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Energy Efficiency Maximization Based on Cooperative Sensing in Cognitive Relay Networks

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Abstract

In this paper, we investigate the energy efficiency maximization problem of cognitive radio systems. We propose to study energy efficiency of cognitive relay transmission scheme based on cooperative spectrum sensing, since empirical studies have shown that optimal sensing time and transmit power are key factors for energy efficiency maximization. We design a method that simultaneously considers the parameters of spectrum sensing time and transmit power. Finally, we conduct deep experiments which show that our proposed approach can significantly improve the throughput and energy efficiency than the non-cooperative spectrum sensing method.

Keywords*: cognitive radio, cooperative spectrum sensing, energy efficiency, cognitive relay transmission, transmit power*

1. Introduction

Due to the widespread of wireless services, the fixed spectrum allocation scheme can not meet the constantly increasing service demand. However, cognitive radio enables unlicensed users to utilize idle licensed spectral bands through spectrum sensing. It is well known that spectrum sensing is a fundamental problem in cognitive radio system and different spectrum sensing techniques have been proposed. Among them, energy detection is the most popular technique owing to its low complexity, and the advantage that it has no requirements on the priori knowledge of primary user signal [1].

Secondary users may suffer severe fading from factors such as multi-path, shadow effects and building penetration. To address this challenges, multiple secondary users can work together to detect the presence of the primary user, which is called cooperative sensing. Cooperative sensing can efficiently improve the sensing performance [2]. Each secondary user reports its local sensing results to the fusion center which predicts whether the primary user is present or absent by utilizing fusion rules [3, 5]. Once an available spectrum hole is detected, secondary users can exploit the opportunity to transmit their data without affecting the use of primary user. Cooperative transmission between secondary users can significantly enhance the capacity of cognitive radio networks. There are mainly three relay protocols which are amplify-and-forward (AF), decode-and-forward (DF) and compress-and-forward (CF) [4, 6].

Spectrum sensing and throughput tradeoff were investigated in [5, 7, 8], in which people discovered that optimal spectrum sensing time is key for maximizing the throughput of cognitive radio networks. Optimal spectrum sensing overhead could minimize the outage probability of cognitive transmission [9]. Energy efficiency and throughput of direct transmission could be maximized by optimal sensing time in cognitive radio networks [10, 16]. There is a unique globally optimal link adaptation to maximize energy efficiency [11]. Energy-efficient channel management scheme was presented in [12]. The conclusion is that there exists a unique globally optimal transmit power for secondary user to achieve the maximum energy efficiency [13]. Power efficiency was proposed in [15] by direct transmission in cognitive radio networks. However, this paper has not taken cooperative sensing and cognitive relay transmission into account.

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To solve above problems, we propose considering transmit power and cooperative sensing time together in cognitive radio networks. We prove that there exists global optimal sensing time and optimal transmit power to achieve the maximum of power efficiency.

The rest of this paper is organized as follows: Section II outlines system model and expressions, followed by the energy detector and cooperative sensing in Section III. Section IV gives the cooperative relay transmission model based on AF protocol. Energy efficiency is defined in Section V and simulation results are provided in Section VI. Finally, Section VII concludes the paper.

2. System Model

In this section, we propose a cognitive relay network as shown in Figure 1, where one cognitive relay (CR) helps cognitive source (CS) for its data transmission, which is described as follows in detail. Each transmission link between any two nodes is modeled as a Rayleigh fading channel. One can see that the whole cognitive transmission process can be divided into two phases: the detection of the idle licensed spectrum band and cognitive relay transmission. The allocation of time duration between spectrum sensing and cognitive relay transmission is depicted in Figure 2, which is composed of one sensing slot and one data transmission slot. Suppose that τ is spectrum sensing duration and T is frame duration, then data transmission duration is $T-\tau$.

