Adaptive Energy-Efficient Design of Cooperative Spectrum Sensing in Cognitive Radio Networks

Jing-Wei Liang, Jian-Xin Dai, Yi-Chen Liu, Xing-Zhou Zhou and Man Xu

Abstract Cognitive radio is a promising technology which can be used to solve the shortage of spectrum resource. As sensing nodes of the network, secondary users are usually battery powered. Making full use of the energy should be considered by balancing the tradeoff of energy and throughput. In this paper, we consider the overall throughput and energy consumption of the system. We propose a model for throughput and energy consumption with an adaptive factor to discuss the influences of sensing time and number of secondary users, and analyze the existence of an optimal point that get the maximum value of energy efficiency. Simulation results show that energy efficiency always have the optimal points in different fusion rules. Our findings indicate that cognitive radio network design, based on energy efficiency consideration, is feasible.

Keywords Cognitive radio · Energy efficiency · Adaptive factor

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1 Introduction

Cognitive radio (CR) is a potential solution to the scarcity of spectrum resource. Current inflexible spectrum allocation policy causes spectrum shortage problem and low utilization ratio [1].

In CR network, the spectrum bands are allocated to primary users (PU). Secondary users (SU) should sense the radio environment and adaptively choose the transmission parameters according to sensing result to avoid the interference to Pus [2]. It is a fundamental issue in CR networks that SUs should be able to efficiently and effectively detect the presence of Pus [3, 4]. The PU is the owner of the channel and SUs rent the spectrum when it is idle. To improve the opportunity of SUs to access the spectrum channel, we can use multiple SUs that work corporately to sense a single channel.

The basic tradeoff in the cooperative spectrum sensing method is as follows: if more SUs are assigned to sense one channel, higher sensing performance can be achieved, however, the total transmission power of the signal measurement and the overhead traffic in the secondary networks grows approximately linearly with the number of cooperating SUs [5]. It is an important issue to balance the two aspects, throughput and energy to achieve the maximum usage of spectrum and energy resource. Considering that SUs are always battery-powered, energy efficiency is important for CR networks.

Deng divided the sensors into a number of non-disjoint feasible subset such to extend the lifetime of sensors [6]. Hu et al. [7] focused on the optimization of the final decision threshold to maximize the energy efficiency for different signal channels. Nardelli et al. [8] provided a throughput analysis based on location information. Monemian and Mahdavi [9] supposed a new energy-based sensor selection algorithm was proposed to provide approximately the same lifetimes for sensors via the appropriate design of cooperative spectrum sensing.

In this paper, we provide an optimization model to discuss the system performance in with respect to energy efficiency and introduce an adaptive factor to make the model more flexible. We analyze the model and give the simulations of different fusion rules.

2 System Model

Since spectrum and energy are both precious resources that should be considered. We propose a model of throughput and energy consumption with adaptive factor to discuss the influences of sensing time and number of secondary users.

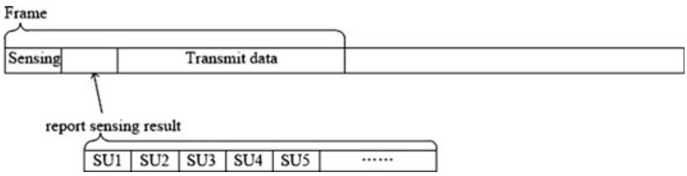

Fig. 1 Frame structure of cooperation spectrum sensing

2.1 Frame Structure of Cooperative Spectrum Sensing

Figure 1 shows the frame structure of cooperative spectrum sensing [1]. It can be divided into three different parts: sensing, reporting and transmitting slots. SUs periodically sense the spectrum for an ideal channel. In cognitive radio network (CRN), all SUs sense the spectrum. The primary channel sensing result of SUs will then be transmitted to the base station. The base station analyzes the data and determines if the spectrum is ideal.

2.2 Energy Detection

Each sensor performs spectrum sensing independently. The sensor will compare the collected energy E_{i} with a predefined threshold ε to determine if the channel is busy.

