Joint Optimization of Sensing Period and Transmission Time for Energy-Efficient CRSNs

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ABSTRACT
Cognitive radio technology can enable secondary users (SUs) to occupy licensed bands in a non-interference way. SUs perform spectrum sensing to determine the presence of primary user (PU). Spectrum sensing period and transmission time are the critical parameters for the sensing performance and the secondary throughput, respectively. In this paper, a joint optimization of sensing period and transmission time is proposed for cognitive radio sensor network (CRSNs). The joint optimization model is established by taking the network energy efficiency and interference caused by SU's traffic into consideration. By using the optimization model, we try to figure out the optimal sensing period and transmission time which can guarantee the network energy efficiency and maximize the network throughput jointly. The performance of the proposed optimization model is evaluated through a set of simulations, and the existence of the optimal sensing period and transmission time is verified.

CCS Concepts
• Mathematics of computing~Network optimization

Keywords
Cognitive radio sensor network, sensing period, transmission time, energy efficiency, interference.

1. INTRODUCTION
Cognitive radio (CR) is a promising technique to improve spectral efficiency, and it has been widely applied in various wireless networks [1-2]. It can enable the secondary users (SUs) to occupy the licensed bands opportunistically without causing interference to primary user (PU). SUs perform spectrum sensing to determine the presence of PU, and transmit data if PU is detected to be idle. Sensing period and transmission time are the critical parameters for the sensing performance and the secondary throughput. How to improve the secondary throughput under the condition of minimizing the interference to PU is very important.

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In cognitive radio sensor networks (CRSNs), wireless sensor devices powered by batteries have to suffer the energy constraint. Therefore, energy-efficient design is the essential consideration for CRSNs. Both sensing period and transmission time have a big impact on network energy efficiency and the interference to PU. Concretely, if sensing period is increased, the sensing performance can be improved. However, the energy consumption for spectrum sensing also increases. If sensing period is very short, energy consumption can be reduced, while the bad sensing performance will result in more interference to PU. In terms of transmission time, if transmission time is long, more secondary throughput can be achieved. However, it will also increase the probability yielding more interference to PU. On the other hand, if transmission time is very short, even though PU can be provided a good protection, it will also degrade the secondary throughput.

There are some recent works on how to improve the network energy efficiency. Li *et al*. [3] proposed an energy-efficient technique with sensing time optimization for cooperative spectrum sensing. They investigated the influence of sensing time on the energy efficiency. Jiang *et al*. [4] investigated the spectrum sensing and nodes selection method to jointly optimize the energy and spectrum efficiency. A dynamic censored spectrum sensing scheme is employed for each sensor node to decide when to stop sensing. However, the above works did not consider the interference to PU when PU becomes busy again during SU's transmission. Xing *et al*. [5] investigated new approaches for spectrum sensing by exploring the tradeoff between energy consumption and the secondary throughput. In order to determine when the next spectrum sensing should be performed, they proposed an energy-aware model to derive the optimal sensing interval. However, the sensing period which is a critical parameter for sensing performance is not considered.

Inspired by the previous works, we propose a scheme to jointly optimize the sensing period and the transmission time in this paper. The interference to PU caused by SU's transmission is also considered at the same time. An optimization model is established to investigate the tradeoff between the energy efficiency and the interference to PU. By maximizing the objective function, the optimal sensing period and the transmission time are calculated.

The rest of the paper is organized as follows. Section 2 presents the system model. In Section 3, the problem formulation for sensing period and transmission time optimization is presented. In Section 4, the performance of the proposed scheme is evaluated. Section 5 concludes the paper and introduces the future work.

2. SYSTEM MODEL
We consider a simple CRSN model which is consist of one PU and a pair of transmitter-receiver SUs. The SU performs the

spectrum sensing for time t_s to determine the presence of PU. If the sensing result shows that PU is idle, SU will transmit data for time t_t. Otherwise, SU will keep silent for time t_t to wait for performing the next spectrum sensing. It is worth noting that the fixed frame time T is not assumed in this paper. We jointly optimize the sensing period t_s and transmission time t_t, and then the frame time $T = t_s + t_t$ can be calculated.

