Optimal Resource Optimization for Cluster-Based Energy-Efficient Cognitive IoT

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Abstract. In this paper, a cluster-based energy-efficient Cognitive Internet of Things (CIoT) is proposed, which can harvest the radio frequency (RF) energy of the primary user (PU) to supply energy consumption of spectrum sensing. A joint optimization problem of time and node is presented to maximize the spectrum access probability of the CIoT. The simulations show that there are optimal resource allocations to improve both spectrum efficiency and energy efficiency of CIoT.

Keywords: CIoT · Energy harvesting · Cluster · Joint optimization

1 Introduction

Cognitive radio (CR) has been proposed to improve the utilization of the finite spectrum resources through using the idle spectrum of primary user (PU) by chance. However, the interference brought to the PU has to be avoided through spectrum sensing, which may find the presence of the PU by detecting the received signal [1]. Energy detection is used to measure the strength of the received signal, and the presence of the PU can be decided if the signal strength is above a presettled threshold. However, energy detection performance can be decreased when the received signal to noise ratio (SNR) is very low [2]. Cooperative spectrum sensing can be used to improve spectrum sensing performance in fading and shadowing channel, which can obtain a final decision on the presence of the PU by combining local sensing results from multiple CR users locating at different sensing areas [3].

Listen-before-talk mode has been proposed to improve spectrum access of the CR and avoid bringing interference to the PU by dividing the frame structure into sensing slot and transmission slot, in which the detection result in the

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sensing slot decides the CR status in the transmission slot [4]. It has been proven that there is a sensing-throughput tradeoff in CR, i.e., an optimal sensing time can be achieved to maximize the throughput of the CR. An optimization of cooperative spectrum sensing is proposed to decrease cooperative overhead through obtaining the jointly optimal sensing time and number of cooperative users [5]. Since the CR has the function of sensing spectrum environment, the CR user can be seen as a sensor, which may be applied in sensor network and Internet of Things (IoT) [6]. IoT has been used to connect the things with the Internet through information sensing devices such as radio frequency identification (RFID), which can automatically and intelligently collect, transmit and process information in order to realize the scientific management of the networks. IoT is widely applied in intelligent transportation, environmental protection, government work, public safety, safe home, industrial monitoring and environmental monitoring etc., which has improved system efficiency and reduced human intervention of the network [7]. However, the shortage of spectrum resources has limited the development of the IoT greatly [8]. Currently, cognitive IoT (CIoT) combining with CR is proposed to provide flexible and dynamic spectrum access and expand available spectrum of the IoT. However, the spectrum sensing of the CIoT may consume some time and energy, thus decreasing both transmission time and transmission power [9].

Energy harvesting has been recently proposed to collect radio frequency (RF) energy of wireless signals by converting AC signal to DC voltage using a rectifier circuit. The RF energy is stored in a rechargeable battery to supply system operations, thus, energy harvesting can be seen as an effective method to realize energy-efficient communications [10]. Hence, in this paper we have proposed a cluster-based energy-efficient CIoT which can harvest the RF energy of the PU signal while performing spectrum sensing.

2 System Model

We consider a CIoT constituting of N nodes and a PU network covering L subchannels. The IoT is divided into D clusters and each cluster has $S = N/D$ nodes. Each cluster selects a cluster head to manage the nodes within the cluster. As shown in Fig. 1, the frame structure of the CIoT is divided into sensing slot and transmission slot, and the CIoT can communicate only when the absence of the PU has been detected in the channel. In the traditional CIoT, the nodes can only sense the PU using the stored battery energy, which decrease the transmission performance due to great sensing energy consumption. However, the proposed cluster-based energy-efficient CIoT has the function of energy harvesting, which can harvest the RF energy of the PU signal to supply energy consumption of spectrum sensing, and each cluster can perform either cooperative spectrum sensing or energy harvesting within sensing slot, as shown in Fig. 2.