The false alarm probability and detection probability of the sensor are defined as:

$$P_f = \Pr\{D_i = 1|H_0\} = \Pr\{E_i > \varepsilon_i|H_0\} = Q\left(\frac{\varepsilon - f_s\tau}{\sqrt{2f_s\tau}}\right), \tag{1}$$

$$P_d = \Pr\{D_i = 1|H_1\} = \Pr\{E_i > \varepsilon_i|H_1\} = Q\left(\frac{\varepsilon - f_s\tau - \gamma}{\sqrt{2f_s\tau + 4\gamma}}\right), \tag{2}$$

where $\gamma = \sigma_x^2/\sigma_n^2$ is the received signal-to-noise ratio, H_1 indicates when the channel is busy and H_0 indicates when the channel is ideal.

2.3 Cooperative Spectrum Sensing

Multiple sensors can be coordinated to perform cooperative spectrum sensing to solve the hidden terminal problem by fusing the sensing result of all SUs to avoid errors. The sensors forward their decisions to the base station. The base station fuses these decisions to make the final decision. The decision fusion rules at base station are “OR”, “AND” and “K/N”. The “OR” rule can be stated as:

$$\begin{cases} Q_d = 1 - \prod_{i=1}^{N}(1 - P_{d,i}) \\ Q_f = 1 - \prod_{i=1}^{N}(1 - P_{f,i}) \end{cases}. \quad (3)$$

The "AND" rule can be stated as:

$$\begin{cases} Q_d = \prod_{i=1}^{N} P_{d,i} \\ Q_f = \prod_{i=1}^{N} P_{f,i} \end{cases}. \quad (4)$$

The "K/N" rule can be stated as:

$$\begin{cases} Q_d = \Pr\{D_i = 1|H_1\} = \Pr\left\{\sum_{i=1}^{N} D_i \geq k|H_1\right\} \\ Q_d = \Pr\{D_i = 1|H_1\} = \Pr\left\{\sum_{i=1}^{N} D_i \geq k|H_1\right\} \end{cases}. \quad (5)$$

2.4 Model Description

The cooperative radio network has four states. A SU can transmit data when it is $p(H_0|H_0)$ or $p(H_0|H_1)$. Since data transmission fails at $p(H_0|H_1)$, the normalized throughput of SU is:

$$R_S(L,\tau) = C_S\left(\frac{T - \tau - LT_R}{T}\right)\left(1 - Q_f(L,\tau)\right)p(H_0), \quad (6)$$

where C_S is the channel capacity, L represents the number of cooperative spectrum sensing users, τ is sensing time, T is the length of time frame, T_R is the result reporting time of one SU, $Q_f(L,\tau)$ is false positive probability. We suppose that data can only be transmitted successfully at $p(H_1|H_1)$, the normalized throughput of SU is:

$$R_P(L,\tau) = C_P Q_d(L,\tau)p(H_1). \quad (7)$$

Power consumption can be shown as four different parts:

1. Spectrum channel is ideal and SU transmits data. $p(H_0|H_0)$
   In this situation, the power cost is $C_{00}(L,\tau) = L\tau P_S + LT_R P_R + LTP_C + (T - \tau - LT_R)P_T + P_{CP}T$.

2. PU does not transmit data and fusion center gives an incorrect result. $p(H_1|H_0)$. The power cost of this situation is $C_{10}(L, \tau) = L\tau P_S + LT_R P_R + LTP_C + P_{CP}T$.
3. PU transmits data in the channel and fusion center does not detect it. $p(H_0|H_1)$ The power cost is $C_{01}(L, \tau) = L\tau P_S + LT_R P_R + LTP_C + (T - \tau - LT_R)P_T + P_{CP}T + P_{TP}T$.
4. PU transmits data and the fusion data gives the right result. $p(H_1|H_1)$ The power cost of this situation is $C_{11}(L, \tau) = L\tau P_S + LT_R P_R + LTP_C + P_{CP}T + P_{TP}T$.

Hence we get the average power cost:

$$\begin{aligned} P(L,\tau) &= p(H_0|H_0)C_{00}(L,\tau) + p(H_1|H_0)C_{10}(L,\tau) \\ &\quad + p(H_0|H_1)C_{01}(L,\tau) + p(H_1|H_1)C_{11}(L,\tau). \end{aligned} \tag{8}$$

P_s is the power of sensing the spectrum, P_R is the power of reporting result to base station, P_T is the SU's power of transmitting packets, P_C is the power lost in circuit. P_{CP} is the circuit loss of PU, P_{TP} is the transmission power of PU.