In the proposed scheme, the spectrum sensing is not perfect. We use miss detection probability and false alarm probability to evaluate the performance of spectrum sensing. Miss detection occurs when the SU fails to detect the busy state of PU. False alarm occurs when the SU falsely detects the busy state of PU. Therefore, miss detection will result in the interference to PU, and false alarm will degrade the secondary throughput. We assume that the SU's transmission is valid only when the state of PU is idle. Therefore, based on the sensing result and the PU's state, we have five different scenarios.

S1: SU successfully detects the idle state of PU, and transmits data for time t_t. In this case, PU always keeps the idle state during SU's transmission. Therefore, there is no interference to PU.

S2: SU successfully detects the idle state of PU, and transmits data for time t_t. However in this case, PU becomes busy again during SU's transmission. Therefore, the SU's transmission causes the interference to PU. Since SU's transmission is assumed to be invalid when PU is busy, there is no secondary throughput during the interference time.

S3: SU successfully detects the busy state of PU, and keeps silent for time t_t to wait performing the next spectrum sensing.

S4: SU fails to detect the busy state of PU, and transmits data for time t_t. In this case, miss detection occurs, PU is interfered by SU's transmission and there is no secondary throughput.

S5: SU falsely detects the busy state of PU, and keeps silent for time t_t to wait performing the next spectrum sensing. In this case, the false alarm occurs, and there is no secondary throughput.

3. PROBLEM FORMULATION

In this section, we jointly optimize the sensing period and the transmission time. We investigate the tradeoff between the network energy efficiency and the interference to PU. The secondary throughput, energy consumption and the interference to PU are calculated, respectively. And then the optimization problem formulation is established.

3.1 Energy Detector Based Spectrum Sensing

A binary hypothesis is utilized to formulate spectrum sensing. H_0 and H_1 denote the hypothesis of the idle and the busy states of PU, respectively. p_0 and p_1 denote the probabilities of H_0 and H_1, respectively. Therefore, It is known that $p_0 + p_1 = 1$.

It is assumed that PU switches between idle and busy state, and the behaviors of PU follow continuous time Markov chain. Therefore, we can get the following transition matrix [6]:

$$p(t) = \frac{1}{\alpha+\beta}\begin{bmatrix} \alpha + \beta e^{-(\alpha+\beta)t} & \beta - \beta e^{-(\alpha+\beta)t} \\ \alpha - \alpha e^{-(\alpha+\beta)t} & \beta + a e^{-(\alpha+\beta)t} \end{bmatrix}, \qquad (1)$$

where α and β are the rate of occurrence of PU's busy and idle states, respectively. Therefore, we can get that $p_0 = \frac{\alpha}{\alpha+\beta}$, and $p_1 = \frac{\beta}{\alpha+\beta}$. If PU is idle at time t_0, then the probability that PU becomes busy at time $t_0 + t$ is given by $\frac{1}{\alpha+\beta}(\beta - \beta e^{-(\alpha+\beta)t})$. We assume that the duration PU keeps busy or idle state is bigger than T. Therefore, the probability PU's state changes more than one time during T is negligible.

In this paper, the energy detector is applied for spectrum sensing, which is widely used due to its simplicity and requiring no prior knowledge of PU. The test statistic of an energy detector $T(y)$ can be expressed as follows.

$$T(y) = \sum_{n=1}^{N} |y(n)|^2 , \qquad (2)$$

where N is the number of sensing samples. $y(n)$ is the sampled signal. Concretely, $y(n) = u(n)$ when the PU's state is H_0, and $y(n) = u(n) + s(n)$ when the PU's state is H_1. $u(n)$ is the noise which is a Gaussian iid random process with mean of zero and variance of σ_u^2, $s(n)$ is the PU' signal which is an iid random process with mean of zero and variance of σ_s^2. The test statistic follows the central and non-central chi-square distribution with $2N$ degrees of freedom under the hypotheses H_0 and H_1, respectively [7]. The test statistic can be approximated as a Gaussian random process because central limit theorem can be applied when the value of N is large enough.

