Throughput and Sensing Bandwidth Tradeoff in Cognitive Radio Networks

Wenshan Yin, Pinyi Ren, and Shuangcheng Yan

School of Electronics and Information Engineering
Xi'an Jiaotong University, Xi'an, China 710049
{yws.xjt,yansc}@stu.xjtu.edu.cn, pyren@mail.xjtu.edu.cn

Abstract. Within the sequential sensing and transmission paradigm (SSTP), spectrum sensing over the whole primary user (PU) band always suspends secondary user (SU) data transmission in the sensing interval. Delay incurred by this kind of suspension may be intolerable to delay sensitive SU services. To alleviate this problem, we adopt a parallel sensing and transmission paradigm (PSTP), within which the SU transmits and senses simultaneously. In this paper, we investigate the relationship between the achievable SU throughput and bandwidth allocated for spectrum sensing within the PSTP, under the constraint that the PU is sufficiently protected. We also study the delay improvements of the PSTP over that of the SSTP. Both theoretical analyses and simulation results that there exists an optimal sensing bandwidth that maximizes the achievable SU throughput within the PSTP. Furthermore, compared to the SSTP, the SU delay is reduced by using the PSTP.

Keywords: Delay, throughput, bandwidth, spectrum sensing.

1 Introduction

The rapid developments of wireless systems and services place high pressure on the limited radio spectrum resources. However, field measurements show that most of the licensed primary user (PU) spectrum resources are underutilized [1]. Cognitive radio (CR) has been proposed to alleviate the problem of spectrum scarcity by improving the spectrum utilization [2].

It is required that the unlicensed secondary user (SU) should not cause harmful interference to the licensed PU, which makes the spectrum sensing function one of the key technologies in the implementation of CR [3]. To provide sufficient protection to the PU, it is required that the probability of detection be no smaller than a prescribed value within the sensing interval [4]. Under this constraint, when the SU receives weak PU signal, the probability of false alarm may be high, which always lead to low spectrum utilization. Further more, shadowing and fading generally degrades the performance of spectrum sensing [5].

Abundant works on spectrum sensing are carried out within the sequential sensing and transmission paradigm (SSTP) over the whole PU band. Authors in

P. Ren et al. (Eds.): WICON 2011, LNICST 98, pp. 12–22, 2012.

[6] derived the optimal spectrum sensing time that maximizes the achievable SU throughput. To improve achievable SU throughput [7], the SU transmits when the channel states between SU transceivers are good, and sense the PU activity otherwise. To improve spectrum utilization [8], the SU adaptively chooses the sensing action based on historical information. The maximum channel throughput both of the PU and SU systems are derived in [9]. A new spectrum sharing scheme based on spectrum sensing is proposed in [10]. The SU transmits with a high rate when the PU is detected to be present, and transmits with a low rate otherwise. Lots of works on spectrum sensing are also based on the parallel sensing and transmission paradigm (PSTP), within which the PU band is divided into two parts for spectrum sensing and SU transmission, respectively. In [11], the authors reduce the average detection time by fixed relay and variable relays schemes. In [12], a cooperation strategy is introduced to exchange sensing information between SUs and reduce the detection delay.

It is well known within the SSTP over the whole PU spectrum band, the SU must suspend its data transmission in the sensing interval. Although the achievable SU throughput can be maximized under the PU protection constraint [6], the SU generally experiences long data transmission delay. For some time delay sensitive services, transmission delay caused by interruption generally degrades the quality of service (QoS) to the SU. Furthermore, the time interval allocated for spectrum sensing within each frame is quite limited. When the received PU signal strength at the SU receiver is low, the spectrum sensing results are quite unreliable, which results in low achievable SU throughput. Within the PSTP [11] [12], the SU can sense the PU activity and transmit its data simultaneously. Therefore, the SU data transmission delay can be reduced. However, under the PU protection constraint, with a fixed bandwidth allocated for spectrum sensing within a fixed frame, the average achievable throughput of the SU can be low in different wireless environments.