Suppose there are K clusters to sense the PU and $D-K$ clusters to harvest energy. The nodes of each sensing cluster sense the PU by energy detection with the sampling number M and send their energy statistics to the cluster head

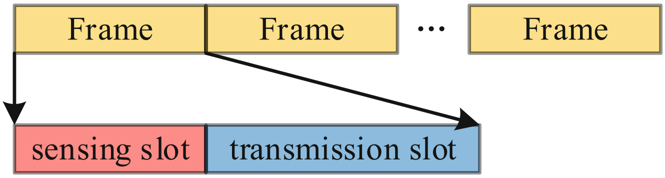

Fig. 1. Frame structure of CIoT.

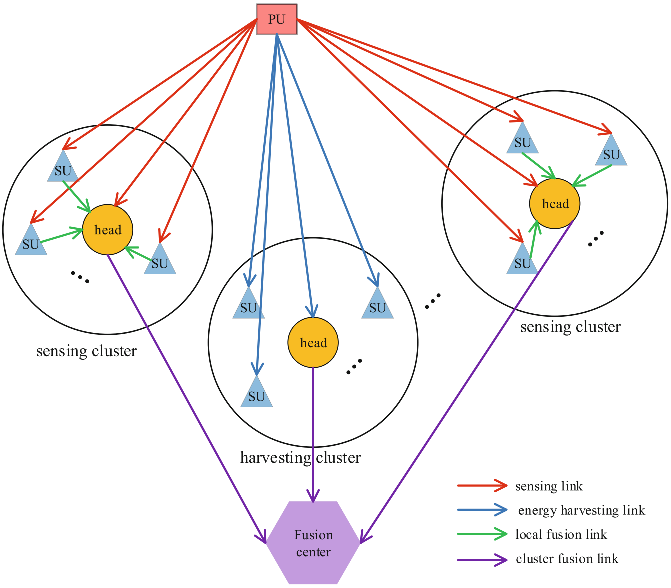

Fig. 2. Network structure of CIoT.

that makes a 1-bit decision by comparing the average accumulated statistic to a threshold λ. Probabilities of false alarm and detection at the cluster head i for $i = 1, 2, ..., K$ are given by [5]

$$P_i^f = Q\left(\left(\frac{\lambda}{\sigma^2} - 1\right)\sqrt{SM}\right) \tag{1}$$

$$P_i^d = Q\left(\left(\frac{\lambda}{\sigma^2} - \gamma - 1\right)\sqrt{\frac{SM}{(\gamma+1)^2}}\right) \tag{2}$$

where the function $Q(x)$ is defined by

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{+\infty} \exp\left(-\frac{\omega^2}{2}\right)\ \mathbf{d}\omega \tag{3}$$

All the sensing cluster heads send local 1-bit decisions to the fusion center that makes a final decision on the presence of the PU by combining these

1-bit decisions using OR rule [3]. The cooperative probabilities of false alarm and detection are given by

$$Q_f = 1 - (1 - P_i^f)^K \tag{4}$$

$$Q_d = 1 - (1 - P_i^d)^K \tag{5}$$

From (5), with a given Q_d, P_i^d is obtained as follows

$$P_i^d = 1 - (1 - Q_d)^{\frac{1}{K}} \tag{6}$$

From (2), sensing threshold is calculated as follows

$$\lambda = \left(\frac{Q^{-1}\left(1 - (1 - Q_d)^{\frac{1}{K}}\right)}{\sqrt{SM}} + 1 \right) (\gamma + 1)\sigma^2 \tag{7}$$

Substituting (7) to (1) and (4), Q_f is deduced as follows

$$Q_f = 1 - \left(1 - Q(Q^{-1}(P_i^d)(\gamma + 1) + \gamma\sqrt{SM})\right)^K \tag{8}$$

