Optimal sensing period in cooperative relay cognitive radio networks

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Abstract

Cognitive radio is an efficient technique to improve spectrum efficiency and relieve the pressure of spectrum resources. In this paper, we investigate the spectrum sensing period in cooperative relay cognitive radio networks; analyze the relationship between the available capacity and the signal-to-noise ratio of the received signal of second users, the target probability of detection and the active probability of primary users. Finally, we derive the closed form expression of the optimal spectrum sensing period in terms of maximum throughput. We simulate the probability of false alarm and available capacity of cognitive radio networks and compare optimal spectrum sensing period scheme with fixed sensing period one in these performance. Simulation results show that the optimal sensing period makes the cognitive networks achieve the higher throughput and better spectrum sensing performance than the fixed sensing period does. Cooperative relay cognitive radio networks with optimal spectrum sensing period can achieve the high capacity and steady probability of false alarm in different target probability of detection. It provides a valuable reference for choosing the optimal spectrum sensing period in cooperative relay cognitive radio networks.

Keywords: Wireless communications, cognitive radio networks, cooperative relay, spectrum sensing, throughout

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1. Introduction

With the rapid growth of wireless applications and services, especially of device-to-device (D2D) communication services, the irreproducible spectrum resource becomes more and more precious and scarce. It has resulted in the severe conflict between the increasing demands for spectrum resources and the scarcity of the available spectrum resources [1]. The present wireless communication spectrum is allocated by a fixed principle. Therefore, the spectrum efficiency is very low [2-3]. Cognitive radio (CR) is a promising spectrum sharing technology which may be able to resolve the conflict [4-5].

In order to maximize the throughput of cognitive radio networks, the sensing period should be as short as possible. But a short sensing period will result in degradation of the spectrum sensing performance. Throughput, probability of detection, probability of false alarm and sensing period are interrelated each others [6]. However, spectrum sensing and spectrum access can be combined to design an optimal access protocol to maximize the throughput of cognitive networks when the performance of spectrum sensing is given [7]. Bourdena and et al have showed the relationship between the throughput and the spectrum sensing period as well as detection probability, and proposed the tradeoff between the sensing period and throughput [8]. By incorporating the sensing-access tradeoff in the design of spectrum sensing, the throughput cognitive network can be significantly improved [9]. In order to maximize the throughput of cognitive radio networks, an optimal access strategy, which joints the spectrum sensing period and detection period, is designed [10]. Optimizing the sensing time and the power allocation of cognitive users can also improve the throughput of cognitive networks [11-13].

Cooperative relay could effectively improve the performance of wireless networks and has attracted increasing attention [14-15]. A cooperative neighboring cognitive radio Nodes is proposed to identify the selfish SU in order to improve the utilization of resources [16]. In cooperative relay cognitive radio networks, SUs can play the role as relays of PUs or other SUs. It indicates that cooperative relay would improve the performance and save the energy of PUs or SUs when there is no direct link between the transmitters and receivers or the direct link is too weak [17]. The relay of SUs may speed up the transmission of PUs or other SUs. As a reward, the SUs may obtain more idle time to transmit their data [18]. Li and et al investigated joint relay selection and power allocation to maximize the system throughput and improve the energy efficiency [19-20]. Mishra and Trivedi proposed an optimal multiple CR relay selection strategy with the channel allocation in which the channel conditions of the cooperative links are used as the metric for selecting the best cognitive radio relay [21]. Zhai and Zhang proposed two kinds of cooperative schemes, two-path successive relay and decode-and-forward, and give the optimal time allocation based on the cooperative schemes respectively to maximize throughput [22]. Sometimes, some SUs are used as the relay of the primary system to minimize the transmission time and increase the spectrum access time for SUs [23-24]; the others are used to transmit the data of the secondary system [25]. El-Malek and Zummo proposed an optimal power allocation between SU's transmission and relay amplifying to maximize the average achievable rate and to minimize the probability of error [26]; Tran and et al. analyzed the packet transmission time in cognitive cooperative radio networks where a secondary transmitter sends packets to a secondary receiver with the help of a secondary relay, and given the analytical expressions of the end-to-end throughput, end-to-end packet transmission time [27]; Hao and et al. investigated sensing-based spectrum sharing access and sensing-based spectrum opportunistic access schemes in cooperative cognitive radio networks with imperfect spectrum sensing, and designed an optimal resource allocation strategy, including sensing time and transmit power, to maximize the ergodic throughput of the secondary system [28]. However, as far as we know, there have been few works on optimizing sensing time to achieve maximum throughput in cooperative relay cognitive radio networks.

Unlike previous works, this paper focuses on the spectrum sensing time and makes effort to find the optimal sensing period for cooperative relay cognitive radio networks to achieve the maximum throughput of cognitive radio networks. According to the actually activity of PUs and the spectrum detected results, the conditional probabilities and available capacities of the cognitive network in the four cases (a PU is active and is actually detected, a PU is active but actually undetected, a PU is inactive but actually detected and a PU is inactive and actually undetected) are analyzed, and the average capacity of the cognitive network is given. It is proved that to maximize the average capacity of the cognitive network is a strict convex optimization. Then, the globally optimal sensing period is derived out.

