Optimization Algorithm for Spectrum Sensing Delay Time in Cognitive Radio Networks Using Decoding Forward Relay

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Abstract

Using decode-and-forward relaying in the cognitive radio networks, the spectrum efficiency can improve furthermore. The optimization algorithm of the spectrum sensing estimation time is presented for the cognitive relay networks in this paper. The longer sensing time will bring two aspects of the consequences. On the one hand, the channel parameters are estimated more accurate so as to reduce the interferences to the authorized users and to improve the throughput of the cognitive users. On the other hand, it shortens the transmission time so as to decease the system throughput. In this time, it exists an optimal sensing time to maximize the throughput. The channel state information of the sub-bands is considered as the exponentially distributed, so a stochastic programming method is proposed to optimize the sensing time for the cognitive relay networks. The computer simulation results using the Matlab software show that the algorithm is effective, which has a certain engineering application value.

Keywords: Cognitive relay networks, decode-and-forward relay, spectrum sensing, random programming.

1. Introduction

With the rapid development of the wireless communication technology, the demand for the spectrum resource has become increasingly tense. To solve this contradiction, the current spectrum management method must be improved. The Cognitive Radio (CR) is one of the most promising techniques to solve the spectrum scarcity. Some existing researches have focused on improving the spectrum efficiency and the power allocation optimization of the cognitive radio system [1]. On the other hand, the cooperative relaying technology is the key technology to improve the spectrum utilization, which has been shown effective to improve the capacity, promote the transmission reliability and increase the coverage of the wireless communication networks. The combination of the cognitive radio and the cooperative relaying technology can effectively improve the performance of the wireless network system and obtain higher spectrum utilization [2]. The cognitive relay networks include two basic strategies, the amplify-and-forward (AF) and the decode-and-forward (DF). In the DF scheme, the relay demodulates the received signal before retransmission, whereas in the AF scheme, the relay just amplifies the received signal only. In this paper, the DF relaying strategy is analysed.

The cognitive user generally applies the listen-before-transmit method to sense the spectrum of the primary user channel at the beginning of each data transmission frame. If the detected channel of the primary user is idle, the cognitive user transmits the data using the channel [3]. G. Ozcan proposed a cooperative detection algorithm of the cognitive radio spectrum based on the amplification and relaying technology [4]. Q. Cui analyzed the influence of the transmission time and power on the energy efficiency of the relay communication under the DF protocol [5]. X. Jiang introduced a power allocation optimization algorithm into the CRNs, proposed an interference evaluation strategy to use the different spectrum and power allocation methods while the secondary users are located in the different service regions of the primary users [6].

In this paper, the cognitive relay network model is used to apply the decode-and-forward protocols, which is put forward by Sendonaris [7][8], and also referred to as the Regenerative Relay (RR) processing mode [9][10]. The main idea is adopted that the information is transmitted from the source to the relay and the destination in the first time slot, then, the relay decode the received information, recode and forward to the destination in the second time slot. The destination decode the two parts of information and combine them to get the original information. In paper [11], Liu pointed out that the performance of the cognitive radio networks is influenced by the sensing time, and longer sensing time will improve the system performance, but also reduce the inter-channel data transmission time. Therefore, appropriately chosing the sensing time is very necessary to improve the performance of the cognitive relay networks. So, in this paper, it is necessary to optimize the spectral sensing time of the cognitive relay networks for the DF scheme.

The main contributions of this paper are summarised as follows: (1) A time-delay model is presented for the spectrum sensing process in the cognitive relay networks using the DF protocol; (2) A stochastic programming method is proposed to solve the time-delay model in

the cognitive relay networks. The rest of this paper is organised as follows. The system model is presented in Section 2. Section 3 proposes the optimization method of the spectrum sensing time in the cognitive DF-relay networks, then the stochastic programming model is introduced to solve the optimization problem. The numerical results and the CRNs' performances are discussed in Section 4. Finally, Section 5 presets the conclusions of this study.