$$T(y) \sim \begin{matrix} \mathcal{N}(N, 2N) & H_0 \\ \mathcal{N}(N(1+\gamma), 2N(1+\gamma)^2) & H_1 \end{matrix}, \qquad (3)$$

where $\gamma = \frac{\sigma_s^2}{\sigma_u^2}$ is the signal to noise ratio (SNR) received from PU. The detection probability p_d and the false alarm probability p_f can be expressed as

$$p_d = p(H_1|H_1) , \qquad (4)$$

$$p_f = p(H_1|H_0) . \qquad (5)$$

Based on the test statistics of $T(y)$, we can rewrite p_d and p_f as follows.

$$p_d = Q\left(\frac{\lambda}{\sqrt{2N}(1+\gamma)} - \sqrt{\frac{N}{2}}\right), \qquad (6)$$

$$p_f = Q\left(\frac{\lambda}{\sqrt{2N}} - \sqrt{\frac{N}{2}}\right), \qquad (7)$$

where λ is the sensing threshold, and it is used to be compared with the received energy power. Concretely, if the received energy power is bigger than λ, PU is considered to be busy. $Q(\cdot)$ is the Q-function which is given as

$$Q(\mathrm{x}) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \exp(-\frac{y^2}{2}) dy . \qquad (8)$$

The number of sensing samples N can be expressed by the following equation [7]:

$$N = 2 t_s W , \qquad (9)$$

where W is the bandwidth of PU signal. The sensing threshold λ can be calculated by Eq. (6).

$$\lambda = \sqrt{2N}(1+\gamma)\left(Q^{-1}(p_d) + \sqrt{\frac{N}{2}}\right). \qquad (10)$$

By substituting Eqs. (9) and (10) into Eq. (7), and we can get:

$$p_f = Q\left((1+\gamma)Q^{-1}(p_d) + \gamma\sqrt{t_s W}\right). \quad (11)$$

In order to guarantee the protection for PU, we set a detection probability threshold p_d^{th} for SU, which means p_d should not be smaller than p_d^{th}. It is known that Q-function is a monotonically decreasing function. Therefore, according to Eq. (11), we can get that p_f decreases as p_d decreases. In order to maximize the secondary throughput, we set $p_d = p_d^{th}$. Therefore, t_s is the only one unknown variable in Eq. (11), and we can get that p_f decreases as t_s increases.

3.2 Problem Formulation

Based on five different scenarios, the secondary throughput can be achieved by S1 and S2. First, we calculate the achievable secondary throughput of S2. According to Eq. (1), we can get that the probability that PU is idle at time t_0 and becomes busy at time $t_0 + t$ is $\frac{1}{\alpha+\beta}(\beta - \beta e^{-(\alpha+\beta)t})$. Therefore, the average interference time to PU when PU becomes busy again during SU's transmission can be calculated as follows.

$$t_i = \frac{1}{t_s + t_t}\int_0^{t_t} \frac{1}{\alpha+\beta}\left(\beta - \beta e^{-(\alpha+\beta)t}\right) dt \quad (12)$$

$$= \frac{\beta}{(\alpha+\beta)(t_s+t_t)}\left(t_t + \frac{1}{\alpha+\beta}\left(e^{-(\alpha+\beta)t_t} - 1\right)\right).$$

The average probability that PU becomes busy again during SU's transmission can be calculated as

$$p_i = \frac{t_i}{t_t}. \quad (13)$$

Since the SU's transmission is invalid when PU becomes busy, the achievable secondary throughput of S2 can be calculated as

$$\psi_{S2} = (1 - p_f)p_0 p_i (t_t - t_i)C, \quad (14)$$

where C is the SU's channel capacity, and it can be expressed as

$$C = log_2(1 + \gamma_s), \quad (15)$$

where γ_s is the SNR that SU transmits data. According to Eq. (13), we can get that the probability PU always keeps idle state during SU's transmission is $1 - p_i$. Therefore, the secondary throughput of S1 can be calculated as

$$\psi_{S1} = (1 - p_f)p_0(1 - p_i)t_t C. \quad (16)$$

Hence, the total secondary throughput can be expressed as

$$\psi_{total} = \psi_{S1} + \psi_{S2}. \quad (17)$$

According to five different scenarios, the energy consumption functions can be formulated as below.