In this paper, we investigate the relationship between the achievable SU throughput and the bandwidth allocated for spectrum sensing within the PSTP. It is shown that the achievable SU throughput is a concave function of the bandwidth allocated for spectrum sensing. Provided that certain protection to PU is guaranteed, the optimal sensing bandwidth that maximizes the SU throughput is derived. We also investigate the SU transmission delay. Compared with the transmission delay within the SSTP, the SU delay is reduced significantly within the PSTP without any loss in the achievable SU throughput. Both simulation and theoretical results show that there is an optimal bandwidth for spectrum sensing that maximizes the SU throughput. Furthermore, the PSTP shows obvious advantage in the SU transmission delay.

This paper is organized as follows. Section 2 presents the system model. In Section 3, the tradeoff between throughput and sensing bandwidth is formulated and analyzed. And in Section 4, simulation results are presented. Finally, brief conclusions are drawn in Section 5.

2 System Model

We consider a CR network within which each SU operates based on the PSTP, which is shown in Fig. 1. The licensed PU band is divided into two parts, over which spectrum sensing and data transmission are carried out simultaneously. The band of width W_s is allocated for exclusive spectrum sensing. In this part of PU band, SU data transmission is forbidden to avoid co-channel interference. The SU transmits frame-by-frame over its data transmission band of width $W - W_s$. The frame duration of the SU signal is T.

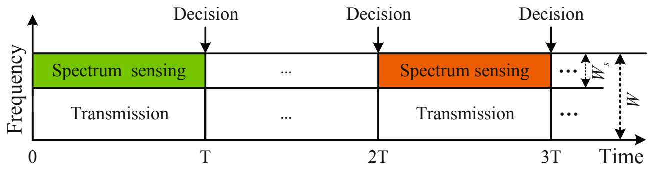

Fig. 1. The parallel sensing and transmission paradigm

Assume without loss of generality that both the PU and SU transmits based on the orthogonal frequency division multiplexing (OFDM) signaling. The sub-carrier distance of the SU signal over its transmission band of width $W - W_s$ is the same as that of the PU signal. Under such an assumption, when the SU simultaneously senses the PU activity and transmits its own data, the out-of-band emission could be neglected, since the transmission process is orthogonal with the sensing process in the frequency domain. The power of the SU signal σ_s^2 is evenly distributed over its transmission bandwidth, with PSD N_s. Then, we have $\sigma_s^2 = N_s (W - W_s)$.

Let H_0 and H_1 be the hypotheses that the PU transmission is inactive and active, respectively. Then, the problem of sensing can be formulated as

$$x[i] = \begin{cases} n[i], & H_0 \\ n[i] + h_p s[i], & H_1 \end{cases} \tag{1}$$

where $i = 1, 2, \cdots, L$, $L = 2TW_s$; $n[i]$ is the zero mean complex additive white Gaussian noise (AWGN) with probability distribution $n[i] \sim CN(0, \sigma_n^2)$, $\sigma_n^2 = N_0 W$, and N_0 is the power spectrum density (PSD) of the AWGN; h_p is the channel gain between the PU transmitter and SU receiver; and $s[i]$ is the PU signal, which is assumed to be a zero mean complex Gaussian process with power σ_p^2 and probability distribution $s[i] \sim CN(0, \sigma_p^2)$ [13]. The power of the PU signal is evenly distributed over its transmission band of width W, with PSD N_p. Therefore, $N_p W = \sigma_p^2$.

The result of spectrum sensing is a binary decision on the presence or absence of the PU signal. To protect the PU from harmful interference, the SU is allowed to transmit only when the PU signal is detected to be absent. When the sensing result indicates that the PU transmission is present, the SU must terminate its transmission until it detects a new spectrum opportunity. Although the SU may stop or restart its transmission when the sensing result claims the presence or absence of the PU signal in the current frame, the spectrum sensing process carries on continuously in the next frame.

3 Throughput and Sensing Bandwidth Tradeoff

As can be seen from Fig. 1, with larger bandwidth allocated for spectrum sensing, the SU can obtain more information on the PU signal and thus better sensing performance. However, the larger the bandwidth allocated for spectrum sensing, the smaller the bandwidth available for SU transmission, which may lead to low achievable SU throughput. Therefore, there exists a tradeoff between the achievable SU throughput and bandwidth allocated for spectrum sensing.