The power efficiency can be represented as:

$$EE(L,\tau,\alpha) = \frac{R_P(L,\tau)(1-\alpha) + R_S(L,\tau)\alpha}{P(L,\tau)} = \frac{R(L,\tau,\alpha)}{P(L,\tau)}. \tag{9}$$

Hence we get the optimization problem:

$$\begin{array}{l} \max\limits_{L,\tau} EE(L,\tau,\alpha) \\ s.t. Q_d(L,\tau) \ge \bar{Q}_d \\ \alpha \in [0,1] \\ 1 \le L \le N \\ L \in N \\ T - \tau - LT_R \ge 0 \\ \tau \ge 0 \end{array}, \tag{10}$$

$\alpha \in [0,1]$ is the adaptive factor.

Theorem If the number of SUs is fixed, analyze the relationship between energy efficiency and length of sensing time. We find the partial derivate of energy efficiency with respect of sensing time, if there exists a point that makes the partial derivate equal to 0, there exists an optimal point that get the maximum value of energy efficiency.

Proof Find the partial derivate of energy efficiency:

$$\frac{\partial EE(L,\tau,\alpha)}{\partial\tau} = \frac{P(L,\tau)\partial R(L,\tau,\alpha) - R(L,\tau,\alpha)\partial P(L,\tau)}{\partial\tau P(L,\tau)^2}. \tag{11}$$

Then we get the partial derivate of throughput and energy:

$$\frac{\partial R(L,\tau,\alpha)}{\partial \tau} = C_1\alpha(1-Q_f(L,\tau)) + C_2\tau\alpha\frac{\partial Q_f(L,\tau)}{\partial \tau} + C_3(1-\alpha)\frac{\partial Q_d(L,\tau)}{\partial \tau}, \quad (12)$$

$$\frac{\partial P(L,\tau)}{\partial \tau} = C_4 + C_5\frac{\partial Q_d(L,\tau)}{\partial \tau} + C_6\frac{\partial Q_f(L,\tau)}{\partial \tau}, \quad (13)$$

where C_1, C_2, C_3, C_4, C_5, and C_6 are constants. We use "AND" rule in (4) as an example to find the partial derivate of false alarm probability and detect probability: $\frac{\partial Q_f}{\partial \tau} = L(1-P_f)^{L-1}\frac{\partial P_f}{\partial \tau}, \frac{\partial Q_d}{\partial \tau} = L(1-P_d)^{L-1}\frac{\partial P_d}{\partial \tau}$. Since $\tau \in [0, T]$, we find the values of terminal points, $\tau = 0, \frac{\partial P_f}{\partial \tau} \to -\infty, \frac{\partial Q_f}{\partial \tau} \to -\infty$. In this model, we fix the value of detection probability, then we have $\frac{\partial Q_d}{\partial \tau} = 0$. Then we get $\frac{\partial EE(L,\tau)}{\partial \tau} > 0$ at the point $\tau = 0$ if $C_S\alpha P(H_0) > C_P(1-\alpha)P(H_1)$. By the same method, we can get $\frac{\partial Q_f}{\partial \tau} \to 0$ at the point $\tau = T$. Then we have $\frac{\partial EE(L,\tau)}{\partial \tau} < 0$. Since it is a continuous function, there always exists a sensing time that satisfies the optimal energy efficiency. Similarly, we can also prove that when the length of sensing time is fixed, there are a specific number of SUs that satisfies the optimal energy efficiency.

3 Simulations

In the following simulations, we suppose the base station can confirm the location of every SU. Signals received by each SU have the same SNR. We set $\gamma_i = -20$ dB, $T = 20$ ms, $T_R = 0.1$ ms, $Q_d = 0.9$. We suppose $P_{TP} = 4P_T$.