2. System Model

The cognitive relay system is composed of a Primary User (PU) and a Seconary User (SU), in which the SU is made up of a Cognitive Source (CS), a Cognitive Relay (CR) and a Cognitive Destination (CD), as shown in **Fig. 1**. G_{rp}, G_{sp} are the channel gains from the CR and the CS to the PU respectively. G_{sd}, G_{sr}, G_{rd} are denoted the channel gains between the CS, CR and CD, as $CS \rightarrow CD, CS \rightarrow CR, CR \rightarrow CD$.
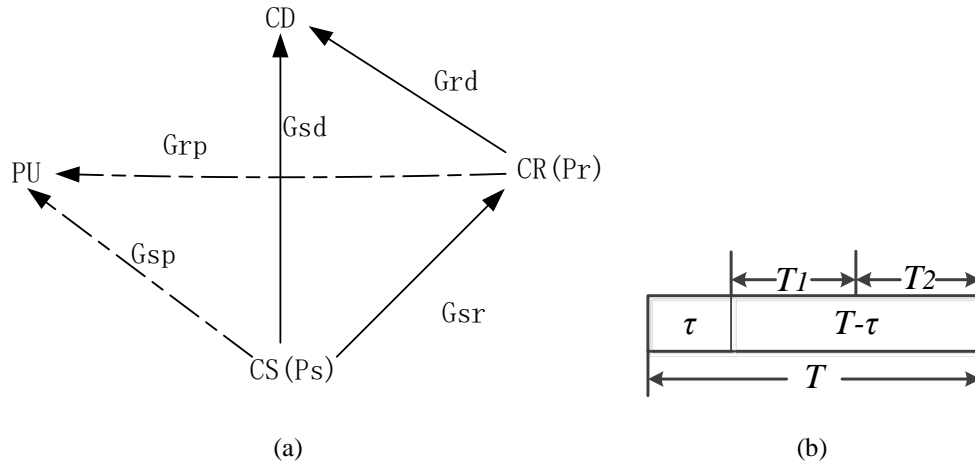

(a)   (b)

Fig. 1. DF cognitive relay network model.

In **Fig. 1** (a), the signal transmission from the CS to the CD is divided into two periods. In the T_1 period, the CS sends a signal, which is received by the CR and the CD; In the T_2 period, the CR transmits the signal received from the CS and decoded using the DF scheme, then, the CD receives the signal and merges it with the received signal at the T_1 period using the maximum ratio combination. The CS also receives the signal transmitted from the CR for the channel estimation. In **Fig. 1**(b), the total time of one data frame is denoted as T, which contains the duration τ for the spectrum sensing and channel estimation. The remaining time $T - \tau$ is used for information transmission, which is devided into two equal periods, $T_1 + T_2$, as shown in **Fig. 1**.

In general, it takes longer in the spectrum sensing, the channel estimation results are more accurate, and there are less interferences to the PU produced by the SU. Moreover, the SU's power allocation algorithm is more reasonable, the data transmission rate is even higher. However, the longer spectrum sensing time can lead to excessive resource consumption of the data transmission, resulting in lower system throughput. Therefore, the spectrum sensing time

delay τ is an optimized parameter, which can balance the effects of the above mentioned both aspects to achieve the highest data transmission rate.

3. Optimization Algorithm of Spectrum Sensing Time Delay

3.1 miss detection probability and false alarm probability

Here, the energy detection method is applied in the spectrum sensing. The transmission signal is a complex-valued MPSK modulation signal with an independent and symmetric cyclic symmetric complex Gaussian white noise. The miss detection probability p_{md} and the false alarm probability p_{fa} can be expressed as

$$p_{md}(\tau) = 1 - Q\left(\left(\frac{\lambda}{N_0} - \eta - 1\right)\sqrt{\frac{\tau f_s}{2\eta + 1}}\right) \tag{1}$$

$$p_{fa}(\tau) = Q\left(\left(\frac{\lambda}{N_0} - 1\right)\sqrt{\tau f_s}\right) \tag{2}$$

Where,

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty \exp\left(-\frac{u^2}{2}\right)du \tag{3}$$

λ is the energy threshold which determines whether the PU is idle or not, η is the signal-to-noise ratio received by the CS from the PU, f_s is the sampling frequency of the CS, N_0 is the noise power.