3.1 Secondary User Spectrum Sensing

For discussion purpose, spectrum sensing is performed by the energy detector [14]. The test statistic of the energy detector can be presented as $\Lambda = \frac{1}{\sigma_n^2}\sum_{i=1}^{2TW_s}\left|x\left[i\right]\right|^2$. According to the central limit theory (CLT), when the product $2TW_s$ is large enough, Λ can be approximated as Gaussian distributed. Under the hypothesis of H_0, $\Lambda|_{H_0} \sim CN\left(2TW_s, 2TW_s\right)$. Under the hypothesis of H_1, $\Lambda|_{H_1} \sim CN\left(2TW_s\left(1+\gamma\right), 2TW_s(1+\gamma)^2\right)$, where γ is the signal to noise ratio (SNR) of the PU signal received at the SU receiver, which is defined as $\gamma = |h_p|^2\frac{N_pW_s}{N_0W_s} = \frac{|h_p|^2\sigma_p^2}{\sigma_n^2}$.

The probability of detection $P_d\left(W_s\right) = \Pr\left(\Lambda \geq \lambda|H_1\right)$ and probability of false alarm $P_f\left(W_s\right) = \Pr\left(\Lambda \geq \lambda|H_0\right)$ are [15]

$$P_f\left(W_s\right) = Q\left(\frac{\lambda}{\sqrt{2TW_s}} - \sqrt{2TW_s}\right) \tag{2}$$

$$P_d\left(W_s\right) = Q\left(\frac{\lambda}{\left(1+\gamma\right)\sqrt{2TW_s}} - \sqrt{2TW_s}\right) \tag{3}$$

where $Q\left(x\right)=\frac{1}{\sqrt{2\pi}}\int_x^{\infty}e^{-t^2/2}dt$, and λ is the sensing threshold.

3.2 Secondary User Data Transmission

In the spectrum sensing process, when $\Lambda \geq \lambda$, the PU is detected to be present; otherwise, the PU is detected to be absent. Once a SU decides that the PU is absent, it tries to access the PU band. Therefore, the SU transmits its data in two cases: the PU transmission is absent, and the SU detected its absence correctly; the PU transmission is present, but the SU missed to detect its presence.

In the first case, only the SU transmits its data over the band of width $W - W_s$. The achievable throughput is

$$C_1\left(W_s\right) = \left(W - W_s\right)\ln\left(1 + \Omega_1\left(W_s\right)\right) \tag{4}$$

where $\Omega_1(W_s) = \frac{|h_s|^2 N_s(W-W_s)}{N_0(W-W_s)}$ is the SNR of the SU and h_s is the channel gain between SU transceivers. Since the SU SNR can be represented as $\rho = \frac{|h_s|^2 N_s(W-W_s)}{N_0(W-W_s)}$, $\Omega_1(W_s)$ can be simplified as $\Omega_1(W_s) = \rho$.

In the second case, both the PU and the SU transmit their data. The PU signal is treated as interference at the SU receiver. Therefore, the achievable SU throughput becomes

$$C_2(W_s) = (W - W_s)\ln(1 + \Omega_2(W_s)) \tag{5}$$

where $\Omega_2(W_s) = \frac{|h_s|^2 N_s(W-W_s)}{(N_P|h_p|^2+N_0)(W-W_s)}$ is the signal to noise-plus-interference ratio (SINR) of the SU. Since $\frac{N_P|h_p|^2(W-W_s)}{N_0(W-W_s)} = \frac{|h_p|^2 N_P W}{N_0 W}$ and $\gamma = |h_p|^2 \frac{N_p W}{N_0 W}$, we have $\Omega_2(W_s) = \frac{\Omega_1(W_s)}{\gamma+1}$. While according to the definition of ρ, $\Omega_2(W_s)$ can be further simplified as $\Omega_2(W_s) = \frac{\rho}{\gamma+1}$.