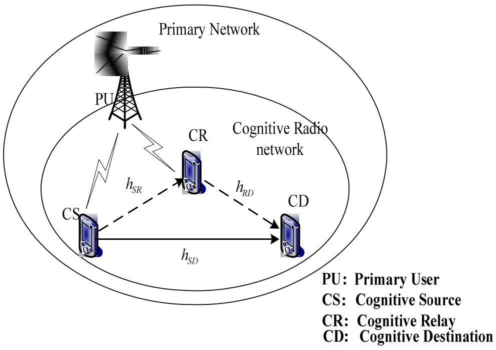

Figure1. Coexistence of a Primary Wireless Network and a Cognitive Relay Network

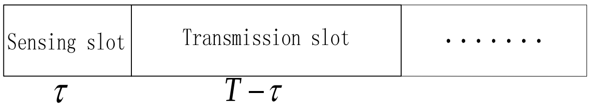

Figure 2. Frame Structure for Cognitive Radio Networks

3. Energy Detector and Cooperative Spectrum Sensing

In this section, we discuss the models of cooperative sensing in cognitive radio networks. In part A, we review the energy detection technique and analyze the relationship between detection probability and false alarm probability. Part B demonstrates the fusion rules.

3.1. Energy Detector

Suppose that there are M cognitive users to take part in spectrum sensing in cognitive radio networks. The binary hypothesis test of ith cognitive user for cooperative sensing at kth time instant is formulated as follows.

$$\begin{aligned} &\mathcal{H}_0 : y_i(k) = n_i(k) \\ &\mathcal{H}_1 : y_i(k) = \sqrt{P_p}\, h_{pi} x(k) + n_{pi}(k) \end{aligned} \tag{1}$$

Where $x(k)$ denotes the signal transmitted by the primary user and $y_i(k)$ is the received signal by the ith cognitive user. P_p stands for the power of PU (primary user), h_{pi} denotes the fading channel coefficient of inter-user link between the ith cognitive user and PU,

$n_i(k)$ and $n_{pi}(k)$ is circularly symmetric complex Gaussian noise with zero mean and variance σ_n^2. Let $\gamma_p = P_p / \sigma_n^2$ be the received SNR of the primary user signal measured at the interest cognitive receiver under hypothesis $\mathcal{H}_1$. $\mathcal{H}_1$ denotes that PU is active, $\mathcal{H}_0$ represents that a spectrum hole can be available for cognitive users. We assume that the probabilities of $\mathcal{H}_0$ and $\mathcal{H}_1$ are $P(\mathcal{H}_0)$ and $P(\mathcal{H}_1)$ respectively, and $P(\mathcal{H}_0)+P(\mathcal{H}_1)=1$.

Energy detection is the most popular spectrum sensing scheme. In this paper, we take energy detection into consideration. The spectrum sensing time is τ, f_s denotes sampling frequency, N represents the number of samples (N is the integer not greater than τf_s). The test statistic for energy detector is given by:

$$T(y) = \frac{1}{N}\sum_{k=1}^{N} \left| y_i(k) \right|^2 \tag{2}$$

Suppose that detection threshold is η, the probability of false alarm and the probability of detection are given by:

$$P_f^i(\tau,\eta) = Q\left(\left(\frac{\eta}{\sigma_n^2} - 1 \right) \sqrt{\tau f_s} \right) \tag{3}$$

$$P_d^i(\tau,\eta) = Q\left(\left(\frac{\eta}{\sigma_n^2} - \gamma_p - 1 \right) \sqrt{\frac{\tau f_s}{2\gamma_p + 1}} \right) \tag{4}$$

Where $Q(x)$ is the complementary distribution function of standard Gaussian, i.e. $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{+\infty} e^{-\frac{t^2}{2}} dt$. For a target probability of detection $\overline{P}_d^i$, the probability of false alarm related to the target detection probability is as follows [5].

$$P_f^i(\tau,\eta) = Q\left[Q^{-1}\left(\overline{P}_d^i \right) \sqrt{\left(2\gamma_p + 1 \right)} + \gamma_p \sqrt{\tau f_s} \right] \tag{5}$$