3.2 Model establishment

Compared with the AF protocol, the DF relay can avoid the noise being amplified and improve the signal quality. The throughput of the cognitive relay network system under the DF protocol can be expressed as,

$$R(\tau, P_s, P_r, \xi) = \frac{T - \tau}{T}\psi(\xi)\min\left(\log_2\left(1 + \frac{\gamma(\xi)}{N_0}\right), \log_2\left(1 + \frac{\beta(\xi)}{N_0} + \frac{\rho(\xi)}{N_0}\right)\right) \tag{4}$$

where $\xi = \left[G_{sd}, G_{sr}, G_{rd}, G_{rp}, G_{sp}, \chi, \tilde{\chi}\right]$ is the vector of the random variables, N_0 is the noise power. χ is the PU channel activity state judgment variable ($\chi \in \{O : Occupied, V : Vacant\}$). $\tilde{\chi}$ represents the cognitive source spectrum sensing decision $\tilde{\chi} \in \{O, V\}$.

$$\tilde{\chi} = \begin{cases} V & \text{CS or CR detects channel vacant} \\ O & \text{CS or CR detects channel occupied} \end{cases} \tag{5}$$

In Eq. 4,

$$\gamma(\xi) = P_s G_{sd}, \quad \beta(\xi) = P_s G_{sr}, \quad \rho(\xi) = P_r G_{rd}. \tag{6}$$

where P_s is the transmission power of the cognitive source CS, P_r is the transmission power of the cognitive relay CR. $\psi(\xi)$ is the indicator function, indicating whether the CS transmits

data or not according to the detection results. If the CS transmits the signal, $\psi(\xi)=1$, otherwise, $\psi(\xi)=0$.

$$\psi(\xi) = \begin{cases} 1 & \tilde{\chi}=V \\ 0 & \tilde{\chi}=O \end{cases} \tag{7}$$

If $v=\Pr(\chi=V)$ is denoted as the channel vacant probability, the probability quality function of $\psi(\xi)$ can be represented as the following equation,

$$\Pr(\psi(\xi)=1) = \left[1-p_{fa}(\tau)\right]v + p_{md}(\tau)(1-v) = p_{\psi 1} \tag{8}$$

The optimization issues can be expressed as,

$$\max_{\tau,P_s,P_r} R(\tau,P_s,P_r,\xi) \tag{9}$$

Subject to,

$$0 \le P_s \le P_s^m,$$
$$0 \le P_r \le P_r^m,$$
$$E\left[I_s(P_s,\xi)\right] \le I_s^a, \tag{10}$$
$$E\left[I_r(P_r,\xi)\right] \le I_r^a,$$
$$0 \le \tau \le T.$$

P_s^m is the maximum power constraint threshold for the cognitive source CS. P_r^m is the maximum power constraint threshold for the CR. In the case of the Rayleigh fading channel, the channel gain complies with the exponential distribution. In general, it is difficult to obtain all the channel state information (CSI), because the cooperation between the PU and the SU may bring a lot of overhead to the PU. So this paper assumes that only the average of the interference channel gain G_{sp}, G_{rp} is known. Assume that I_s^a and I_r^a is the average interference constraint from the CS and the CR to the PU. $E\left[I_s(P_s,\xi)\right]$ is the mean value of the interference power of the CS on the PU, and $E\left[I_r(P_r,\xi)\right]$ is the mean value of the interference power of the CR on the PU.

