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센싱 시간의 최적화를 통해 인지 무선 센서 네트워크를 위한 효율적인 스펙트럼 센싱

(Efficient Spectrum Sensing for Cognitive Radio Sensor Networks via Optimization of Sensing Time)

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요 약 인지 무선 센서 네트워크 (CRSNs)에서 보조 사용자가 (SUs) 주 사용자 (PUs)에 간섭을 주지 않고 기회주의적 방식으로 라이선스 대역을 사용할 수 있다. SUs가 스펙트럼 센싱을 통해 PU의 존재 여부를 확인할 수 있다. 그리고 센싱 시간은 스펙트럼 센싱의 중요한 파라미터이다. 센싱 시간은 센싱 성능과 스루풋 간의 균형을 얻을 수 있다. 본 논문에서는 다른 관점에서 이 균형을 탐구하기를 통해 스펙트럼 센싱을 위한 새로운 기법을 제안한다: a) PU의 검출 (SSPD)과 b)스루풋(SSST)을 극대화을 위한 스펙트럼 센싱이다. 제안한 기법에서 현재 프레임의 첫 번째 센싱 결과에 따라 동적인 두 번째 스펙트럼 센싱을 수행한다. CRSNs에서 에너지 제약을 때문에 네트워크 에너지 효율도 센싱 시간의 최적화를 통해 최대화된다. 시뮬레이션 결과를 통하여 제안된 SSPD과 SSST가 각각의 에너지 효율과 스루풋의 성능을 향상시킬 수 있음을 검증하였다.

키워드: 인지 무선 센서 네트워크, 센싱 시간, 에너지 효율, 보조 사용자의 스루풋, 미스 검출 확률, 허위 경보 확률

Abstract In cognitive radio sensor networks (CRSNs), secondary users (SUs) can occupy licensed bands opportunistically without causing interferences to primary users (PUs). SUs perform spectrum sensing to detect the presence of PUs. Sensing time is a critical parameter for spectrum sensing that can yield a tradeoff between sensing performance and secondary throughput. In this study, we investigate new approaches for spectrum sensing by exploring the tradeoff from a) spectrum sensing for PU detection (SSPD) and b) spectrum sensing for secondary throughput (SSST). In the proposed scheme, the first sensing result of the current frame determines the dynamic performance of the second spectrum sensing. Energy constraint in CRSNs leads to maximized network energy efficiency via optimization of sensing time. Simulation results show that the proposed scheme of SSPD and SSST improves network performance in terms of energy efficiency and secondary throughput, respectively.

Keywords: cognitive radio sensor network, sensing time, energy efficiency, secondary throughput, miss detection probability, false alarm probability

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1. Introduction

Cognitive radio (CR) technology is applied to improve spectral efficiency. It can allow the secondary users (SUs) to occupy the licensed bands which are not utilized by primary users (PUs). Spectrum sensing is critical technology for CR, it is performed by secondary users (SUs) to search the *spectrum hole* or *white space*. In terms of spectrum sensing, the effect of sensing time on spectrum sensing performance is significant. It can yield a tradeoff between sensing performance and secondary throughput.

Miss detection and false alarm are two major metrics to evaluate the spectrum sensing performance. Miss detection occurs when the band is occupied by PU but SUs fail to detect it. As a result, the communication of SUs will cause interference to PU. False alarm is that the band is actually idle but the PU is detected by SUs. Under this situation, SUs cannot use the opportunities of *spectrum hole* or *white space*. Therefore, it can be known that miss detection will cause interference to PU, and false alarm will degrade the secondary throughput.