3.2. Fusion Rule

In order to improve the performance of spectrum sensing, cooperative spectrum sensing is taken into account. When binary local decisions are reported to fusion center, the fusion center will make a final decision based on fusion rules. The commonly used fusion rules are OR rule, AND rule and k out of M rule. We mainly discuss k out of M rule.

k out of M rule: In cognitive radio networks, there are M cognitive users to take part in cooperative sensing. If k out of M cognitive users detect that the primary user is present, the fusion center will declare that the primary user is active. Suppose that all decisions are independent, the detection and the false alarm probabilities under this rule are rewritten as follows.

$$P_D(\tau,k,\eta) = \sum_{i=k}^{M} \binom{M}{i} P_d^i(\tau,\eta)^i \left(1 - P_d^i(\tau,\eta) \right)^{M-i} \tag{6}$$

$$P_F(\tau,k,\eta) = \sum_{i=k}^{M} \binom{M}{i} P_f^i(\tau,\eta)^i \left(1 - P_f^i(\tau,\eta) \right)^{M-i} \tag{7}$$

When the value of k is 1, the k out of M rule is equivalent to OR rule. If the value of k is taken as M, the k out of M rule becomes the AND rule. We can find that there exists different optimal value of k to minimize the false alarm probability for different parameters under the target detection probability constraint through exhaustive searching algorithm. The miss detection probability for cooperative spectrum sensing is given by:

$$P_M\left(\tau,k,\eta\right)=1-P_D\left(\tau,k,\eta\right) \tag{8}$$

4. Cognitive Relay Transmission

The spectrum efficiency can be improved by utilizing cooperative relay to assist the transmission. In this section, we introduce the model of cognitive relay transmission.

Once cognitive users detected spectrum holes, cognitive user will utilize the chance to transmit data to its destination. From Figure 3, we can see that the whole cognitive relay transmission process can be divided into two phases. In phase I, cognitive source (CS) broadcasts its information to both cognitive relay (CR) and cognitive destination (CD). In phase II, CR retransmits received data from CS to CD in amplify-and-forward (AF) mode, while CS doesn't broadcast any information. The whole cognitive relay transmission duration is $T-\tau$. The formula of data transmission from CS to CR and CD can be expressed as:

$$y_r=\sqrt{P_s}h_{sr}x_1+n_{sr} \tag{9}$$

$$y_{d1}=\sqrt{P_s}h_{sd}x_1+n_{sd} \tag{10}$$

CR transmits data to CD in AF mode, which can be formulated as follows:

$$y_{d2}=\beta h_{rd}y_r+n_{rd} \tag{11}$$

Where $\beta=\sqrt{\frac{P_r}{P_s\left|h_{sr}\right|^2+\sigma_n^2}}$ is the amplifier gain [9], h_{sr} h_{sd} and h_{rd} are fading channel coefficients between CS and CR, between CS and CD and between CR and CD, respectively. Throughout the paper, we assume that the channel coefficients are known by receivers but not by transmitters. The channel coefficients of aforementioned wireless links are independent and identically distributed circularly symmetric complex Gaussian random variables with zero mean and variance δ_{sr}^2, δ_{sd}^2 and δ_{sd}^2 respectively.

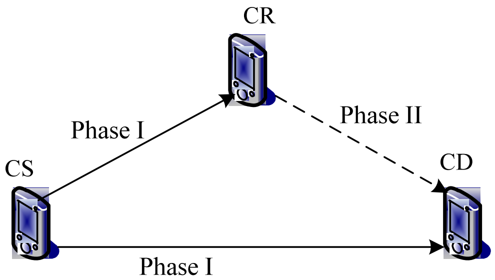

Figure 3. Cognitive Relay Transmission Protocol

The data transmission rate over cognitive relay channel is given by:

$$R=\frac{1}{2}\log_2\left(1+\frac{P_s\left|h_{sd}\right|^2}{\sigma_n^2}+\frac{P_s\left|h_{rd}\beta h_{sr}\right|^2}{\left(\left|h_{rd}\beta\right|^2+1\right)\sigma_n^2}\right)=\log_2\left(1+\frac{P_s\left|h_{sd}\right|^2}{\sigma_n^2}+\frac{P_sP_r\left|h_{sr}\right|^2\left|h_{rd}\right|^2}{\left(P_s\left|h_{sr}\right|^2+P_r\left|h_{rd}\right|^2+\sigma_n^2\right)\sigma_n^2}\right) \tag{12}$$