$$I_s(P_s,\xi) = G_{sp} \cdot P_s \cdot \vartheta(\chi,\tilde{\chi}) \tag{11}$$

where $\vartheta(\chi,\ \tilde{\chi})$ indicates whether the spectrum sensing result will interfere with the subband that the PU is occupying, that is, it equals to 1 while the actual subband is occupied but the result of the spectrum sensing is idle. That is,

$$\vartheta(\chi,\tilde{\chi}) = \begin{cases} 1 & (\chi=O,\tilde{\chi}=V) \\ 0 & others \end{cases} \tag{12}$$

The probabilistic mass function of $\vartheta(\chi,\ \tilde{\chi})$ can be expressed as,

$$\Pr(\ (\chi,\tilde{\chi})=1) = \Pr(\chi=O,\tilde{\chi}=V) = \Pr(\tilde{\chi}=V \mid \chi=O)\Pr(\chi=O) = p_{md}(\tau)v \tag{13}$$

Similarly, the interference power of the CR to the PU can be denoted as,

$$I_r(P_r,\xi) = G_{rp} \cdot P_r \cdot \vartheta(\chi,\tilde{\chi}) \tag{14}$$

As a reasonable assumption, the interference instruction function $\vartheta\left(\chi, \ \tilde{\chi}\right)$ and the channel gain G_{sp}, G_{rp} are not relevant. The tolerable average interference constraint can be expressed as,

$$E\left[I_s\left(P_s,\xi\right)\right]=E\left[P_sG_{sp}\ \left(\chi,\tilde{\chi}\right)\right]=P_sE\left[G_{sp}\ \left(\chi,\tilde{\chi}\right)\right]=P_s\cdot p_{md}\cdot v\cdot\Omega_{sp}\le I_s^a \qquad (15)$$

$$E\left[I_r\left(P_r,\xi\right)\right]=E\left[P_rG_{rp}\ \left(\chi,\tilde{\chi}\right)\right]=P_rE\left[G_{rp}\ \left(\chi,\tilde{\chi}\right)\right]=P_r\cdot p_{md}\cdot v\cdot\Omega_{rp}\le I_r^a \qquad (16)$$

where Ω_{sp} are the mean value of the interference channel gain from the CS on the PU, and Ω_{rp} denotes the interference channel gain from the CR on the PU. It can be seen in Eq. 9-10 that the model is a complex optimization problem which can not be directly calculated. A stochastic programming method is proposed in the following section to solve this complicated problem.

3.3 Stochastic Programming Model

The random programming algorithm includes three basic steps.

Step 1. Solve the problem, $R\left(\tau,\xi\right)$,

$$R\left(\tau,\xi\right)=\max_{P_s,P_r}R\left(\tau,P_s,P_r,\xi\right) \qquad (17)$$

Step 2. Solve the problem, $R\left(\tau\right)$,

$$R\left(\tau\right)=E_\xi\left[R\left(\tau,\xi\right)\right] \qquad (18)$$

Step 3. Solve the problem, $\max_\tau R\left(\tau\right)$.

The average value of the interference channel gains G_{sp}, G_{rp} are assumed to be known. The average transmission power of the CS and the CR can be expressed as,

$$\overline{P}_s=\frac{I_r^a}{E\left[G_{sp}\ \left(\chi,\tilde{\chi}\right)\right]}=\frac{I_r^a}{p_{md}\left(\tau\right)\cdot v\cdot\Omega_{sp}} \qquad (19)$$

$$\overline{P}_r=\frac{I_r^a}{E\left[G_{rp}\ \left(\chi,\tilde{\chi}\right)\right]}=\frac{I_r^a}{p_{md}\left(\tau\right)\cdot v\cdot\Omega_{rp}} \qquad (20)$$

So the signal power received by the CD from the CS channel can be expressed indirectly as,

$$\gamma\left(\xi\right)=min\left(P_m^s,\overline{P}_s\right)G_{sd} \qquad (21)$$

Similarly, the signal power received from the CS to the CR channel, and the signal power received from the CR to the CD channel, are respectively denoted as following.