There are many works on the optimization of sensing time. A scheme for joint optimization of channel sensing time and channel sensing order is proposed in [1]. The optimization problem is formulated to find optimal sensing time which can maximize the secondary throughput. Hao et al. [2] develop a novel adaptive spectrum sensing scheme to improve the average throughput reward. The spectrum sensing duration can be adjusted according to the previous sensing results and channel state information. In [3], authors propose a learning-based spectrum sensing time optimization scheme to maximize the average throughput of the cognitive radio system. By optimizing spectrum sensing time, the objective that maximizing the average throughput of a cognitive radio system is achieved. However, these above-mentioned technologies specific to cognitive radio networks (CRNs) cannot be directly applied in cognitive radio sensor networks (CRSNs), because they do not consider energy restriction. In CRSNs, wireless sensor devices powered by batteries have to suffer the energy constraint. This makes energy-efficient design be the essential consideration for CRSNs.

Inspired by previous works, we propose an efficient spectrum sensing scheme for CRSNs. We investigate two new approaches for spectrum sensing scheme from the views of PU detection and secondary throughput, respectively. In the proposed scheme, the individual spectrum sensing is performed by a single SU, and the SU can dynamically decide to sense the spectrum one or two periods according to the sensing result of the current frame. Concretely, in terms of spectrum sensing for PU detection (SSPD), we prefer to provide a better protection for PUs, and the second spectrum sensing will be performed if sensing result shows that PU is absent. In terms of spectrum sensing for secondary throughput (SSST), we focus on improving the secondary throughput. The second spectrum sensing will be performed when PU is detected to be busy. In addition, the energy efficiency can be maximized by the optimization of sensing time. Through a set of simulations, it is verified that the approach of SSPD can achieve a better performance in terms of network energy efficiency, and the approach of SSST has a higher secondary throughput.

The rest of the paper is organized as follows. The related work is introduced in Section 2. The proposed scheme is investigated with mathematical analysis in Section 3. The performance of the proposed scheme is evaluated by a set of simulations in Section 4. Finally, Section 5 concludes this paper and introduces the future work.

2. Related work

There have been many works on spectrum sensing time optimization for CRNs, but few for CRSNs. Most work specific to CRNs, such as aforementioned work, did not consider the energy consumption. Therefore, they are not directly applied in CRSNs.

In [4], Deng et al. study the energy-efficient spectrum sensing in CR networks using optimal periodic scheduling of a sensor. The duty-cycle of sensing time and scheduling period can efficiently perform spectrum sensing. And a tradeoff among the PU protection, secondary throughput, and lifetime of the sensor is expected. Hai et al. address the problem of energy minimization under detection accuracy constraint [5]. The bounds for the number of sensors are derived firstly. Then authors formulate the optimization problem to find the optimal sensing time and optimal number of sensors that can minimize the energy consumption to prolong the network lifetime. Syed et al. present a novel history assisted spectrum sensing scheme [6]. The history processing database is used to make spectrum sensing decision. In this way, the spectrum sensing scanning can be reduced, and the energy consumption for spectrum sensing can be improved. In [7], authors propose an approach for energy efficient cluster-based spectrum sensing. Subject to PU protection constraints and spectrum utilization requirements, optimal sensing time, data transmission time, and the number of CR users are jointly optimized to maximize energy efficiency of the systems.

Even though [4-7] focus on energy efficient technology, they only perform spectrum sensing once. If the sensing errors (i.e. false alarm and miss detection) occur, there is no chance to correct them. As a result, the achievable secondary throughput will be decreased, and SUs will cause interference to PU.

3. Proposed scheme

In this section, the system model is described. The approaches of SSPD and SSST will be introduced, respectively. The objective function is formulated by mathematical analysis, and the optimal sensing time can be obtained.

3.1 System model

In proposed scheme, a simple CRSN which is consisted of one PU and ten secondary links is assumed. Each secondary link is consisted of one transmitter-receiver pair. The licensed band is divided into several sub-bands. Each SU will perform spectrum sensing on dedicated sub-band. Time is assumed to be divided into equal frame. Each frame contains sensing phase and data transmission phase. At the beginning of each frame, SUs will detect PU for the sensing phase. If the sensing result shows that PU is absent, SUs will transmit data for data transmission phase. Otherwise, SUs will keep silent and wait for the next frame. In addition, it is worth noting that data transmission is assumed to be valid only under the condition that PU is actually absent, i.e. the data transmission is invalid when miss detection occurs.