Let $P(H_0)$ and $P(H_1)$ be the probabilities that the PU is absent and present, respectively. Then, $P(H_0) + P(H_1) = 1$. Consequently, the probabilities of the first case and second case can be respectively presented as $P(H_0)(1 - P_f(W_s))$ and $P(H_1)(1 - P_d(W_s))$. By taking (4) and (5) into account, the total achievable SU throughput can be derived as

$$C(W_s) = P(H_0)(1 - P_f)C_1 + P(H_1)(1 - P_d)C_2 \tag{6}$$

where $P_f = P_f(W_s)$, $C_1 = C_1(W_s)$, $P_d = P_d(W_s)$, and $C_2 = C_2(W_s)$ for presentational simplicity.

3.3 Tradeoff between Throughput and Sensing Bandwidth

For discussion purpose, let $U_1 = P(H_0)\ln(1 + \rho)$ and $U_2 = P(H_1)\ln\left(1 + \frac{\rho}{1+\gamma}\right)$. Then, $C(W_s)$ in (6) can be represented as

$$C(W_s) = \varphi_1(W_s)U_1 + \varphi_2(W_s)U_2 \tag{7}$$

where $\varphi_1(W_s) = (W - W_s)(1 - P_f(W_s))$ and $\varphi_2(W_s) = (W - W_s)(1 - P_d(W_s))$. When the SU transmitter is far away from the SU receiver and close to the PU transmitter, which means that the PU signal strength is much larger than the SU signal strength at the SU receiver, the contribution of the second term on the right hand side of (7) is minimal. However, when the case is opposite, the contribution of the second term becomes dominant.

From the point view of the SU, it is desirable to maximize $C(W_s)$ by choosing the proper sensing bandwidth W_s, i.e.,

$$\max_{0<W_s<W} \quad C(W_s) = \varphi_1(W_s)U_1 + \varphi_2(W_s)U_2 \tag{8}$$

It can be readily shown that the less the bandwidth allocated for spectrum sensing, the higher the achievable SU throughput.

While from the point view of the PU, it is required that the PU be sufficiently protected. To protect the PU, the $P_d(W_s)$ should not be lower than a prescribed value P_d^{th}, i.e., $P_d(W_s) \geq P_d^{th}$ [4]. The larger the $P_d(W_s)$, the better the PU is protected. As can be seen from (3), the larger the sensing bandwidth W_s, the larger the $P_d(W_s)$. However, larger bandwidth allocated for spectrum sensing will result in lower bandwidth available for SU transmission. Furthermore, as can be seen from (2), the $P_f(W_s)$ also increases with increase of W_s. The larger the $P_f(W_s)$, the lower the spectrum utilization. Therefore, it is only necessary to satisfy the basic requirement on protection, i.e., $P_d(W_s) = P_d^{th}$. Consequently, the optimization problem in (8) can be reformulated as

$$\begin{aligned} \max_{0<W_s<W} \quad & C(W_s) = \varphi_1(W_s)U_1 + \varphi_2(W_s)U_2 \\ s.t. \quad & P_d(W_s) = P_d^{th} \end{aligned} \tag{9}$$

According to (2) and (3), for a given $P_d(W_s)$, the $P_f(W_s)$ in (2) can be presented as

$$P_f(W_s) = Q\left((1+\gamma)Q^{-1}(P_d(W_s)) + \sqrt{2TW_s}\gamma\right) \tag{10}$$

Therefore, by employing (10), the optimization problem in (9) is equivalent to

$$\begin{aligned} \max_{0<W_s<W} \quad & \hat{C}(W_s) = (W - W_s)f_1(W_s) \\ s.t. \quad & P_f(W_s) = Q(f_2(W_s)) \end{aligned} \tag{11}$$

where $f_1(W_s) = (1 - P_f(W_s))U_1 + \left(1 - P_d^{th}\right)U_2$, and $f_2(W_s) = (1+\gamma)Q^{-1}\left(P_d^{th}\right) + \sqrt{2TW_s}\gamma$.