$$\beta\left(\xi\right)=min\left(P_s^m,\overline{P}_s\right)G_{sr} \qquad (22)$$

$$\rho\left(\xi\right)=min\left(P_r^m,\overline{P}_r\right)G_{rd} \qquad (23)$$

It is assumed that the transmission channel gain G_{sd}, G_{sr}, and G_{rd} are with the exponential distribution Ω_{sd}, Ω_{sr}, and Ω_{rd}. According to the exponential distribution characteristic, the probability functions of γ, β, ρ comply with the exponential distribution as shown in following.

$$\begin{cases} \Omega_\gamma = min\left(P_s^m, \overline{P}_s\right)\Omega_{sd} \\ \Omega_\beta = min\left(P_s^m, \overline{P}_s\right)\Omega_{sr} \\ \Omega_\rho = min\left(P_r^m, \overline{P}_r\right)\Omega_{rd} \end{cases} \tag{24}$$

Then the conditional probability density of γ, β, ρ is the exponential distribution of $\Omega_\gamma, \Omega_\beta$, and Ω_ρ.

$$\begin{cases} f_{\gamma|\tilde{\chi}=V}(x) = \dfrac{1}{\Omega_\gamma} e^{-\frac{x}{\Omega_\gamma}} \\[2mm] f_{\beta|\tilde{\chi}=V}(y) = \dfrac{1}{\Omega_\beta} e^{-\frac{x}{\Omega_\beta}} \\[2mm] f_{\rho|\tilde{\chi}=V}(z) = \dfrac{1}{\Omega_\rho} e^{-\frac{x}{\Omega_\rho}} \end{cases} \tag{25}$$

According to Eq. 4, $R(\tau)$ can be expressed as

$$R(\tau) = E_\xi\left[R(\tau,\xi)\right]$$

$$= \frac{T-\tau}{T} p_{\psi 1} \times \begin{cases} E_\xi\left[\log_2\left(1+\dfrac{\gamma(\xi)}{N_0}\right)\middle|\tilde{\chi}=V\right], \gamma(\xi) \le \beta(\xi)+\rho(\xi) \\[3mm] E_\xi\left[\log_2\left(1+\dfrac{\beta(\xi)}{N_0}+\dfrac{\rho(\xi)}{N_0}\right)\middle|\tilde{\chi}=V\right], \gamma(\xi) > \beta(\xi)+\rho(\xi) \end{cases} \tag{26}$$

In the case of a known average interference channel gain, the throughput of the first stage can be expressed as

$$R(\tau) = \frac{T-\tau}{T} p_{\psi 1} \overline{R} \tag{27}$$

where

$$\overline{R} = \iiint\limits_{\substack{x<y+z \\ x>0, y>0, z>0}} \log_2\left(1+\frac{x}{N_0}\right) f_{\gamma|\tilde{\chi}=V}(x) f_{\beta|\tilde{\chi}=V}(y) f_{\rho|\tilde{\chi}=V}(z) \, dxdydz$$

$$+ \iiint\limits_{\substack{x>y+z \\ x>0, y>0, z>0}} \log_2\left(1+\frac{y}{N_0}+\frac{z}{N_0}\right) f_{\gamma|\tilde{\chi}=V}(x) f_{\beta|\tilde{\chi}=V}(y) f_{\rho|\tilde{\chi}=V}(z) \, dxdydz \tag{28}$$

which can be calculated as following,

$$\bar{R} = \frac{\Omega_\beta}{\ln 2 \cdot \left(\Omega_\rho - \Omega_\beta \right)} e^{N_0 \left(\frac{1}{\Omega_\gamma} + \frac{1}{\Omega_\beta} \right)} Ei \left[-N_0 \left(\frac{1}{\Omega_\gamma} + \frac{1}{\Omega_\beta} \right) \right]$$

$$+ A \cdot e^{N_0 \left(\frac{1}{\Omega_\gamma} + \frac{1}{\Omega_\rho} \right)} Ei \left[-N_0 \left(\frac{1}{\Omega_\gamma} + \frac{1}{\Omega_\rho} \right) \right] \tag{29}$$