3.2 Energy detector based spectrum sensing

In CRSNs, a binary hypothesis testing problem is utilized to formulate spectrum sensing as follows:

$$\mathcal{H}_0:\ y(n) = u(n), \tag{1}$$

$$\mathcal{H}_1:\ y(n) = x(n) + u(n), \tag{2}$$

where hypothesis $\mathcal{H}_0$ and $\mathcal{H}_1$ indicate that PU is absent and present, respectively. p_0 and p_1 are the probabilities of $\mathcal{H}_0$ and $\mathcal{H}_1$, respectively. The noise $u(n)$ is assumed to be an iid Gaussian random process with zero mean and variance σ_y^2. And the received PU's signal $x(n)$ is an iid random process with mean zero and variance σ_x^2.

In this paper, we employ energy detector as the spectrum sensing scheme. The test statistic can be calculated as below:

$$\mathrm{T}(\mathrm{y}) = \sum_{n=1}^{N} \left| y(n) \right|^2, \tag{3}$$

where $y(n)$ is the sampled signal, N is the number of sample times. The test statistic follows the central and non-central chi-square distribution with 2N degrees of freedom under hypothesis $\mathcal{H}_0$ and $\mathcal{H}_1$, respectively. The test statistic can be approximated as Gaussian, because central limit theorem can be utilized for it if N is large.

$$\mathrm{T}(\mathrm{y}) \sim \begin{cases} \mathcal{N}(N, 2N), & \mathcal{H}_0 \\ \mathcal{N}\left(N(1+\gamma), 2N(1+\gamma)^2\right), & \mathcal{H}_1 \end{cases}, \tag{4}$$

where $\gamma = \sigma_x^2 / \sigma_y^2$ is the signal to noise ratio received from PU. We can get the detection probability p_d and the false alarm probability p_f based on the statistics of T(y).

$$\begin{aligned} p_d &= p\left(\mathrm{T}(y) > \lambda \mid \mathcal{H}_1\right) \\ &= Q\left(\frac{\lambda}{\sqrt{2N}(\gamma+1)} - \sqrt{\frac{N}{2}}\right), \end{aligned} \tag{5}$$

$$\begin{aligned} p_f &= p(\mathrm{T}(y) > \lambda \mid \mathcal{H}_0) \\ &= Q\left(\frac{\lambda}{\sqrt{2N}} - \sqrt{\frac{N}{2}}\right), \end{aligned} \tag{6}$$

where λ is the sensing threshold, and $Q(\cdot)$ is Q function. If the received power is bigger than threshold λ, we consider that PU is present; otherwise, we consider PU is absent. The function of λ can be derived by Eq. (5) as

$$\lambda = \sqrt{2N}\left(1+\gamma\right)\left(Q^{-1}\left(p_d\right)+\sqrt{\frac{N}{2}}\right), \tag{7}$$

where $Q^{-1}(\cdot)$ denotes the inverse function of Q function. Eq. (7) is substituted into Eq. (6) and we can get:

$$p_f = Q\left(\left(1+\gamma\right)Q^{-1}\left(p_d\right)+\gamma\sqrt{\frac{N}{2}}\right). \tag{8}$$

In this paper, in order to guarantee the essential requirement of CRSNs, the false alarm threshold p_f^{th} and the detection probability threshold p_d^{th} are also set for SUs. Specifically, the false alarm threshold of the SU should not be bigger than p_f^{th}, and the detection probability of the SU should not be smaller than p_d^{th}. Because Q function is the monotone decreasing function, in order to minimize p_f and maximize the secondary throughput, in this paper we make $p_d = p_d^{th}$.