It can be derived that the first partial derivative of $\hat{C}(W_s)$ with respect to W_s is

$$\frac{\partial \hat{C}(W_s)}{\partial W_s} = -f_1(W_s) + (W - W_s)\frac{\partial f_1(W_s)}{\partial W_s} \tag{12}$$

where $\frac{\partial f_1(W_s)}{\partial W_s} = \frac{\gamma U_1}{2}\sqrt{\frac{T}{\pi W_s}}\exp\left\{-\frac{[f_2(W_s)]^2}{2}\right\}$. It can also be derived that the second partial derivative of $\hat{C}(W_s)$ with respect to W_s is

$$\frac{\partial^2 \hat{C}(W_s)}{\partial W_s^2} = -2\frac{\partial f_1(W_s)}{\partial W_s} + (W - W_s)\frac{\partial^2 f_1(W_s)}{\partial W_s^2} \tag{13}$$

where the derivative $\frac{\partial^2 f_1(W_s)}{\partial W_s^2} = -f_3(W_s)\exp\left\{-\frac{[f_2(W_s)]^2}{2}\right\}$ and $f_3(W_s) = \frac{\gamma U_1}{4W_s}\sqrt{\frac{T}{\pi W_s}}\left[1 + \sqrt{2TW_s}\gamma f_2(W_s)\right]$.

It can be seen from the first and second partial derivative of $f_1(W_s)$ that $\partial f_1(W_s)/\partial W_s > 0$, and $\partial^2 f_1(W_s)/\partial W_s^2 < 0$, respectively. Since $W - W_s > 0$, we have

$$\frac{\partial^2 \hat{C}(W_s)}{\partial W_s^2} < 0 \quad for \quad 0 < W_s < W \tag{14}$$

which means that $\hat{C}(W_s)$ is a concave function of the sensing band width W_s over the range $0 < W_s < W$. Therefore, there exists an unique optimal sensing bandwidth $W_s^{opt} \in (0, W)$ that maximizes the SU throughput.

Since $\hat{C}(W_s)$ is a concave function of W_s, we can get the optimal sensing bandwidth W_s^{opt} by setting the first derivative of $\hat{C}(W_s)$ to zero, i.e., $\partial \hat{C}(W_s)/\partial W_s = 0$, or equivalently

$$f_1(W_s) - (W - W_s)\frac{\partial f_1(W_s)}{\partial W_s} = 0 \tag{15}$$

There is no closed form solution to (15). However, it can be seen from the convexity of $\hat{C}(W_s)$ that $\partial \hat{C}(W_s)/\partial W_s$ is a monotonic function of W_s. Therefore, equation (15) could be solved by the well known bisection search method.

3.4 Secondary User Transmission Delay

Within the PSTP, the SU suspends its transmission in two cases: the PU is present, and the SU correctly detects its presence; the PU is absent, but the SU falsely detects its presence. The average SU transmission delay in the former and later case is $D_1(W_s) = TP_d(W_s)$ and $D_2(W_s) = TP_f(W_s)$, respectively. Since the probability of the first case is $P(H_1)$, and the probability of the second case is $P(H_0)$, the total transmission delay introduced by the PSTP is

$$D(W_s) = P(H_1)D_1(W_s) + P(H_0)D_2(W_s) \tag{16}$$

Under the PU protection constraint in (9), the transmission delay $D_1(W_s)$ is inevitable, since SU transmission in this case could cause harmful interference to the licensed PU. The transmission delay $D_2(W_s)$ degrades spectrum utilization, which is unnecessary but inevitable, and should be minimized. The total transmission delay $D(W_s)$ is mainly dominated by the first term on the right hand side of (16), although $P(H_0)$ is generally larger than $P(H_1)$.

Under the protection constraint that $P_d(W_s) = P_d^{th}$, the transmission delay $D(W_s)$ in (16) can be transformed to

$$D(W_s) = T\left[P(H_1)P_d^{th} + P(H_0)Q\left[f_2(W_s)\right]\right] \tag{17}$$

It can be seen from (17) that for a given protection constraint P_d^{th} to the PU, the larger the sensing bandwidth W_s, the lower the transmission delay $D(W_s)$. However, the larger the sensing bandwidth, the smaller the bandwidth available for SU data transmission, and thus the lower the achievable SU throughput.