$$- \frac{1}{\ln 2} e^{\frac{N_0}{\Omega_\gamma}} Ei \left[-\frac{N_0}{\Omega_\gamma} \right]$$

where

$$A = \frac{\Omega_\gamma^2 \Omega_\rho \Omega_\beta - \Omega_\gamma^2 \Omega_\rho^2 + \Omega_\gamma \Omega_\rho^2 + 2 \cdot \Omega_\gamma^2 \Omega_\rho + \Omega_\beta \Omega_\rho^2 - \Omega_\beta^2 \Omega_\gamma + \Omega_\gamma \Omega_\rho \Omega_\beta}{\ln 2 \cdot \left(\Omega_\gamma + \Omega_\beta \right) \cdot \left(\Omega_\gamma + \Omega_\rho \right) \cdot \left(\Omega_\beta - \Omega_\rho \right)} \tag{30}$$

and $Ei(x) = \int_{-\infty}^{x} e^t \big/ t \, dt$. Then, the system throughput $R(\tau)$ is obtained as follows.

$$R(\tau) = \frac{T - \tau}{T} p_{\psi 1} \times \left(\frac{\Omega_\beta}{\ln 2 \cdot \left(\Omega_\rho - \Omega_\beta \right)} e^{N_0 \left(\frac{1}{\Omega_\gamma} + \frac{1}{\Omega_\beta} \right)} Ei \left[-N_0 \left(\frac{1}{\Omega_\gamma} + \frac{1}{\Omega_\beta} \right) \right] \right.$$

$$\left. + A \cdot e^{N_0 \left(\frac{1}{\Omega_\gamma} + \frac{1}{\Omega_\rho} \right)} Ei \left[-N_0 \left(\frac{1}{\Omega_\gamma} + \frac{1}{\Omega_\rho} \right) \right] - \frac{1}{\ln 2} e^{\frac{N_0}{\Omega_\gamma}} Ei \left[-\frac{N_0}{\Omega_\gamma} \right] \right) \tag{31}$$

To solve the optimization function shown in Eq. 31 is very complex and difficult using the usual unconstrained optimization algorithm, because of the minimum function existing in Eq. 24. The Monte Carlo algorithm is used to obtain the maximum throughput.

4. Experimental Results and Analysis

The simulation parameters are set as shown in **Table 1** [12].

Table 1. Simulation parameter setting.

Parameters	Values
λ	0.055
N_0	$0.05 mW$
η	$-6 dB$
T	$5 ms$
f_s	$10K$ samples/s
v	0.7

The communication system apply in the complex MPSK modulation with the parameters set in **Table 1**. The index distribution rate of each channel gain Ω_{sd}, Ω_{sr}, Ω_{rd}, Ω_{rp}, and Ω_{sp} are set 1.

P_m^s and P_m^r are set -10dBm. The communication networks are simulated using the MATLAB software to solve Eq. 31. The Monte Carlo method is used with 1000 times of the test number. The optimal time obtained as 0.615ms. The result is as shown in **Figs. 2-5**. the sensing time τ gets longer, the throughput firstly increases and reaches a maximum value, then starts to decrease. There is a maximum value of the throughput with the optimal solution of the sensing time τ_0.
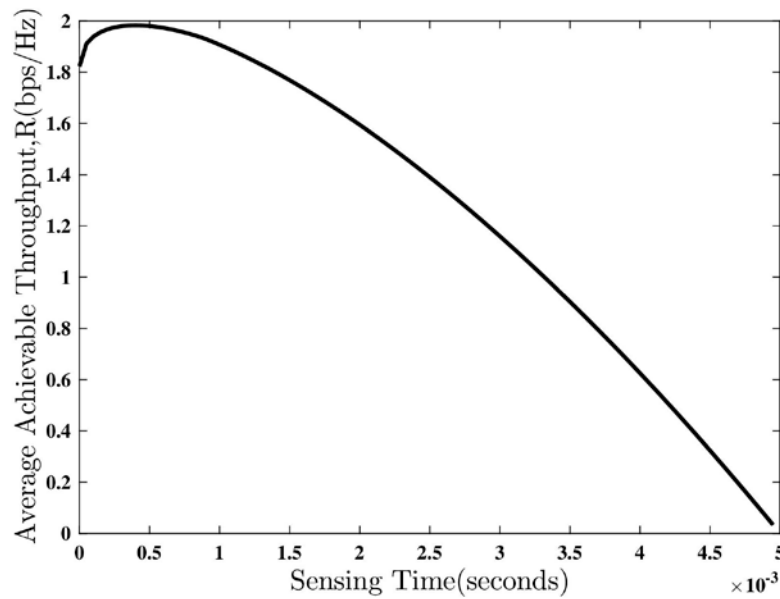