3.3 SSPD

In terms of SSPD, from the PU's perspective, we prefer to provide a better protection for PU. SU performs spectrum sensing one period and then wait for the next frame if PU is detected to be present. If sensing result shows PU is idle, SU will perform spectrum sensing again to verify the absence of PU. If sensing result still shows PU is absent, data will be transmitted. Therefore, according to the proposed spectrum sensing scheme, 6 cases can be listed as below. d_0 and d_1 denote sensing results corresponding to the absence and presence of PU, respectively

S1: PU is actually present, and sensing result is d_1.

S2: PU is actually present, and the first and the second sensing results are d_0 and d_1, respectively.

S3: PU is actually present, while both of the first and the second sensing results are d_0.

S4: PU is actually absent, while the sensing result is d_1.

S5: PU is actually absent, and both of the first and the second sensing results are d_0.

S6: PU is actually absent, and the first and the second sensing results are d_0 and d_1, respectively.

According to above-mentioned 6 cases, it is known that S1 and S2 can detect PUs successfully; S3 can lead to the problem of miss detection; S4 and S6 can cause the problem of false alarm; S5 can bring valid secondary throughput. So miss detection probability p_m^{SSPD} can be expressed as

$$p_m^{SSPD} = p_1\left(1-p_d\right)^2. \tag{9}$$

Since the secondary throughput is achieved by S5. Therefore, the average throughput can be expressed as

$$R(\tau) = p_0\left(1-p_f\right)^2\left(T-2\tau\right)C, \tag{10}$$

where T is the length of frame, τ denotes sensing time. C is the channel capacity of SU. And energy consumption functions corresponding to 6 cases can be formulated as below.

$$E_1 = p_1 p_d E_s \tau, \tag{11}$$

$$E_2 = 2p_1\left(1-p_d\right)p_d E_s \tau, \tag{12}$$

$$E_3 = p_1\left(1-p_d\right)^2\left(2E_s\tau + E_t\left(T-2\tau\right)\right), \tag{13}$$

$$E_4 = p_0 p_f E_s \tau, \tag{14}$$

$$E_5 = p_0\left(1-p_f\right)^2\left(2E_s\tau + E_t\left(T-2\tau\right)\right), \tag{15}$$

$$E_6 = 2p_0\left(1-p_f\right)p_f E_s \tau, \tag{16}$$

$$E_{total} = E_1 + E_2 + E_3 + E_4 + E_5 + E_6, \tag{17}$$

where E_1, E_2, E_3, E_4, E_5, and E_6 represent the energy consumption of S1, S2, S3, S4, S5, and S6, respectively. E_{total} is the average of the total energy consumption. E_s and E_t denote energy consumption of spectrum sensing and data transmission for unit time. In this paper, the definition of energy efficiency in [8] is used. Therefore the objective function of energy efficiency can be expressed as

$$\psi\left(\tau\right) = \frac{R\left(\tau\right)}{E_{total}}, \quad s.\ t.\ p_f \le p_f^{th}. \tag{18}$$

The value of τ which can maximize ψ is the optimal spectrum sensing time. The exhaustive search method is utilized to figure out the maximum value of ψ.

3.4 SSST

In terms of SSST, from the SUs' perspective, the main objective is to maximize the secondary throughput. SU performs spectrum sensing one period and then transmit data if PU is detected to be absent. If sensing result shows PU is busy, SU will perform spectrum sensing again to verify whether PU is present or not. If the second sensing result shows that PU is absent, SU will transmit data. If

PU is still detected to be present, SU will keep silent and wait for the next frame. Therefore, according to above-mentioned, 6 cases can also be listed as below.

S1: PU is actually present, and both of the first and the second sensing results are d_1.

S2: PU is actually present, and the first and the second sensing results are d_1 and d_0, respectively.

S3: PU is actually present, while sensing result is d_0.

S4: PU is actually absent, and the sensing result is d_0.

S5: PU is actually absent, and the first and the second sensing results are d_1 and d_0, respectively.

S6: PU is actually absent, while both of the first and the second sensing results are d_1.