For comparison, the transmission delay within the SSTP [6] under the PU protection constraint can be presented as

$$D(\tau, W) = \tau + \left(P(H_0)P_f(\tau, W) + P(H_1)P_d^{th}\right)(T - \tau) \tag{18}$$

where $P_f(\tau, W) = Q\left((1+\gamma)Q^{-1}\left(P_d^{th}\right) + \sqrt{2\tau W}\gamma\right)$ is the probability of false alarm within the SSTP. It has to be pointed out that within the SSTP, data transmission is interrupted with probability one in each sensing interval τ, and the sensing bandwidth is W rather than W_s.

The probability of detection within the SSTP can be presented as $P_d(\tau, W) = Q\left(\frac{\lambda}{(1+\gamma)\sqrt{2\tau W}} - \sqrt{2\tau W}\right)$. It can be shown that when $W_s T = W\tau$, we have $P_f(\tau, W) = P_f(W_s)$ and $P_d(\tau, W) = P_d(W_s)$. Define the relative delay as $\Delta D(\tau, W_s) = D(\tau, W) - D(W_s)$. Then,

$$\Delta D(\tau, W_s) = \tau\left(1 - P(H_0) P_f(W_s) - P(H_1) P_d^{th}\right) \tag{19}$$

For the convenience of discussion, define $p_{00} = 1 - P_f(W_s)$, $p_{01} = P_f(W_s)$, $p_{11} = P_d^{th}$, and $p_{10} = 1 - P_d^{th}$. Then, equation (19) can be transformed into

$$\Delta D(\tau, W_s) = \tau\left(1 - P(H_0) p_{01} - P(H_1) p_{11}\right) \tag{20}$$

Since $\Delta D(\tau, W_s)/\tau = P(H_0) p_{00} + P(H_1) p_{10} > 0$, we have

$$\Delta D(\tau, W_s) > 0 \tag{21}$$

Therefore, if the optimal spectrum sensing time τ^{opt} within the SSTP and the optimal spectrum sensing bandwidth within the PSTP satisfy the condition that $\frac{W_s^{opt}}{W} = \frac{\tau^{opt}}{T}$, we have $P_f(\tau^{opt}, W) = P_f(W_s^{opt})$, $P_d(\tau^{opt}, W) = P_d(W_s^{opt})$, and $\Delta D(\tau^{opt}, W_s^{opt}) > 0$. Thus, the SU transmission delay within the SSTP is reduced compared to that within the PSTP.

4 Simulation Results

In the simulation, we assume that the PU system transmits based on the DVB-T signaling [16]. The bandwidth of the PU is $W = 6MHz$. The number of subcarriers of the the PU signal is 2048. The sampling rate over the spectrum sensing band is the same as the bandwidth allocated for spectrum sensing. The frame duration of the SU is $T = 100ms$. The subcarrier distance of the SU signal is the same as that of the PU signal. The SU SNR ρ is set to be $20dB$. The probability that the PU occupies its licensed channel is 0.3, which means that $P(H_1) = 0.3$, and $P(H_0) = 1 - P(H_1) = 0.7$. The basic protection level to the licensed PU is $P_d^{th} = 0.9$ [4]. Each simulation result is averaged over 5000 realizations.

Figure 2 shows the probability of false alarm $P_f(W_s)$ versus the sensing bandwidth W_s for a given probability of detection $P_d(W_s) = 0.9$. The theoretical probability of false alarm is derived according to (10). It can be seen that simulation results comply with theoretical results very well. It can also be observed that the probability of false alarm decreases monotonically with the increase of PU SNR γ since the SU obtains stronger PU signal. Moreover, the probability of false alarm decreases with the increase of sensing bandwidth W_s. This is mainly because that with the increase of W_s, the SU obtains more information on the PU signal.