Suppose the frame time is T, the local sensing time of each node is t_s, and the sensing information reporting time of cluster head is t_r. Each cluster head sends sensing information in the allocated time slot to avoid generating transmission conflict. t_r can be set as a constant according to the maximal distance from the cluster head to the fusion center. The reporting time within one cluster can be ignored due to the short transmission distance from node to head. Thus, the average transmission time is given by $t_d = T - t_s - Kt_r$. The number of sampling nodes $M = t_s f_s$ where f_s is sampling frequency. Hence, the average spectrum access probability of the CIoT is given by

$$P_{acc} = \frac{T - t_s - Kt_r}{T} \left((1 - Q_f)P_{h0} + (1 - Q_d)P_{h1}\right) \tag{9}$$

where P_{h0} and P_{h1} denote absence and presence of the PU, respectively, which satisfy $P_{h0} + P_{h1} = 1$. With a given Q_d, P_{acc} is rewritten as follows

$$P_{acc} = \frac{T - t_s - Kt_r}{T} \left(\left(1 - Q\left(Q^{-1}\left(1 - (1 - Q_d)^{\frac{1}{K}}\right)(\gamma + 1) + \gamma\sqrt{St_s f_s}\right)\right)^K P_{h0} + (1 - Q_d)P_{h1} \right) \tag{10}$$

The other $D - K$ clusters harvest the RF energy within sensing time t_s. The average aggregate harvested energy of $(D - K)S$ nodes is given by

$$E_H = (D - K)S(p_s h^2 P_{h1} + p_n)t_s \tag{11}$$

where p_s is the PU power, p_n is the noise power and h is the average channel gain from the PU to the CIoT. Suppose the sensing power of each node is p_r and the sensing information reporting power is p_u, the aggregate consumed sensing energy within sensing time is given by

$$E_S = K(Sp_r t_s + p_u t_r) \tag{12}$$

3 Joint Time and Node Optimization

In this paper, we try to maximize the spectrum access probability of the CIoT subject to the constraints that the detection probability Q_d is above the lower bound α and the harvested energy E_H is larger than the consumed sensing energy E_S. The optimization problem is formulated as follows

$$\max_{t_s,K} P_{acc} \tag{13a}$$

$$\text{s.t. } Q_d \geq \alpha \tag{13b}$$

$$E_H \geq E_S \tag{13c}$$

$$t_s + Kt_r \leq T \tag{13d}$$

which is hard to be solved directly. The optimization problem can be solved using the alternating direction optimization (ADO).

3.1 Sensing Time Optimization

Firstly, fixing K, Eq. (13) becomes a convex optimization problem about τ, which is described as follows

$$\max_{t_s} P_{acc} = \frac{\hat{T} - t_s}{T} \left(\left(1 - Q(\varPhi + \varPsi\sqrt{t_s})\right)^K P_{h0} + (1 - Q_d)P_{h1} \right) \tag{14a}$$

$$\text{s.t. } Q_d \geq \alpha \tag{14b}$$

$$E_H \geq E_S \tag{14c}$$

$$0 \leq t_s \leq \hat{T} \tag{14d}$$

where $\hat{T} = T - Kt_r$, $\varPhi = Q^{-1}\left(1 - (1 - Q_d)^{\frac{1}{K}}\right)(\gamma + 1)$ and $\varPsi = \gamma\sqrt{Sf_s}$. Since $Q(x)$ is a monotonically decreasing function, $\varPhi$ decreases with the increase of Q_d. Hence, P_{acc} decreases with the increase of Q_d, which indicates that P_{acc} can achieve the maximal value only when $Q_d = \alpha$. With $E_H \geq E_s$, we can obtain $t_s \geq t_s^{min}$. t_s^{min} is given by

$$t_s^{min} = \frac{p_u t_r}{S\left(\left(\frac{D}{K} - 1\right)(p_s h^2 p_{h1} + p_n) - p_r\right)} \tag{15}$$

where $(D - K)(p_s h^2 p_{h1} + p_n) - Kp_r > 0$ must be guaranteed where we can get $K < \frac{D(p_s h^2 p_{h1} + p_n)}{p_s h^2 p_{h1} + p_n + p_r}$. Hence, the initial value of K should be chosen within the range from 1 to $\left\lceil \frac{D(p_s h^2 p_{h1} + p_n)}{p_s h^2 p_{h1} + p_n + p_r} \right\rceil$. Then the optimization problem (13) is rewritten as follows

$$\max_{t_s} P_{acc} = \frac{\hat{T} - t_s}{T} \left(\left(1 - Q(\varPhi + \varPsi\sqrt{t_s})\right)^K P_{h0} + (1 - \alpha)P_{h1} \right) \tag{16a}$$

$$\text{s.t. } t_s^{min} \leq t_s \leq \hat{T} \tag{16b}$$

t_s^* can be achieved using the Newton iterative method that is described in Algorithm 1.