3.1 Simulations Results of "AND" Rule

Horizontal axis indicates the value of sensing time in Fig. 2a and the number of SUs in Fig. 2b. We use different linetypes to distinguish the value of τ and L, use different symbols to distinguish the value of α. As we can see from the Fig. 2a, α effectively affects the value of energy efficiency. Maximum value is higher when α is 0.8. It is because of the high expense the PU paid while transmitting the same amount of data. As we can see from the Fig. 2b, we can see from the figure that if α is higher, which means consider less about the throughput of PU, the value of energy efficiency is lower when sensing time is 1 ms.

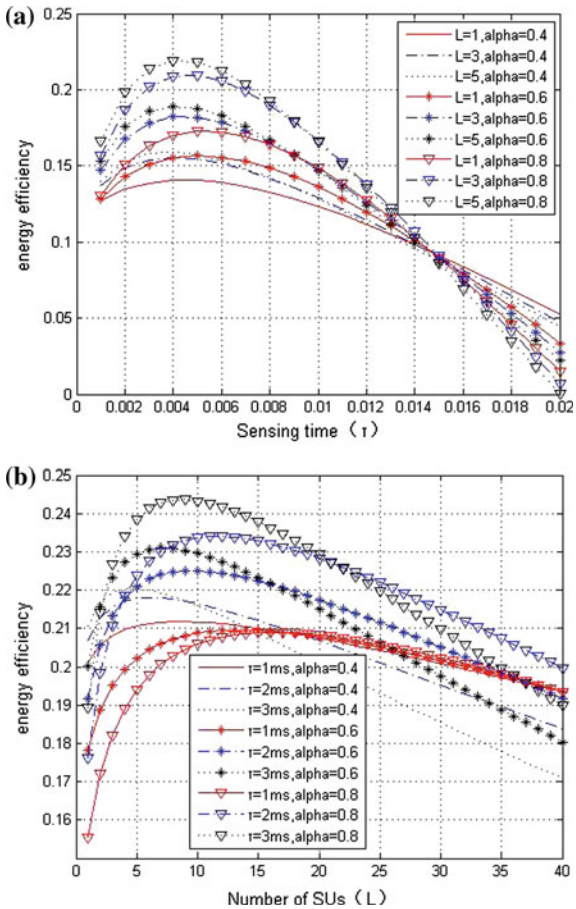

Fig. 2 Simulations results of “AND” rule, **a** energy efficiency versus the sensing time, **b** energy efficiency versus number of SUs

3.2 Simulations Results of “OR” Rule

The “OR” rule in (3) means if all SUs report the same result of spectrum sensing, then the fusion center determines the situation is true. The “OR” rule is always used to protect the access of PU. As such, the SUs have fewer chances to use the channel. As we can see from Fig. 3a, the energy efficiency of the model increase at first and after reaching the optimal point, decrease as the sensing time grows up. Figure 3b shows us as L increases the energy efficiency firstly increase and then decrease. The value of energy efficiency is affected by different parameters. Given three different specific sensing time to observe how the number of SUs influence the energy efficiency.