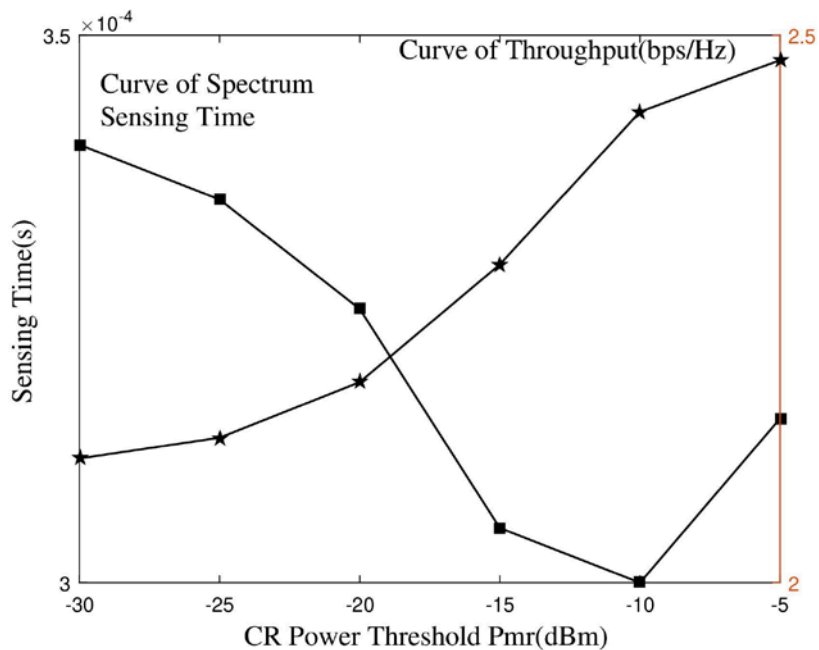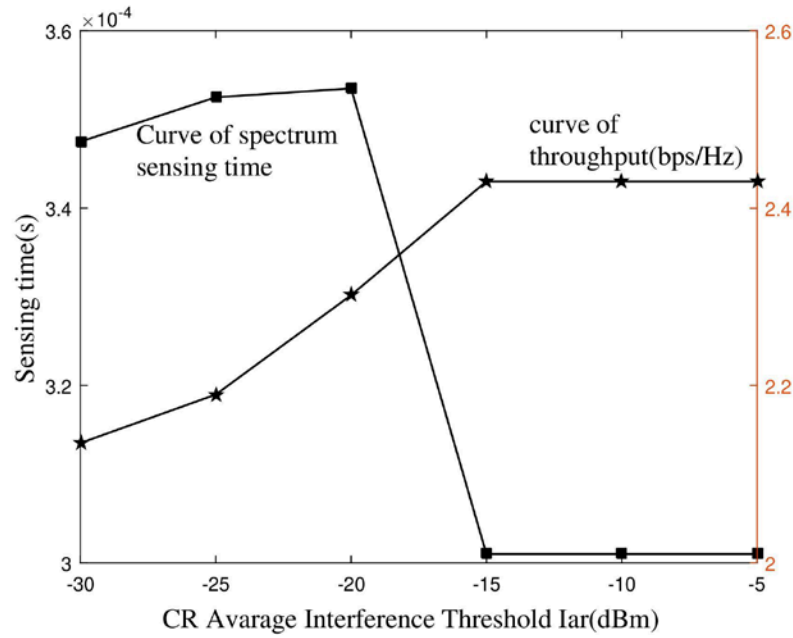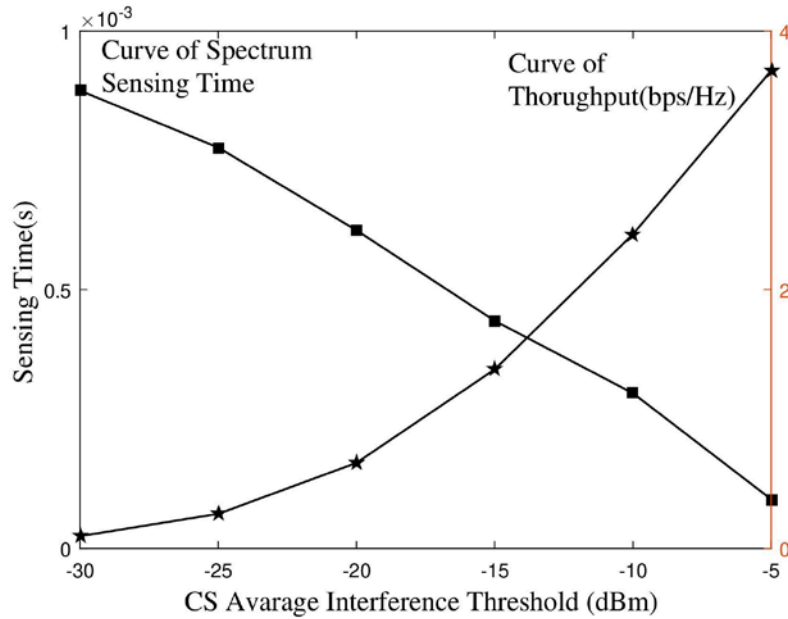**Fig. 2.** DF Cognitive relay network spectrum sensing time delay optimization diagram.