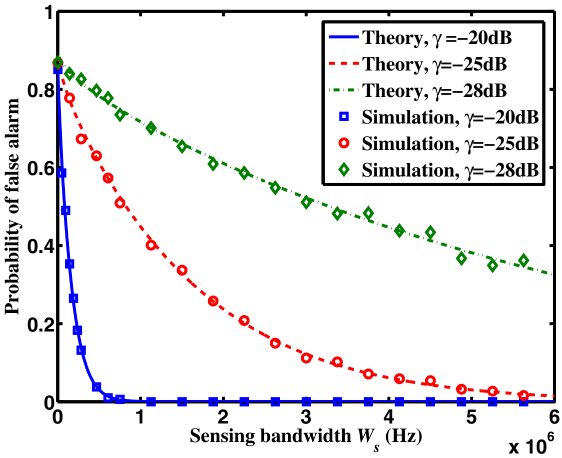

Fig. 2. Probability of false alarm $P_f(W_s)$ within the PSTP

Figure 3 shows the normalized throughput of the SU versus the sensing bandwidth W_s. The normalized throughput of the SU is defined as $C(W_s)/W$. The theoretical normalized SU throughput is derived according to (7). It can be seen that theoretical results are verified by simulation. On the one hand, the optimal sensing bandwidth that achieves the maximum throughput increases with the decrease of PU SNR. On the other hand, the larger the PU SNR γ, the higher the achievable SU throughput. By comparing Fig. 3 with Fig. 2, it can also be seen that lower probability of false alarm does not necessarily results in higher SU throughput. Since simulation results comply with theoretical results, we will only show theoretical results hereafter for simplicity.

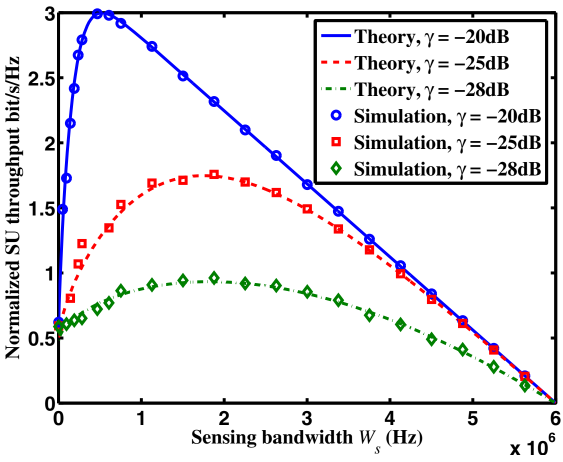

Fig. 3. Normalized SU throughput within the PSTP

Figure 4 compares the average SU transmission delay $D(\tau, W)$ when the optimal spectrum sensing time τ^{opt} is given with $D(W_s)$ when the optimal spectrum sensing bandwidth W_s^{opt} is given. Three conclusions can be drawn from the figure. First, the transmission delay $D(W_s^{opt})$ is generally lower than $D(\tau^{opt}, W)$. Second, the relative delay $\Delta D(\tau^{opt}, W_s^{opt})$ is a concave function of γ. This is mainly because that, when γ is large, the PU can be detected quickly; otherwise, the SU can be considered outside the coverage of the PU and no spectrum sensing function is needed. Third, $\Delta D(\tau^{opt}, W_s^{opt})$ increases with the increase of frame length T. However, the frame length T is dependent on practical consideration.

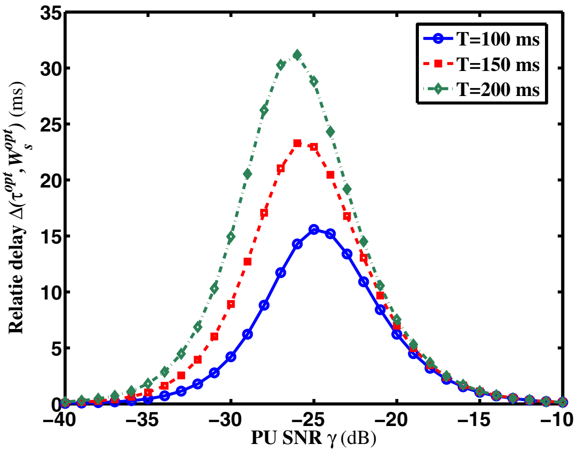

Fig. 4. Relative transmission delay

5 Conclusions

In this paper, we investigated the tradeoff between sensing bandwidth and achievable SU throughput in cognitive radio networks. The investigation is based on a PSTP, within which the licensed PU band is divided into two parts, one part allocated for spectrum sensing and the other part for transmission. We obtained the optimal bandwidth for sensing the PU signal that maximizes the achievable SU throughput, under the constraint that certain protection to the PU is guaranteed. We also showed that compared to the SSTP, the PSTP have advantage in average transmission delay. Simulation results confirmed our analyses.