$$E_1 = (1 - p_f)p_0(1 - p_i)(t_s E_s + t_t E_t), \quad (18)$$

$$E_2 = (1 - p_f)p_0 p_i (t_s E_s + t_t E_t), \quad (19)$$

$$E_3 = p_d p_1 t_s E_s, \quad (20)$$

$$E_4 = (1 - p_d)p_1(t_s E_s + t_t E_t), \quad (21)$$

$$E_5 = p_f p_0 t_s E_s, \quad (22)$$

$$E_{total} = E_1 + E_2 + E_3 + E_4 + E_5, \quad (23)$$

where E_1, E_2, E_3, E_4, and E_5 represent the energy consumption of S1, S2, S3, S4, and S5, respectively. E_{total} denotes the average total energy consumption. E_s and E_t are the energy consumption of spectrum sensing and data transmission for the unit time,

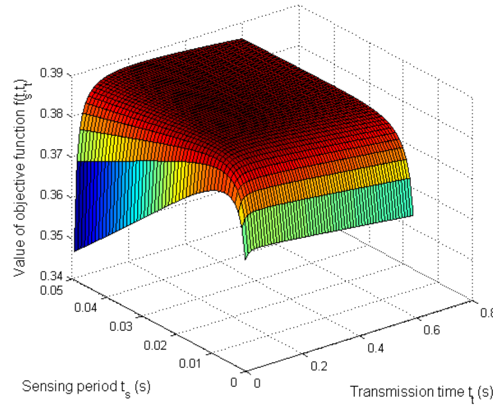

Figure 1. The variation of objective function $f(t_s, t_t)$ with increasing t_s and t_t.

respectively. In this paper, energy efficiency is defined as the number of bits transmitted per unit of energy consumption [8]. Therefore, the network energy efficiency can be expressed as

$$\eta = \frac{\psi_{total}}{E_{total}}. \quad (24)$$

We want to investigate the tradeoff between the energy efficiency and the interference to PU. It is worth noting that both S2 and S4 can yield the interference to PU. We use the interference time as the measurement. Therefore, we can calculate the total average interference time as below.

$$\tau = p_0 p_i (1 - p_f) t_i + p_1 (1 - p_d) t_t, \quad (25)$$

where $p_0 p_i (1 - p_f) t_i$ and $p_1(1 - p_d)t_t$ are the average interference time of S2 and S4, respectively. In order to formulate the objective function, the sigmoid function is utilized to normalize the energy efficiency η and the interference to PU τ, which is defined as below.

$$S(x) = \frac{1}{1 + e^{-x}}. \quad (26)$$

The sigmoid function is a monotonically increasing function, and it can map the variable to the interval [0, 1]. Therefore, the objective function can be expressed as

$$f(t_s, t_t) = S(\eta) - S(\tau). \quad (27)$$

In Eq. (27), t_s and t_t are the only unknown variables in objective function. The exhaustive search method is utilized to find the optimal t_s and t_t which can jointly maximize the value of $f(t_s, t_t)$.

4. PERFORMANCE EVALUATION

In this section, the performance of the proposed scheme is evaluated with the help of MATLAB. We show the variation of the objective function $f(t_s, t_t)$ with the varying t_s and t_t. To evaluate the performance of the proposed scheme, the simulation parameters are set as below. $\alpha = 0.2$ s, $\beta = 0.1$ s, $\gamma = -20$ dB, W=6MHz, $\gamma_s = 20$ dB. E_s and E_t are set as 0.1W and 3W, respectively. We set $p_d^{th} = 0.9$ according to IEEE 802.22

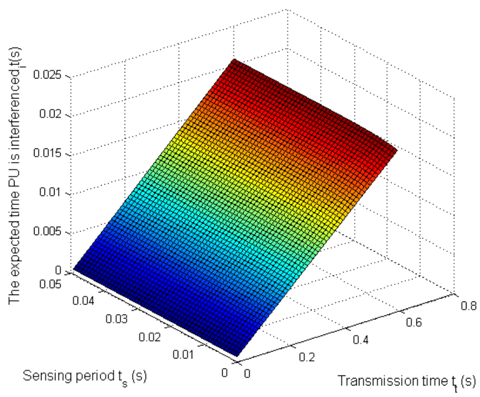

Figure 4. The variation of τ with increasing t_s and t_t.