According to above-mentioned 6 cases, it is known that S1 can detect PUs successfully; S2 and S3 can lead to the problem of miss detection; S4 and S5 can achieve the secondary throughput; S6 will lead to the problem of false alarm. So miss detection probability p_m^{SSPD} can be expressed as

$$\begin{aligned} p_m^{SSST} &= p_1 p_d\left(1-p_d\right)+p_1\left(1-p_d\right) \\ &= p_1\left(1-p_d^2\right). \end{aligned} \tag{19}$$

Since the throughput can be achieved by S4 and S5. Therefore, the average throughput can be expressed as

$$\begin{aligned} R(\tau) = p_0\left(1-p_f\right)\left(T-\tau\right)C + \\ p_0 p_f\left(1-p_f\right)\left(T-2\tau\right)C, \end{aligned} \tag{20}$$

and energy consumption functions corresponding to 6 cases can be formulated as below.

$$E_1 = 2p_1 p_d^2 E_s \tau, \tag{21}$$

$$E_2 = p_1 p_d\left(1-p_d\right)\left(2E_s\tau + E_t\left(T-2\tau\right)\right), \tag{22}$$

$$E_3 = p_1\left(1-p_d\right)\left(E_s\tau + E_t\left(T-\tau\right)\right), \tag{23}$$

$$E_4 = p_0\left(1-p_f\right)\left(E_s\tau + E_t\left(T-\tau\right)\right), \tag{24}$$

$$E_5 = p_0 p_f\left(1-p_f\right)\left(2E_s\tau + E_t\left(T-2\tau\right)\right), \tag{25}$$

$$E_6 = 2p_0 p_f^2 E_s \tau, \tag{26}$$

$$E_{total} = E_1 + E_2 + E_3 + E_4 + E_5 + E_6. \tag{27}$$

The objective function is also formulated by Eq. (18).

4. Performance evaluation

In this Section, we show the performance of the approaches of SSPD and SSST, and compare them with the scheme proposed in [9]. The simulation for the performance evaluation is implemented with MATLAB. In order to evaluate the performance of the proposed scheme, simulation parameters are set as below. C=6.6582bit/sec/Hz, p_d^{th} = 0.9, p_f^{th} = 0.1, T = 0.2s, E_s = 0.1W, E_t = 3W, γ = −20dB. Since T = 0.2s, in order to enable the second spectrum sensing to be performed successfully for the proposed scheme, the optimal sensing time will be obtained in the interval (0, 0.1).

Fig. 1 shows the variation of energy efficiency with the increasing sensing time when p_0 = 0.7 is given (In fact, p_0 can be any value in the interval (0, 1). Here we want to fix p_0 as 0.7 to show the variation of energy efficiency with the increasing sensing time). From Fig. 1, we can get that both energy efficiency of SSPD and SSST will increase with the increasing sensing time at first. And then after the optimal point of SSPD and SSST, the energy efficiency of SSPD and SSST decreases again. The reason is that false alarm probability is decreased with increasing sensing time, and this implies that more opportunities of spectrum hole can be utilized by SU, and more throughputs can be achieved. However, due to the fixed frame time T, data transmission time will be decreased with the increasing sensing time. It will affect the throughput of SU when sensing time is large. That is the reason why energy efficiency of SSPD and SSST is decreased again. Fig. 1 also confirms that the optimal sensing time which can maximize the network energy efficiency exactly exists. It can also be seen that the energy efficiency of SSPD is always higher than SSST. The reason is that SSPD prefers to provide a better protection for PUs. And therefore, more unnecessary energy consumption for invalid data transmission can be saved.