Algorithm 1. Sensing time optimization.

```
Input: $i = 0$, $t_s^{(i)} \in [t_s^{min}, \hat{T}]$ and estimation error $\delta$;
while $|t_s^{(i)} - t_s^{(i-1)}| > \delta$ do
    set $t_s^{(i+1)} = t_s^{(i)} - \frac{\nabla P_{acc}\left(t_s^{(i)}\right)}{\nabla^2 P_{acc}\left(t_s^{(i)}\right)}$
    set $i = i + 1$;
end while
Output: $t_s^* = t_s^{(i)}$.
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3.2 IoT Node Optimization

Fixing t_s, the optimization problem (13) about K is rewritten as follows

$$\max_{t_s} P_{acc} = t_r \frac{\tilde{T} - K}{T} \left(G(K) P_{h0} + (1 - \alpha) P_{h1}\right) \tag{17a}$$

$$\text{s.t. } 0 \leq K \leq \tilde{T} \tag{17b}$$

where $\tilde{T} = \frac{T - t_s}{t_r}$, $G(K) = \left(1 - Q(\Phi + \Psi\sqrt{t_s})\right)^K$. From $E_H \geq E_S$, we can get that

$$K \leq \frac{SDt_s(P_s h^2 p_{h1} + p_n)}{S(p_s h^2 p_{h1} + p_n + p_r)t_s + p_u t_r} \tag{18}$$

The optimal K^* can be achieved using the enumeration method, which is described as follows

$$K^* = \underset{K=1,2,\ldots,K^{max}}{\operatorname{argmax}} P_{acc}(K) \tag{19}$$

We optimize t_s and K alternatively until both of them are convergent. The joint optimization algorithm of t_s and K is described as Algorithm 2.

Algorithm 2. Joint optimization algorithm.

```
Input: $i = 0$, $t_s^{(i)}$ and $K^{(i)}$;
while any of $t_s$ and $K$ is not convergent or the maximal iteration number has been
      reached do
    fixing $t_s = t_s^{(i)}$, optimize $K$ using (19) and set $K^{(i+1)} = K^*$;
    fixing $K = K^{(i+1)}$, optimize $t_s$ using Algorithm 1 and set $t_s^{(i+1)} = t_s^*$;
    set $i = i + 1$;
end while
Output: $t_s^* = t_s^{(i)}$ and $K^* = K^{(i)}$.
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4 Simulations and Discussions

The simulation parameters are set as follows. The absence and presence probabilities of the PU $P_{h0} = P_{h1} = 0.5$, the frame time $T = 10$ ms, the reporting time $t_r = 0.05$ ms, the number of IoT nodes $N = 150$, the number of clusters $D = 30$, the sampling frequency $f_s = 100$ KHz, the PU power $p_s = 1$W, the noise power $p_n = 0.01$ W, the sensing power $p_r = 0.1$ W and the information reporting power $p_u = 0.1$ W. Moreover, the channels obey the Rayleigh distributions (Fig. 3).

It has been indicated that there is an optimal set of sensing time t_s and number of sensing clusters K that maximizes the spectrum access probability of the CIoT. When $t_s = 0.5$ ms and $K = 12$, the maximal $P_{acc} = 0.3952$. Figure 4 shows P_{acc} changing with t_s when $K = [1, 10, 20]$. It is seen that P_{acc} firstly improves and then decreases as t_s increases, which has proven the convex optimization of (14). P_{acc} improves due to the increased spectrum sensing performance but decreases because of the decreased spectrum access time, thus, there is a tradeoff between sensing time and spectrum access. The relationship between spectrum access and energy harvesting is shown in Fig. 5. We can see that P_{acc} firstly improves but then drops rapidly with the increase of harvested energy E_H. Because small E_H can supply the energy used for spectrum access, but large E_H may consume great spectrum resource such as time and nodes. Hence, there is a tradeoff between spectrum access and energy harvesting.

