterative complexity of the joint optimization algorithm is $O(1/\delta^2)$, and the half searching algorithm is implemented in each iteration. Hence, the aggregate time complexity is given by $O\left(\frac{1}{\delta^2}\log_2\frac{1}{\delta}\right)$.

3 Simulation Results

In the simulations, we suppose that the frame length $T = 10$ s, the PU's state probabilities $P(H_0) = 0.2$ and $P(H_1) = 0.8$, and the SNR between the SU's transmitter and receiver $\gamma_s = 5$ dB.

Figure 3 shows the SU's throughput R changing with the spectrum sensing time τ and the channel searching time ξ, with the fixed number of channels $L = 10$. In this figure we also set the sampling frequency $f_s = 1$ kHz, the detection probability $P_d = 0.99$, and the SNR between the SU and the PU $\gamma_p = -10$ dB. It is seen that R is a convexity, which indicates that there deed exist the optimal τ and ξ that make R reach the maximum. When $\tau = 1.8$ s and $\xi = 0.56$ s, the maximum $R = 4.23$ bit·Hz^{-1}. Figure 4 shows R versus $f_s = (200, 400, 600, 800, 1\text{ k})$ Hz with $\gamma_p = -15 \sim -5$ dB. It is seen that R improves with the increasing of f_s, because the spectrum sensing performance of detecting PU also improves. However, compared to $f_s = 800$ Hz, the improvement on the throughput of $f_s = 1$ kHz is not obvious, which indicates that overmany sampling nodes will not improve the sensing performance notably, but increase the difficulty of designing hardware. Hence, it is very important to choose an appropriate sampling frequency according to our demands.
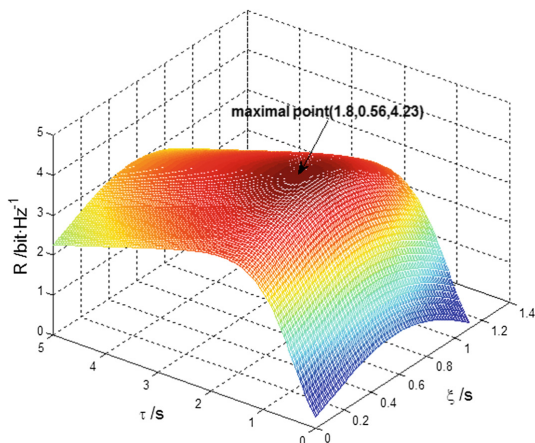
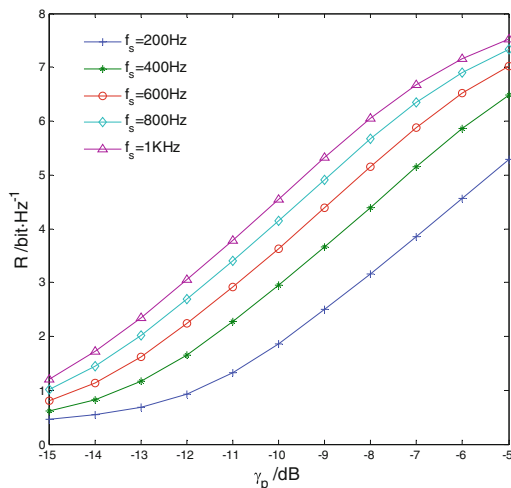**Fig. 3.** Throughput changing with sensing time and searching time

Fig. 4. Throughput versus sampling frequency with different SNR

4   Conclusions

In the proposed sensing-throughput tradeoff scheme, the SU is allowed to transfer to a new idle channel to continue communication through spectrum searching, when the presence of the PU is detected. The SU's throughput is maximized through jointly optimizing the sensing time, the searching time and the number of available channels. Through analyzing the simulation results, we get the following outlines: there deed exist the optimal solutions to the proposed scheme; the proposed scheme outperforms the conventional scheme obviously; an appropriate sampling frequency should be chosen according to our demands.

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