Fig. 3. CR Power Threshold to Spectrum Sensing time Transform diagram.

Fig. 4. CR average interference constraint on the spectrum sensing time transform diagram.

Fig. 5. The time-delay transformation diagram of the spectrum sensing time delay is realized by the average interference constraint of the cognitive relay network.

As shown in **Fig. 3**, the interchange of the spectrum sensing time and the system throughput can obtain by changing the power threshold of the CR. It can be seen from the figure that as the power threshold increases, the spectrum sensing time shortens and the throughput increases. So allocating more power to the channel can reduce the spectrum sensing delay.

As shown in **Fig. 4**, the best interchange trend of the spectrum sensing time and the throughput can obtain by changing the CR average interference constraint I_a^r. From the figure, we can see that the average interference constraint become smaller, the spectrum sensing delay is longer, while the corresponding system throughput decreases.

Fig. 5 shows the interchange trend of the best spectrum sensing time and the system throughput by changing the average interference constraint of the CS. It can be seen from the figure that as the average interference constraint decreases, the spectrum sensing time becomes longer, while the system throughput decreases, which is consistent with the analysis in the previous section.

5. Conclusion

The main problem addressed in this paper is to increase the spectrum efficiency of cognitive relay networks. The cognitive radio networks assisted by single-channel cooperative relay adopts the DF mode to improve the spectrum efficiency and increase the communication reliability. The cognitive relay networks using the spectrum sensing mode of listen-first-then-pass, therefore, spent the spectrum sensing time, which affects the throughput and the interference of the channel transmission. The spectrum sensing time for the cognitive relay network can be optimized on the channel interference and the power constraints. The stochastic programming method is used to solve the problem through transforming the uncertainty factors in the constraint into deterministic factors, and an optimal design method of the spectrum sensing channel estimation time is proposed. The computer simulation results show that this method is effective which has certain engineering value.

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