Where P_s is transmit power of cognitive source, P_r denotes the transmit power of cognitive relay, $P_t = P_s + P_r$ represents the total transmit power of cognitive system. For simplicity, cognitive source and cognitive relay are allocated equal power, and $P_s = P_r = 0.5P_t$. The optimal location of cognitive relay sits at the mid-point between the cognitive source and the cognitive destination for the AF mode [18].

5. Energy Efficiency

In this section, we investigate the power efficiency of cognitive radio networks. The relationship between spectrum sensing and throughput has been researched in cognitive radio network [5, 7]. We know that there is an optimal spectrum sensing time to maximize the throughput. In cognitive radio networks, the optimal transmit power can reduce total transmit power without significant performance degradation. We define the energy efficiency as follows.

$$\xi = \frac{Th\left(P_t, \tau\right)}{E\left(P_t, \tau\right)} \tag{13}$$

Let $Th\left(P_t, \tau\right)$ be the throughput of cognitive radio networks. There are two scenarios that the cognitive user can communicate with cognitive destination. Scenario 1: When the primary user is not present and no false alarm is generated by the cognitive users. Scenario 2: If the primary user is active while the cognitive users miss detect the presence of the primary user. Then the overall throughput of the cognitive network is given by:

$$Th\left(P_t, \tau\right) = \frac{T-\tau}{T}\left[P\left(H_0\right)\left(1-P_F\right)R + P\left(H_1\right)P_M R\right] \tag{14}$$

R is the transmission rate, P_t is the transmit power. The probability that cognitive user can make use of the licensed spectrum bands is as follows.

$$P = P\left(H_0\right)\left(1-P_F\right) + P\left(H_1\right)P_M \tag{15}$$

The energy that consumed in a frame mainly contains three parts: circuit energy consumption, spectrum sensing energy consumption and data transmission energy consumption. Then the overall energy consumption for non-cooperative sensing within a frame is as follows.

$$E\left(P_t, \tau\right) = \tau P_\tau + P_c T + P\left(T-\tau\right)0.5P_t \tag{16}$$

The whole energy consumption for cooperative sensing within a frame is given by:

$$E^c\left(P_t, \tau\right) = \tau M P_\tau + P_c T + P\left(T-\tau\right)0.5P_t \tag{17}$$

Where P_τ denotes the spectrum sensing power of each cognitive user, P_c stands for the circuit power.

6. Simulation Results

In this section we report the simulation results in order to compare the performance of the proposed schemes.

Let detection probability $\overline{P}_D = 0.95$ for both cooperative sensing scheme and non-cooperative sensing scheme throughout the paper to provide sufficient protection for the primary user. The other system parameters are set as follows: $P\left(H_0\right)=0.8$, sampling frequency $f_s=1M\mathrm{Hz}$ and frame duration $T=25ms$.

We analyze the throughput of cognitive relay networks based on cooperative sensing scheme over Rayleigh fading channels. The channel variances of three nodes in cognitive relay networks are $\delta_{sd}^2=1$, $\delta_{sr}^2=2$ and $\delta_{rd}^2=2$ respectively. Then, we compare the throughput of cognitive relay network based on the 3 out of 5 rule with that of non-cooperative sensing scheme, as shown in Figure 4. We can know that cooperative sensing can sufficiently improve the throughput of cognitive relay networks than non-cooperative sensing.

Figure 5 exhibits the throughput versus transmit power based on different fusion rules under $\gamma_p=-15\mathrm{dB}$ for different fusion rules. The throughput based on the 3 out of 5 rule is optimal, and that of AND rule is the worst.