We evaluate the effects of the spectrum sensing period and the active probability of PUs on the capacity, and examine the effects of the signal-to-noise ratio (SNR) of the received signal on the optimal sensing period, respectively. It proves that the cognitive network with the optimal sensing period has higher throughput and better spectrum sensing performance than the one with fixed sensing period. It also provides a valuable reference for choosing the optimal spectrum sensing period in cooperative relay cognitive radio networks.

This paper is organized as follows. Section 2 describes the system model of cooperative relay cognitive radio networks. Section 3 discusses the spectrum sensing with energy detector and the performance. Section 4 analyzes the capacity of cooperative relay cognitive radio networks. Section 5 derives the optimal sensing period. Some simulation results are shown in Section 6. Finally, concluding remarks and future directions are presented in Section 7.

2. System Model

We consider a cooperative relay cognitive radio network in which the channel between the primary transmitter (PT) to the base station (BS) is weak. PU agrees to cooperate with SUs to accelerate PU's data transmission. The transmission of PU is assisted by the SU to relay with the decode-and-forward (DF) protocol. For the sake of simplicity, we assume that there is one PU transmitter, one base station and one second user pair (the SU transmitter (ST) and SU receiver (SR)) in the cooperative relay cognitive radio network. The channels between the nodes are slowly fading Rayleigh channels, where the channel gains are considered to be invariant in one slot. h_{pb}, h_{ps}, h_{sb} and h_{ss} denote the channel gains between PT to BS, PT to ST, ST to BS and ST to SR, respectively, as shown in **Fig. 1**.

In the cooperative relay cognitive radio network, ST should sense its surrounding spectrum first if it wants to transmit its data. When it finds any idle spectrum, it will access the spectrum, and then transmit its data. Otherwise, it will wait until the idle spectrum is found. The hypothesis test of whether the spectrum is idle or not can be formulated as a binary hypothesis testing

$$\begin{cases} H_0: & r(t) = \omega(t) \\ H_1: & r(t) = h_{ps} p(t) + \omega(t) \end{cases} \tag{1}$$

where H_0 is the hypothesis when PU is inactive, H_1 is the hypothesis when PU is active, $p(t)$ is the transmitted signal of the PT with zero mean and variance σ_s^2, $\omega(t)$ is the additive white Gaussian noise (AWGN) with zero mean and variance σ_n^2, $0 \le t \le \tau$, τ is the period of the spectrum sensing. Moreover, $p(t)$ and $\omega(t)$ are independent each other.

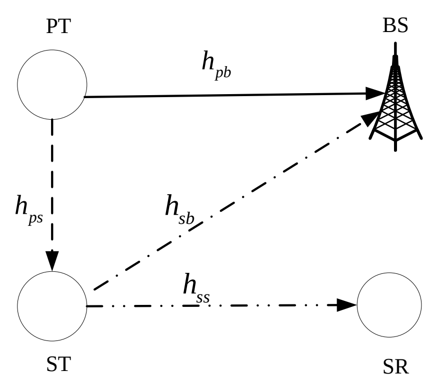

Fig. 1. Model of cooperative relay cognitive radio networks

3. Spectrum Sensing Based on Energy Detector

Energy detection is the most popular spectrum sensing method due to its low computational and implementation complexity. Let f_s denote the sampling frequency. The number of samples N is a maximum integer not greater than τf_s. For the sake of simplicity, we assume $N = \tau f_s$. The test statistic for energy detector is given by

$$\varepsilon = \frac{1}{N}\sum_{n=0}^{N-1}|\gamma(n)|^2 \tag{2}$$

where

$$\begin{cases} H_0: \ r(n) = \omega\left(\dfrac{n}{f_s}\right) \\ H_1: \ r(n) = h_{ps} p\left(\dfrac{n}{f_s}\right) + \omega\left(\dfrac{n}{f_s}\right) \end{cases} \tag{3}$$

Then, the probability of false alarm P_{fa} and the probability of detection P_d .are given respectively by

$$P_{fa} = \Pr ob(\varepsilon \geq \lambda \mid H_0) \tag{4}$$

and

$$P_d = \Pr ob(\varepsilon \geq \lambda \mid H_1) \tag{5}$$

where λ is a given decision threshold.

Note that ε is a random variable obeying Gauss chi-square distribution with N degrees of freedom. According to the central limitation theorem, ε will tend to be a Gaussian random variable when N is large enough [29]. Then, the probability density function (PDF) of ε under H_0 can be approximated by a Gaussian distribution with mean $\mu_0 = \sigma_n^2$ and variance $\sigma_0^2 = 2\sigma_n^4 / N$ as follows

$$f_0(x) = \sqrt{\frac{N}{4\pi\sigma_n^4}} \exp\left(-\frac{N(x-\sigma_n^2)^2}{4\sigma_n^4}\right) \tag{6}$$

and, the PDF of ε under H_1 can be approximated by a Gaussian distribution with mean $u_1 = \sigma_s^2 + \sigma_n^2 = (\gamma+1)\sigma_n^2$ and variance $\sigma_1^2 = 2(\gamma+1)^2 \sigma_n^4 / N$ as follows

$$f_1(x) = \sqrt{\frac{N}{4\pi(\gamma+1)^2 \sigma_n^4}} \exp\left(-\frac{N(x-(\gamma+1)\sigma_n^2)^2}{4(\gamma+1)^2 \sigma_n^4}\right) \tag{7}$$

where γ is the SNR of the received signal in the ST.