Figure 2. The variation of $f(t_s)$ with increasing t_s.

cognitive radio WRAN standard [9]. Since γ_s is set to 20dB, the

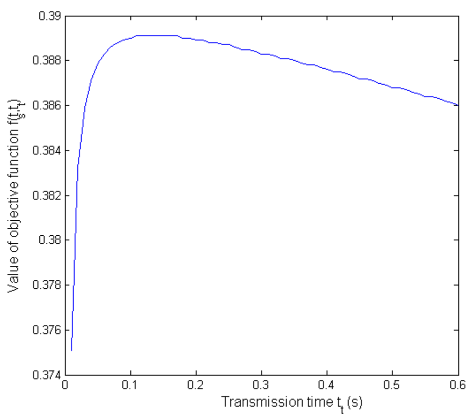

Figure 3. The variation of $f(t_t)$ with increasing t_t.

SU's channel capacity $C = log_2(1 + \gamma_s) = 6.6582$ bits/sec/Hz.

Fig. 1 shows the variation of the objective function $f(t_s, t_t)$ with the increasing t_s and t_t. By utilizing the exhaustive search method, we can get that when $t_s = 0.017s$, and $t_t = 0.14s$, the objective function $f(t_s, t_t)$ has the maximum value. Therefore, the optimal frame time $T^* = t_s + t_t = 0.157s$ can be achieved. In order to analyze the simulation result of Fig. 1, we will fix t_t and t_s to show the variation of objective function with increasing t_s and t_t, respectively.

Fig. 2 and Fig. 3 show the variation of the objective function with the increasing t_s and t_t when t_t is fixed at 0.14s and t_s is fixed at 0.017s, respectively. In Fig. 2, it can be seen that with increasing t_s, the value of objective function increases at first. After the optimal sensing period t_s^*, it decreases again. The reason is that p_f decreases as t_s increases. Therefore, the secondary throughput can be improved. When $t_s \geq t_s^*$, the longer sensing period results in more energy consumption. Therefore, the value of $f(t_s)$ decreases again. In Fig. 3, the value of $f(t_t)$ also increases at first with increasing t_t, and then after optimal transmission time t_t^*, it decreases again. The longer transmission time can bring more secondary throughput. However, the probability that PU becomes busy again during SU's transmission also increases. If PU becomes busy again during SU's transmission, not only no secondary throughput can be achieved, the energy consumption for data transmission is also meaningless. That is why $f(t_t)$ decreases again when $t_t \geq t_t^*$.

Fig. 4 shows the variation of the interference time τ with increasing t_s and t_t. We can see that t_s has almost no influence on the interference time, and the value of τ increases as t_t increases. Even though the increasing t_t can bring more secondary throughput, the interference time τ also increases. When PU becomes busy during SU's transmission, even though energy is exhausted for data transmission, this kind of data transmission is invalid. This is the reason why $f(t_s, t_t)$ varies as shown in Fig. 1.

5. CONCLUSION AND FUTURE WORK

In this paper, we propose a joint optimization scheme for energy-efficient CRSN. We jointly optimize the sensing period and the transmission time. The interference to PU is also considered. By investigating the tradeoff between the energy efficiency and the interference to PU, we can get the optimal sensing period and transmission time. Analytical and simulation results show that there exists the optimal sensing period and transmission time which can maximize the objective function. For the future work, we will consider a better method to find the maximum value of objective function. Furthermore, a more complex simulation environment will be considered, and we will improve the simulation by appending the comparisons with other schemes proposed in other papers.

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