Fig. 2 shows the variation of the secondary throughput with increasing sensing time when p_0 = 0.7 is given (Here p_0 can also be any value in the interval (0, 1)). The secondary throughput of SSST is higher than SSTD. Since SUs in the scheme of SSST will perform spectrum sensing again when sensing result shows that PU is present. If false alarm occurred during the first spectrum sensing is corrected by the second spectrum sensing, more throughput can be

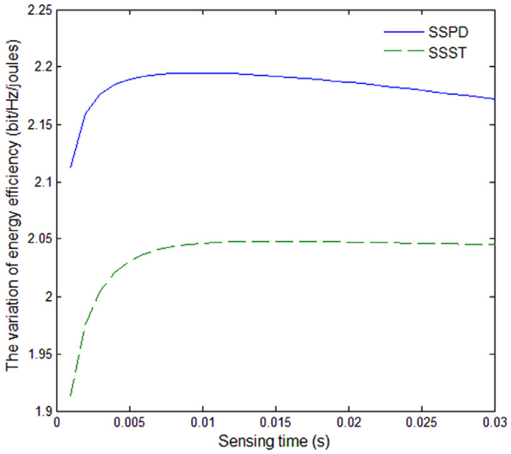

그림 1 센싱 시간에 따른 에너지 효율

Fig. 1 The variation of energy efficiency with increasing sensing time

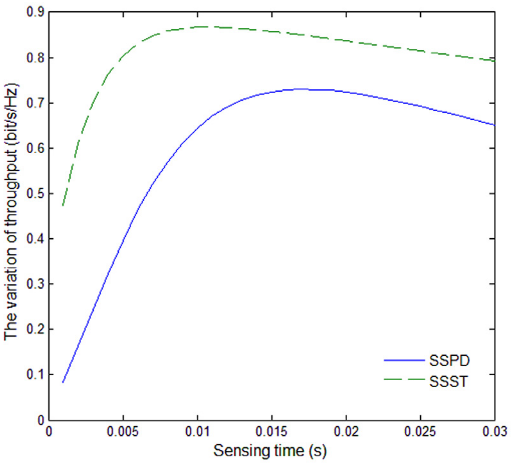

그림 2 센싱 시간에 따른 스루풋

Fig. 2 The variation of throughput with increasing sensing time

achieved. That is the reason why the throughput of SSST is higher than SSTD. We can also get that even though the secondary throughput of SSST is higher than SSTD, the energy efficiency of SSST is still lower than SSTD. The energy consumption for the invalid data transmission has more effects on improving the network energy efficiency.

Fig. 3 shows the variation of the false alarm probability with increasing sensing time. Since SUs in the scheme of SSST will perform the second spectrum sensing again when sensing result is d_1. In this

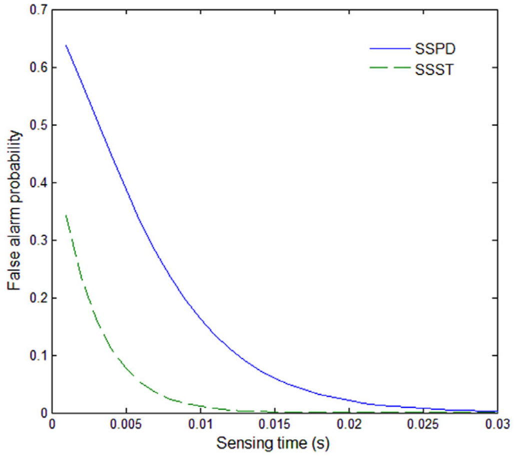

그림 3 센싱 시간에 따른 허위 경보 확률

Fig. 3 The variation of false alarm probability with increasing sensing time

way, the sensing error caused by false alarm has a certain probability to be corrected by the second spectrum sensing. The false alarm probability of SSST is always lower than SSPD, and therefore the SUs in the scheme of SSST can make better use of spectrum hole and have a higher secondary throughput.