Therefore, the probability of false alarm can be approximated by

$$P_{fa}(\lambda,\tau) = Q\left(\frac{\lambda-\sigma_n^2}{\sigma_n^2}\sqrt{\frac{N}{2}}\right) = Q\left[\left(\frac{\lambda}{\sigma_n^2}-1\right)\sqrt{\frac{N}{2}}\right] = Q\left[\left(\frac{\lambda}{\sigma_n^2}-1\right)\sqrt{\frac{\tau f_s}{2}}\right] \tag{8}$$

and the probability of detection can be approximated by

$$P_d(\lambda,\tau) = Q\left(\frac{\lambda-(\gamma+1)\sigma_n^2}{(\gamma+1)\sigma_n^2}\sqrt{\frac{N}{2}}\right) = Q\left[\left(\frac{\lambda}{(\gamma+1)\sigma_n^2}-1\right)\sqrt{\frac{\tau f_s}{2}}\right] \tag{9}$$

where $Q(x)$ is the complementary distribution function and is defined as follows

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{\frac{-t^2}{2}} dt \tag{10}$$

It is obvious that both the probability of false alarm P_{fa} and probability of detection P_d are the functions of decision threshold λ and spectrum sensing period τ . If the target probability of detection P_d is given, the decision threshold λ can be derived out from

$$Q^{-1}(P_d)=\left[\left(\frac{\lambda}{(\gamma+1)\sigma_n^2}-1\right)\sqrt{\frac{\tau f_s}{2}}\right] \tag{11}$$

Then, the probability of false alarm P_{fa} is the function of only spectrum sensing period τ and can be rewritten as follows

$$P_{fa}(\tau)=Q\left((\gamma+1)Q^{-1}(P_d)+\gamma\sqrt{\frac{\tau f_s}{2}}\right) \tag{12}$$

4. Capacity of Networks

In cooperative relay cognitive radio networks, the SU will play as the relay of the PU when the channel between the PT to the BS is bad, i.e, $h_{pb} << h_{ps}$ and $h_{pb} << h_{sb}$. Assume that the state of PU, H_0 or H_1, remains unchanged in one slot. In each slot, a SU first senses its surrounding spectrum. If the SU finds there is no PUs in the band (the band is idle), it will access the band, and then transmit its data. If the SU finds there is a PU in the band, it will operate as the relay of the PU. When the PU finishes its transmission, PU will release the band; and then, the SU will begin to access the band to transmit its data. **Fig. 2** shows the slot structures of the cognitive radio network when PU is active (H_1) and inactive (H_0) respectively. In the case of H_1, slot T is divided into four subslots. The first one is the spectrum sensing time, τ, in which PT transmits its own data to BS and ST senses the spectrum in the band; the second one is the subslot, t_1, in which PU transmits data to relay node ST; the third is the subslot, t_2, in which ST relays PU's data to the BS; and the last one is the time, $T-\tau-t_1-t_2$, in which the band is idle and ST can transmit its own data to SR. In the case of H_0, slot T is divided into two subslots. The first one is the spectrum sensing time, τ, and the other is the time, $T-\tau$, in which ST can transmit its own data to SR.

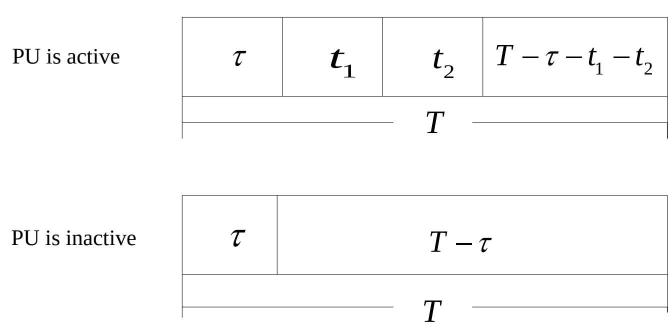

Fig. 2. Slot structures of cognitive networks

Let q be the probability with which a PU is active, $\hat{H}_0$ be the state in which a PU is not detected, $\hat{H}_1$ be the state in which a PU is detected, P_{PT} be the transmitted power of the PT and P_{ST} be the transmitted power of the ST. There are four cases when a SU (ST) detects whether a PU (PT) is active or inactive: a PU is detected when it is active actually; a PU is not detected when it is active actually; a PU is detected when it is inactive actually; and a PU is not detected when it is inactive actually.