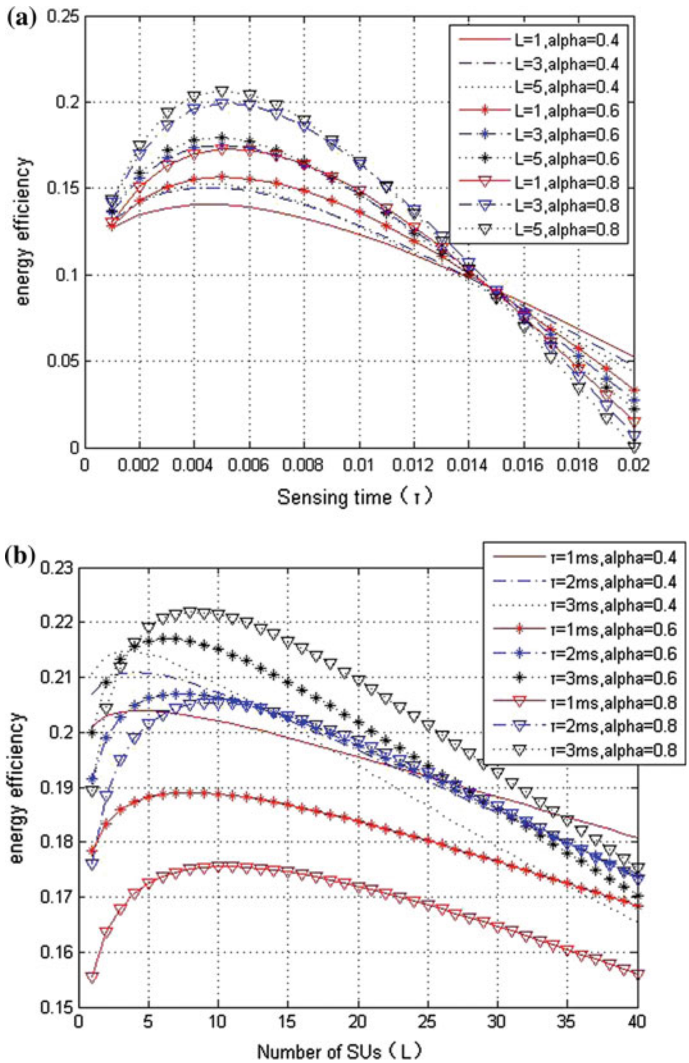

Fig. 3 Simulations results of "OR" rule, **a** energy efficiency versus the sensing time, **b** energy efficiency versus number of SUs

3.3 *Simulations Results of "K/N" Rule*

If more than half of the SUs report the same result, the fusion center decides the result to be true. We can see from the Fig. 4a that the curves of energy efficiency are also convex. There must have a point for every spectrum sensing to get the best

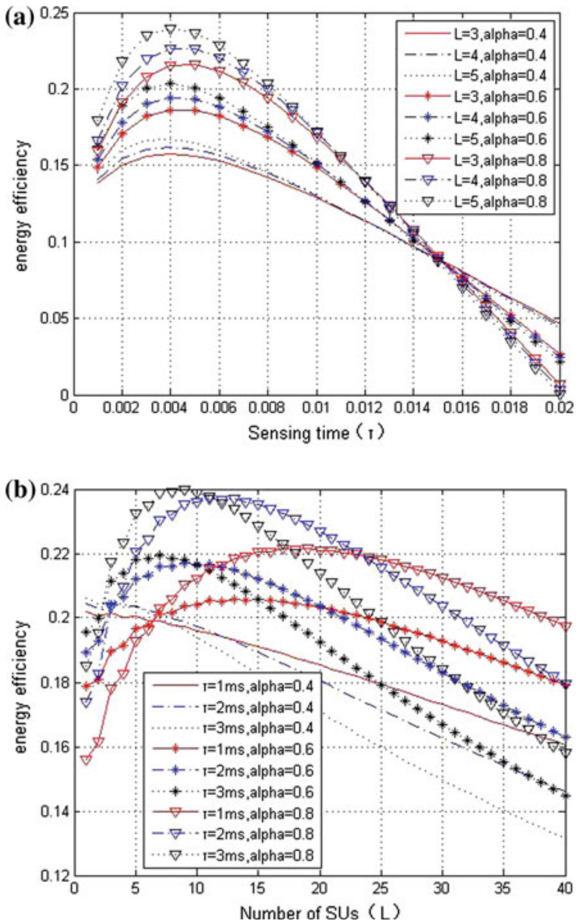

Fig. 4 Simulations results of "K/N" rule, **a** energy efficiency versus the sensing time, **b** energy efficiency versus number of SUs

energy efficiency. As we can see from Fig. 4b, the curve is not smooth because of the half value rounded up if the number is not integer. Its influence is very obvious when the number of SUs is small.

4 Conclusion

Multiple SUs working cooperatively in cognitive radio improved the usage rate of spectrum, but spectrum is not the only resource needed to be considered. Energy consumption is also a very important when designing the CR network. We have proposed an energy efficiency model with an adaptive factor to discuss the influence of sensing time and number of SUs. The adaptive factor can be used to make the model fit different situations. The value of the adaptive factor indicates the degree of

PU's channel protection. From this model we can determine the proper values for the sensing time and the number of SUs to make the network worked effectively. By considering both energy and spectrum resources we can find the proper network to make the best profit. In this paper, we consider only one primary user and channel. The reality is complex, we will introduce more variables in our future works.

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