Acknowledgments. The research reported in this paper (Corresponding Author Pinyi Ren) is supported by the National Hi-Tech Research and Development Plan of China under the Grant 2009AA011801, the National Natural Science Foundation of China under the Grant 60832007, it is also supported by the National Science and Technology Major Project of China under the Grant 2010ZX03005-003.

References

1. FCC, Spectrum policy task force report (November 2002), http://www.fcc.gov/sptf/files/SEWGFinalReport-1.pdf
2. FCC, Notice of proposed rule making FCC 04-113: Unlicensed operation in the TV broadcast bands (ET Docket No.04-186) (May 2004), http://www.naic.edu/~phil/rfi/fccactions/FCC-04-113A1.pdf
3. Yücek, T., Arslan, H.: A survey of spectrum sensing algorithms for cognitive radio applications. IEEE Commun. Surveys Tuts. 11(1), 116–130 (2009)
4. Zeng, Y.H., Liang, Y.C., Lei, Z., Oh, S.W., Chin, F., Sun, S.: Worldwide regulatory and standardization activities on cognitive radio. In: DySPAN, Singapore, pp. 1–9 (April 2010)
5. Ma, J., Li, G.Y., Juang, B.H.: Signal Processing in Cognitive Radio. IEEE Proc. 97(5), 805–823 (2009)
6. Liang, Y.C., Zeng, Y.H., Peh, E.C.Y., Hoang, A.T.: Sensing-throughput tradeoff for cognitive radio networks. IEEE Trans. Wireless Commun. 7(4), 1326–1337 (2008)
7. Hoang, A.T., Liang, Y.C., Zeng, Y.H.: Adaptive joint scheduling of spectrum sensing and data transmission in cognitive radio networks. IEEE Trans. Commun. 58(1), 235–246 (2010)
8. Choi, K.W.: Adaptive sensing technique to maximize spectrum utilization in cognitive radio. IEEE Trans. Veh. Technol. 59(2), 992–998 (2010)
9. Shen, J., Jiang, T., Liu, S., Zhong, Z.: Maximum channel throughput via cooperative spectrum sensing in cognitive radio networks. IEEE Trans. Wireless Commun. 8(10), 5166–5175 (2009)
10. Kang, X., Liang, Y.C., Garg, H.K., Zhang, L.: Sensing based spectrum sharing in cognitive radio networks. IEEE Trans. Veh. Technol. 58(8), 4649–4654 (2009)
11. Ganesan, G., Li, Y., Bing, B., Li, S.: Spatiotemporal sensing in cognitive radio networks. IEEE J. Sel. Areas Commun. 26(1), 5–12 (2008)
12. Li, H., Dai, H., Li, C.: Collaborative quickest spectrum sensing via random broadcast in cognitive radio systems. IEEE Trans. Wireless Commun. 9(7), 2338–2348 (2010)
13. Yin, W., Ren, P.: A suboptimal spectrum sensing scheme for OFDM signal in cognitive radios. In: Globecom, Miami, pp. 1–6 (December 2010)
14. Urkowitz, H.: Energy detection of unknown deterministic signals. IEEE Proc. 55(4), 523–531 (1967)
15. Proakis, J.G.: Digital Communication, 4th edn., translated by Junli Zhang etc. Publishing House of Electronic Industry (2006)
16. ETSI EN 300 744 V1.6.1, Digital Video Broadcasting (DVB): Framing structure, channel coding and modulation for digital terrestrial television, http://www.dvb.org/technology/standards/index.xml