When a PU is actually active and is detected, the conditional probability and available capacity of the channel between ST and SR can be described respectively as follows

$$\begin{cases} Pr_{11} = Pr(\hat{H}_1 \mid H_1) = qP_d \\ C_{11} = (T - \tau - t_1 - t_2)\log_2(1 + P_{ST}h_{ss}^2 / \sigma_n^2) \end{cases} \tag{13}$$

When a PU is actually active but is not detected, the conditional probability and available capacity of the channel between ST and SR can be described respectively as follows

$$\begin{cases} Pr_{01} = Pr(\hat{H}_0 \mid H_1) = q(1 - P_d) \\ C_{01} = (T - \tau)\log_2(1 + P_{ST}h_{ss}^2 / \sigma_n^2) \end{cases} \tag{14}$$

When a PU is actually inactive but is detected, the conditional probability and available capacity of the channel between ST and SR can be described respectively as follows

$$\begin{cases} Pr_{10} = Pr(\hat{H}_1 \mid H_0) = (1-q)P_{fa}(\tau) \\ C_{10} = (T - \tau - t_1 - t_2)\log_2(1 + P_{ST}h_{ss}^2 / \sigma_n^2) \end{cases} \tag{15}$$

When a PU is actually inactive and is not detected, the conditional probability and available capacity of the channel between ST and SR can be described respectively as follows

$$\begin{cases} Pr_{00} = Pr(\hat{H}_0 \mid H_0) = (1-q)[1 - P_{fa}(\tau)] \\ C_{10} = (T - \tau)\log_2(1 + P_{ST}h_{ss}^2 / \sigma_n^2) \end{cases} \tag{16}$$

The average capacity of the channel between ST and SR is given by

$$\begin{aligned} \overline{C}(\tau) &= Pr_{11}C_{11} + Pr_{01}C_{01} + Pr_{10}C_{10} + Pr_{00}C_{00} \\ &= [T - \tau - (t_1 + t_2)(qP_d + P_{fa}(\tau) - qP_{fa}(\tau))]\log_2(1 + P_{ST}h_{ss}^2 / \sigma_n^2) \end{aligned} \tag{17}$$

Define

$$K_1 = \log_2(1 + P_{PT}h_{pb}^2 / \sigma_n^2) \tag{18}$$

$$K_2 = \log_2(1 + P_{PT}h_{ps}^2 / \sigma_n^2) \tag{19}$$

$$K_3 = \log_2(1 + P_{PT}h_{sb}^2 / \sigma_n^2) \tag{20}$$

and

$$K_4 = \log_2(1 + P_{PT}h_{ss}^2 / \sigma_n^2) \tag{21}$$

We have

$$t_1 = \left(\frac{K_1}{K_2}\right)T \tag{22}$$

and

$$t_2 = \left(\frac{K_1}{K_3}\right)T \tag{23}$$

Then, the average capacity can be simplified as follows

$$\bar{C}(\tau) = [T - \tau - \left(\frac{K_1}{K_2} + \frac{K_1}{K_3}\right)T(qP_d + P_{fa}(\tau) - qP_{fa}(\tau))]K_4 \tag{24}$$

At this point, the problem of optimizing sensing time τ can be formulated as follows

$$\max_{\tau} \quad \left\{\bar{C}(\tau)\right\} \tag{25}$$

5. Optimal Spectrum Sensing Period

In this section, we will first show that the optimization problem in (25) is strictly a convex optimization problem, then give the globally optimal solution.

The first and second derivatives of $\bar{C}(\tau)$ with respect to τ are expressed respectively as follows

$$\bar{C}'(\tau) = [-1 - (1-q)\left(\frac{K_1}{K_2} + \frac{K_1}{K_3}\right)TP_{fa}'(\tau)]K_4 \tag{26}$$

$$\bar{C}''(\tau) = -(1-q)\left(\frac{K_1}{K_2} + \frac{K_1}{K_3}\right)TP_{fa}''(\tau)K_4 \tag{27}$$

where

$$P_{fa}'(\tau) = -\frac{\gamma\sqrt{f_s}}{4\sqrt{2\pi\tau}}\exp\left(-\frac{\left(\alpha + \gamma\sqrt{\frac{\tau f_s}{2}}\right)^2}{2}\right) \tag{28}$$

$$P_{fa}''(\tau) = \frac{\gamma\sqrt{f_s}}{8\tau\sqrt{2\pi}}\left[\frac{1}{\sqrt{\tau}} + \left(\alpha + \gamma\sqrt{\frac{\tau f_s}{2}}\right)\gamma\sqrt{\frac{f_s}{2}}\right]\exp\left(-\frac{\left(\alpha + \gamma\sqrt{\frac{\tau f_s}{2}}\right)^2}{2}\right) \tag{29}$$

and

$$\alpha = \sqrt{2\gamma + 1}Q^{-1}(P_d) \tag{30}$$

It is evident that $P_{fa}{}'(\tau) < 0$ and $P_{fa}{}''(\tau) > 0$.

It is noted that $K_1 > 0$, $K_2 > 0$, $K_3 > 0$ and $K_4 > 0$. Therefore, we have

$$\bar{C}''(\tau) < 0 \tag{31}$$

That is to say the problem (25) is strictly a convex optimization problem.