We compare the throughput of cognitive relay networks versus sensing time based on the 3 out of 5 rule with that of non-cooperative sensing for different transmit power. Figure 6 shows the comparison results for two sensing schemes. We can see that the throughput of cognitive relay networks can be maximized by utilizing the optimal sensing time. For cooperative sensing scheme, the optimal sensing time is $\tau=3.5ms$. The optimal sensing time for non-cooperative sensing scheme is taken as $7ms$. Therefore, cooperative sensing scheme not only improves the throughput of cognitive relay networks but also reduces the sensing time. The performance of cooperative sensing scheme is superior to that of non-cooperative sensing scheme. In addition, the throughput of cognitive relay networks becomes higher and higher when the transmit power increases for two sensing schemes.

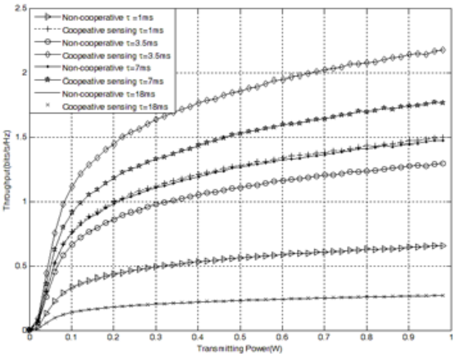

Figure 4. Throughput Versus Transmit Power with $\gamma_p=-15\mathrm{dB}$

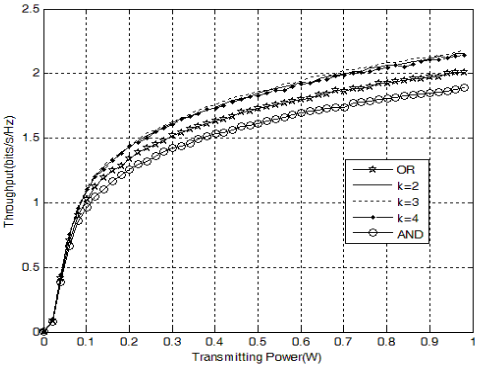

Figure 5. Throughput Versus Transmit Power

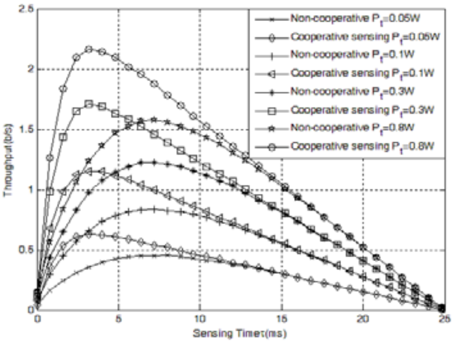

Figure 6. Throughput Versus Sensing Time

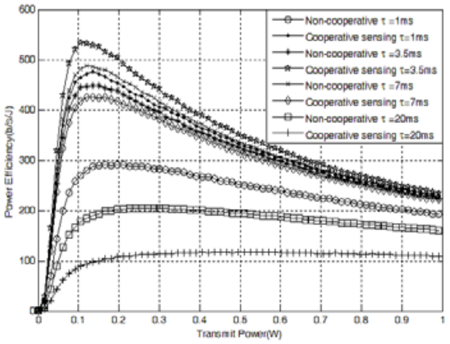

Figure 7. Power Efficiency Versus Transmit Power

We simulated the energy efficiency of cognitive relay networks based on both cooperative sensing scheme and non-cooperative sensing scheme. Suppose that circuit power is $P_c = 0.04\mathrm{W}$ and spectrum sensing power is $P_\tau = 0.02\mathrm{W}$ under $\gamma_p = -15\mathrm{dB}$. We can see from Figure 7 that there exists the optimal value of transmit power to maximize the energy efficiency for two sensing schemes under different sensing time. We also can know that the energy efficiency is related to sensing time τ. Proper sensing time can optimize the energy efficiency of cognitive networks. The energy efficiency can achieve the maximum when the sensing time is $\tau = 3.5ms$ for cooperative sensing, while the optimal sensing time $\tau = 7ms$ maximizes the energy efficiency of non-cooperative sensing scheme.