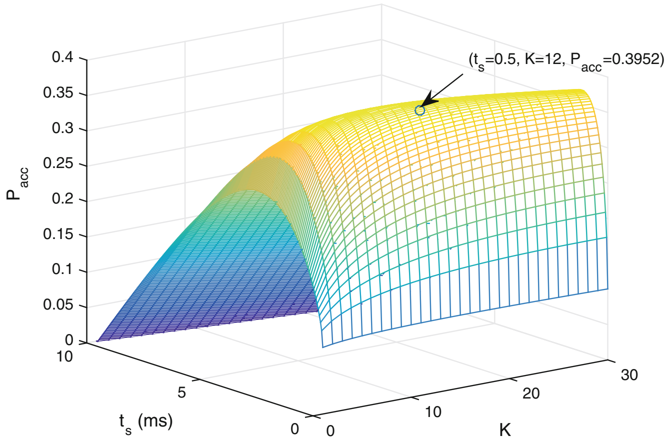

Fig. 3. Spectrum access probability changing jointly with local sensing time and the number of sensing clusters.

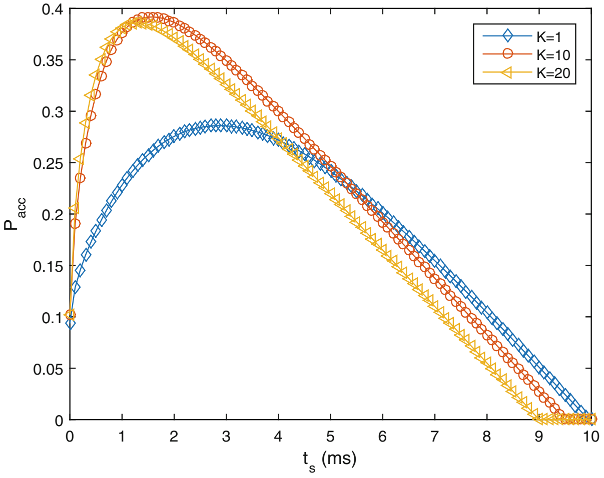

Fig. 4. Spectrum access probability changing with local sensing time.

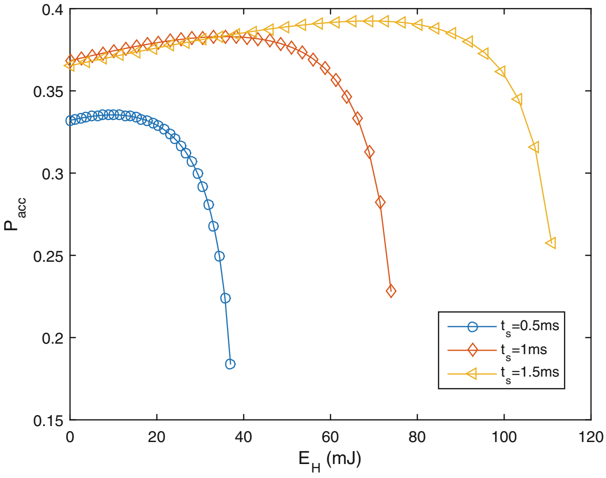

Fig. 5. Spectrum access probability changing with harvested energy.

5 Conclusions

In this paper, a cluster-based energy-efficient CIoT is proposed to improve both spectrum efficiency and energy efficiency, which can harvest the RF energy of the PU while performing spectrum sensing. The frame structure of the CIoT is divided into sensing slot and transmission slot. In the sensing slot, some clusters detect the PU while the other clusters harvest the RF energy, and the harvested energy is used to supply the consumption of spectrum sensing for guaranteeing transmission energy in the transmission slot. We try to maximize the spectrum access probability of the CIoT using a joint optimization algorithm of sensing time and number of sensing clusters. From the simulations, there is an optimal set of sensing time and number of sensing clusters that maximizes the spectrum access probability, and spectrum access probability firstly improves but then drops rapidly with the increase of harvested energy.

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