By letting $C'(\tau) = 0$, we have

$$P_{fa}{}'(\tau) = -\frac{1}{(1-q)\left(\frac{K_1}{K_2} + \frac{K_1}{K_3}\right)T} \tag{32}$$

Taking (28) into consideration, we have

$$\frac{1}{(1-q)\left(\frac{K_1}{K_2} + \frac{K_1}{K_3}\right)T} = \frac{\gamma\sqrt{f_s}}{4\sqrt{2\pi\tau}} exp\left(-\frac{\left(\alpha + \gamma\sqrt{\frac{\tau f_s}{2}}\right)^2}{2}\right) \tag{33}$$

or

$$\sqrt{\tau}\exp\left(\frac{\left(\alpha + \gamma\sqrt{\frac{\tau f_s}{2}}\right)^2}{2}\right) = K_0 \tag{34}$$

where

$$K_0 = \frac{(1-q)T\gamma\sqrt{f_s}\left(\frac{K_1}{K_2} + \frac{K_1}{K_3}\right)}{4\sqrt{2\pi}} \tag{35}$$

Define

$$f(\tau) = \sqrt{\tau}\exp\left(\frac{\left(\alpha + \gamma\sqrt{\frac{f_s\tau}{2}}\right)^2}{2}\right) \tag{36}$$

we get the globally optimal solution, i.e., the optimal sensing period, as follows

$$\tau_{opt} = f^{-1}(K_0) \tag{37}$$

6. Simulation Results and Analysis

In this section, we present some simulation results to show the capacity and spectrum sensing performance of cooperative relay cognitive radio networks with the optimal sensing period (OSP) using Monte Carlo simulations. We suppose that the system sampling frequency f_s is 100 MHz, the transmitted power of PU P_{PT} is 20 mW, the transmitted power of SU P_{ST} is 50 mW, the power of AWGN N_0 is 10^{-3} mW and the slot duration period T is 1 ms.

Fig. 3 shows the available capacity of cognitive networks versus the sensing period when the active probability of a PU q = 0.3 and the SNR of the signal received γ = -10 dB. For different target probabilities of detection, there are different optimal sensing periods in term of maximum available capacity (throughput), which have been marked with 'o' in the figure. As the target probability of detection increases, the sensing period is prolonged, and the available capacity is reduced. That is to say the target probability of detection is higher, the sensing period is longer, and the available capacity of SUs is lower. This is because a higher target probability of detection needs a longer sensing time. It results in a shorter access time of SUs, and then a smaller available capacity.

Fig. 4 illustrates the maximum capacity of cognitive radio networks versus the active probability of PUs for different target probabilities when the SNR of the signal received γ = -10 dB. As the active probability increases, the access probability of SUs will drop, and the available maximum capacity will decrease. The higher the target probability of detection under the same active probability, the longer the sensing period is, the smaller the maximum capacity of networks is.

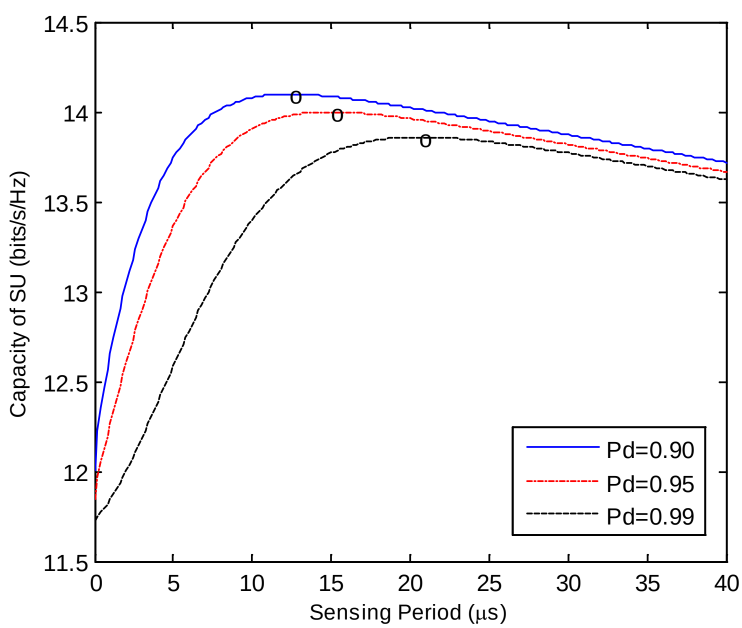

Fig. 3. Capacity of cognitive networks versus sensing period when q = 0.3 and γ = -10 dB.