Figure 8 illustrates the comparison results of the energy efficiency versus sensing time with the same parameters as in Figure 7 under different transmit power. It is obvious that the optimal sensing time of cooperative sensing scheme is evidently lower than that of non-cooperative sensing scheme. When sensing time $\tau = 2.5ms$ and transmit power $P_t = 0.12\mathrm{W}$, the energy efficiency of cooperative sensing scheme is optimal. For non-cooperative sensing scheme, the optimal sensing is $\tau = 7ms$.

Figure 9 and 10 demonstrates three dimensional graphic of energy efficiency for two sensing schemes respectively. We can see that there exist optimal sensing time and optimal transmit power to maximize the energy efficiency of cognitive relay networks. For non-cooperative sensing scheme, the optimal value can be achieved at $\tau = 7ms$ and $P_t = 0.121\mathrm{W}$. However, the energy efficiency of cooperative sensing scheme is optimized at $\tau = 2.5ms$ and $P_t = 0.116\mathrm{W}$. Forthermore, the maximum of energy efficiency for cooperative sensing scheme is higher than that of non-cooperative sensing scheme.

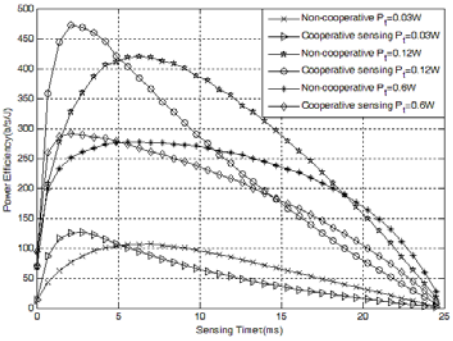

Figure 8. Power Efficiency Versus Sensing Time

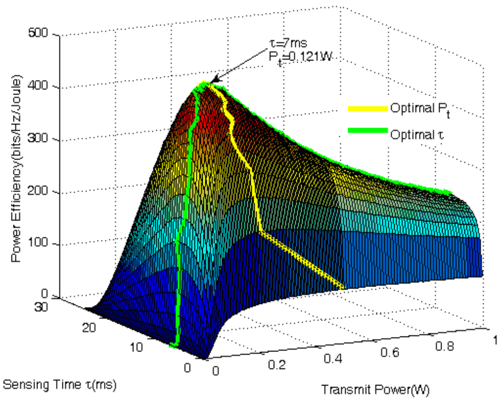

Figure 9.Energy efficiency of Non-cooperative Sensing Scheme

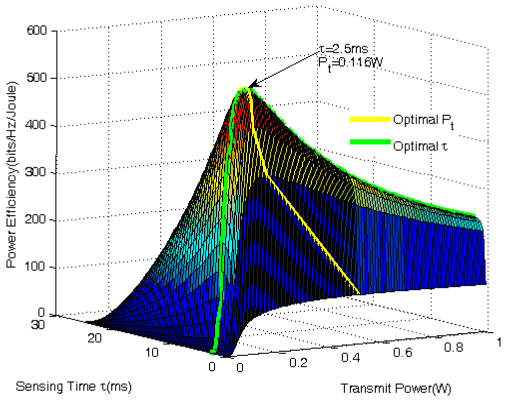

Figure 10. Energy Efficiency of Cooperative Sensing Scheme

6. Conclusion

In this paper, we have investigated the energy efficiency of cognitive relay transmission model based on cooperative sensing scheme. The simulation results show that we can find the most suitable transmit power and optimal sensing time to maximize the energy efficiency of cognitive relay networks. Furthermore, computer simulations demonstrate that the energy efficiency based on cooperative sensing scheme is superior to that of non-cooperative sensing scheme.

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