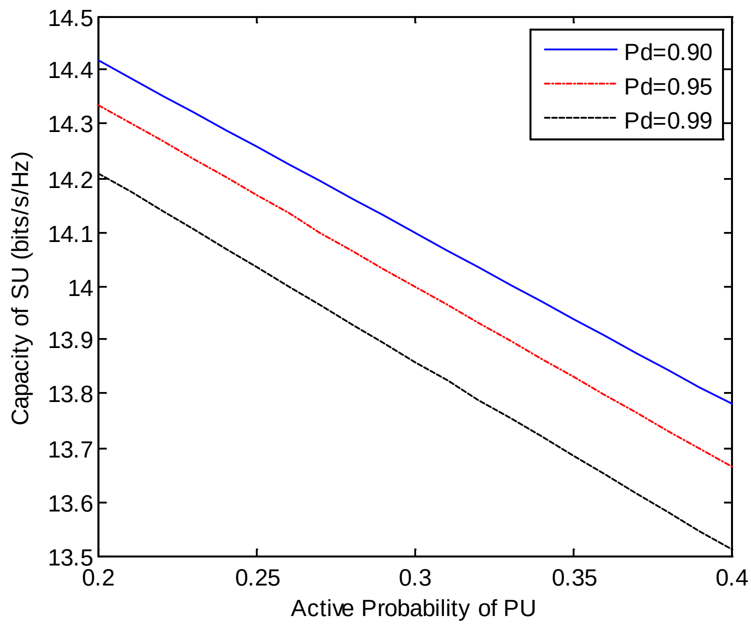

Fig. 4. Capacity of cognitive networks versus active probability of PU when γ = -10 dB.

Fig. 5 shows the optimal sensing period of the networks versus the SNR of the signal received when the active probability of PUs q = 0.3 and the target probability of detection P_d = 0.95. It is obvious that the SNR affects the optimal sensing period significantly. As we know, the available capacity of cognitive networks depends on the probability of false alarm and sensing period. The higher the probability of false alarm, the lower the access probability is, the smaller the available capacity is; the shorter the sensing period, the longer the access time is, the larger the available capacity is. When the SNR is low, the probability of false alarm is high, the sensing period has a little effect on the available capacity. As the SNR increases, the probability of false alarm will be decreased, the optimal sensing period will be prolonged to achieve a high capacity. When the SNR is larger than -16 dB or so, the probability of false alarm is very low and stable. Right now, as the SNR increases, the sensing period should be shortened to achieve a high capacity.

Fig. 6 describes the probability of false alarm of networks versus the sensing period when q = 0.3 and γ = -10 dB. As discussed above, the probability of false alarm is a function with sensing period when the target probability of detection is given. As the sensing period increases, the probability of false alarm will decrease obviously. However, the higher the target probability of detection is, the lower the given decision threshold is, and the higher the probability of false alarm is.

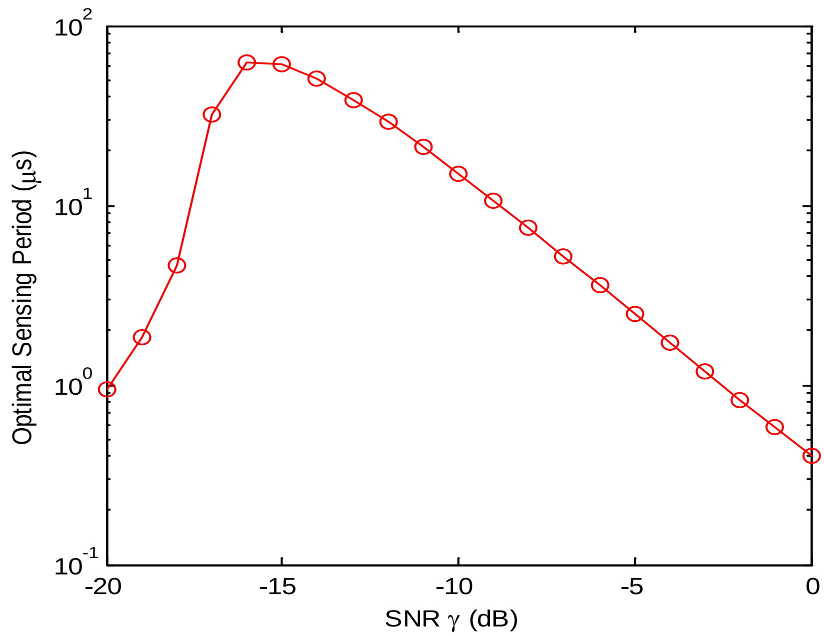

Fig. 5. Optimal sensing period versus SNR when q = 0.3 and P_d = 0.9

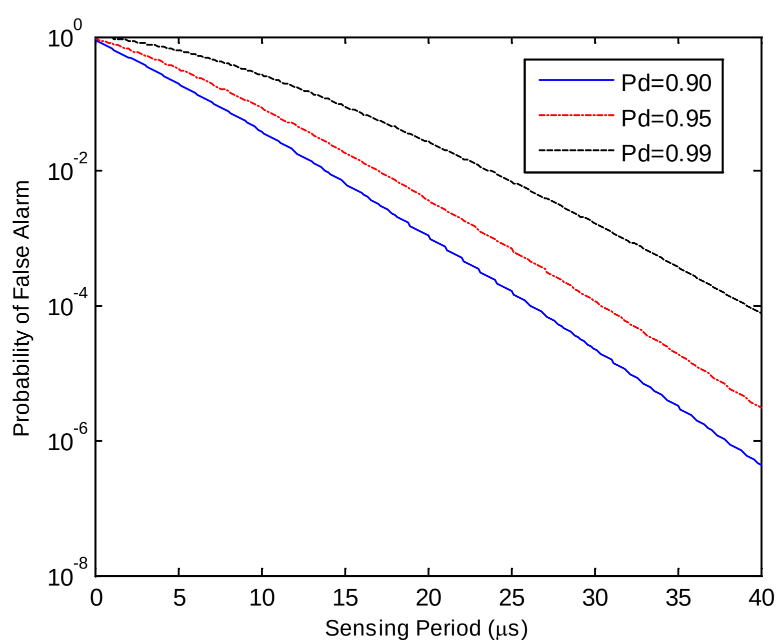

Fig. 6. Probability of false alarm versus sensing period when q = 0.3 and γ = -10 dB

Fig. 7 compares the available capacity of optimal sensing period with that of fixed sensing period when q = 0.3 and P_d = 0.95. As the SNR becomes high, the available capacity increases. When the SNR is very low ($\gamma < -18$ dB), the probability of false alarm is very high and almost independent of the sensing period, and the available capacity is very low; when the SNR is low ($-18 \le \gamma < -9$ dB), the profit in the decline of the probability of false alarm is larger than the loss in diminution of the transmitting period for SUs, and CR networks with longer sensing period can achieve higher capacity; when the SNR is high ($\gamma \ge -9$ dB), the profit in diminution of the transmitting period for SUs is larger than the loss in the rise of the probability of false alarm, and CR networks with shorter sensing period can achieve higher capacity. But CR networks with optimal sensing period can always achieve higher capacity. Obviously, the optimal sensing period strategy is better than fixed one.

Fig. 8 shows the comparison of the probabilities of false alarm versus target probability of detection when q = 0.3 and γ = -10dB. From the expression (12), we know that the probability of false alarm is the inverse function of the spectrum sensing period. As the increasing of spectrum sensing period, the number of the sample of signal detected is increased, and the probability of false alarm will decrease. In the optimal sensing period (OSP) scheme, the spectrum sensing period is optimized to obtain the maximum available capacity. The spectrum sensing period is a tradeoff one. Therefore, the probability of false alarm with optimal sensing period is larger than that with long sensing period (30 μs) but smaller than that with short sensing period (5 μs). However, as target probability of detection increases, the probabilities of false alarm with fixed sensing period go up, but the probability of false alarm with optimal sensing period is steady and almost unchanged.

Fig. 9 presents the comparison of the available capacities versus target probability of detection. As target probability of detection increases, although all of the available capacities decrease, the capacity with optimal sensing period is always larger than others.

From **Fig. 8** and **Fig. 9**, we see that although the probability of false alarm with optimal sensing period is larger than the probability of false alarm with long sensing period (30 μs), the available capacity with optimal sensing period is larger than the one with long sensing period. Prolonging the sensing period would reduce the transmitting period for SUs while cutting down the probability of false alarm. Therefore, we should optimize the sensing period in CR networks.

Fig. 10 illustrates the comparison of the available capacities between the cooperative relay cognitive radio network with the optimal sensing period proposed in this paper and the traditional cognitive radio network without relay [6]. In the cooperative relay cognitive radio network, SUs work as the relay to accelerate the transmission of the PU when PU is active. As a result, SUs can occupy more time to use the idle spectrum resources to transmit their data. It is obvious that available capacity of networks with relay is higher than that without relay.

From **Fig. 3** to **Fig. 10**, we conclude that the cognitive networks with optimal sensing period could achieve maximum capacity.

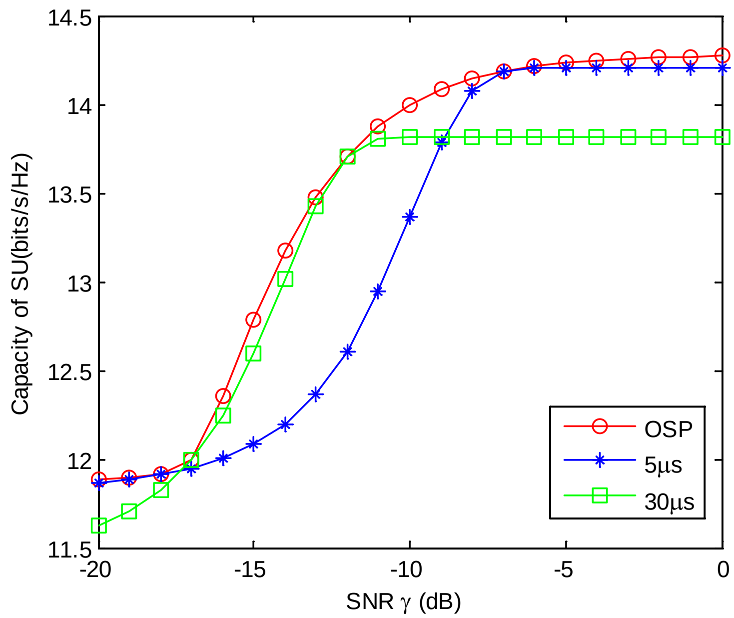

Fig. 7. Comparison of available capacities between OSP and fixed sensing period under different SNR

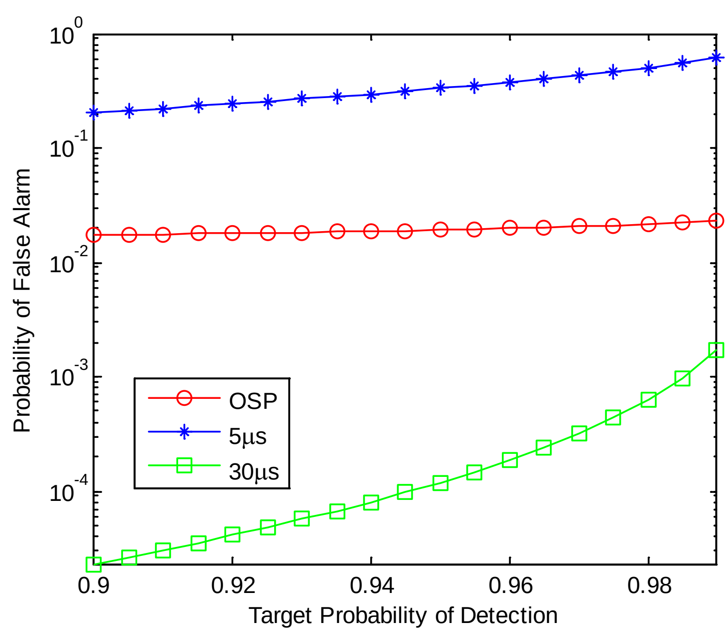

Fig. 8. Comparison of probabilities of false alarm between OSP and fixed sensing period under different target probability of detection

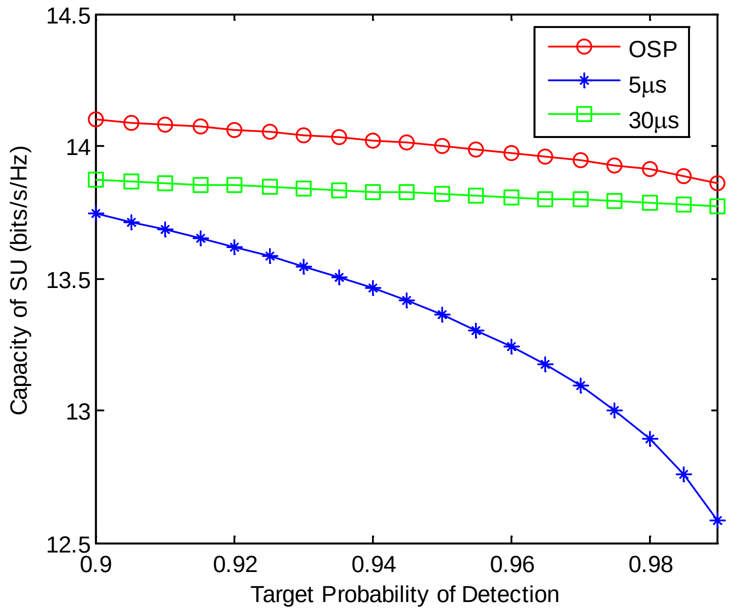

Fig. 9. Comparison of available capacities between OSP and fixed sensing period under different target probability of detection

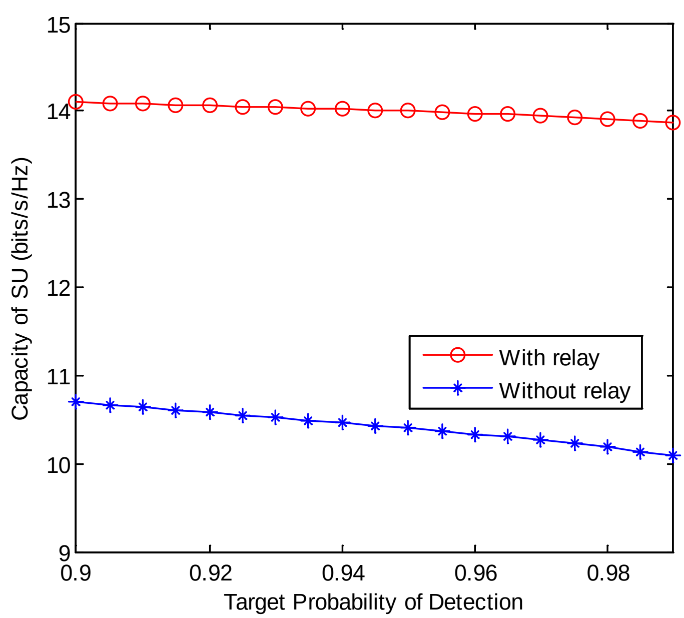

Fig. 10. Comparison of available capacities of networks between with relay and without relay under different target probability of detection

7. Conclusion

In this paper, we focus on the spectrum sensing period in cooperative relay cognitive radio networks and derive out the optimal spectrum sensing period to achieve the maximum throughput. We compare the available capacity and probability of false alarm in different cases. We conclude that the cooperative relay cognitive radio network with optimal spectrum sensing period offers obvious advantages over the fixed spectrum sensing period. It provides a valuable reference for choosing the optimal spectrum sensing period in cooperative relay cognitive radio.

This work opens up a path for some future researches. In order to improve the throughput of cognitive radio networks, the cooperative relay is an efficient way. This paper only discusses the optimal spectrum sensing period in cooperative cognitive radio network with single relay. We will further work on the optimal spectrum sensing period in cooperative cognitive radio network with multi-relay.

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