The proposed scheme is also compared with the minimizing mean detection time scheme proposed by Luo et al. [9]. The sensing time is maximized subject to the constraints of detection probability and false alarm probability, and the maximum remaining time is left for data transmission. Fig. 4 shows the optimal energy efficiency with the varying p_0. We can get that the optimal energy efficiency of SSPD is always higher than Luo [9] and SSST. The reason is that the miss detection of SSPD is lower. According to Eq. (9), we can get that p_m^{SSPD} is $(1-p_d)$ and $(1-p_d)/(1+p_d)$ times of the miss detection probability of Luo [9] and SSST, respectively. In this paper, because p_d is fixed as 0.9, the miss detection probability can be decreased by 10 and 19 times compared with Luo [9] and SSST, respectively. Even though the SSPD spends more time to detect PU when sensing result is d_0, due to the lower miss detection probability, PU can be protected better. More invalid data transmission can be avoided, and more unnecessary energy consumption can be saved. In this way, the network energy efficiency can be promoted.

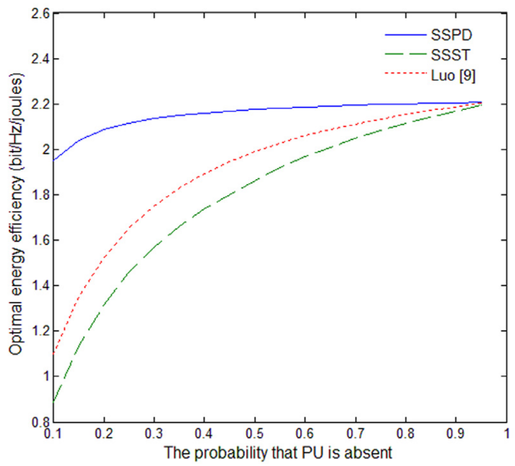

그림 4 에너지 효율의 비교

Fig. 4 Comparison of energy efficiency

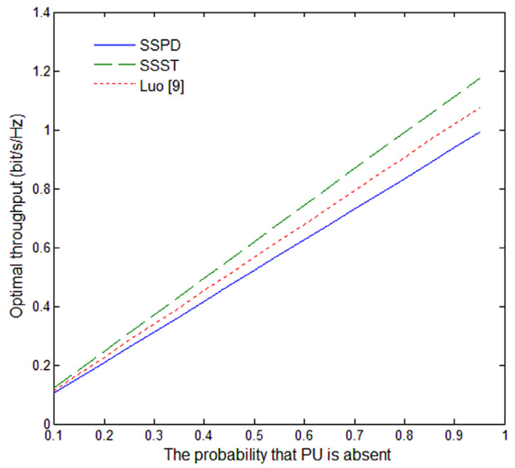

그림 5 스루풋의 비교

Fig. 5 Comparison of throughput

Fig. 5 shows the comparison of throughput. We can see that the scheme of SSST has the best performance in terms of the secondary throughput. Since the false alarm probability of Luo [9] and SSPD is higher than SSST, SSST can achieve the highest secondary throughput. Therefore, through a set of simulations, we can get that the approach of SSPD has the best performance in terms of network energy efficiency, and the approach of SSST has the highest secondary throughput.

5. Conclusion and future work

In this paper, we proposed a novel spectrum sensing scheme and investigate new approaches for spectrum sensing from the views of PU detection and secondary throughput. According to the sensing result of the current frame, SUs can dynamically decide to perform spectrum sensing one or two periods. In order to provide a better protection for PU, SUs will detect PU again to confirm the absence of PU when sensing result shows that PU is absent. From the view of SUs, SUs will perform spectrum sensing again to achieve more secondary throughput when sensing result shows that PU is present. Finally, a set of simulations validate that SSPD can provide a better protection for PU, and have a higher energy efficiency, and SSST can achieve the higher secondary throughput by the lower false alarm probability. In the future, we will focus on the sensing interval and optimize the energy efficiency further.

References

[1] A. Ewaisha, A. Sultan, and T. ElBatt, "Optimization of Channel Sensing Time and Order for Cognitive Radios," *Proc. Wireless Communications and Networking Conference (WCNC)*, pp. 1414-1419, 2011.

[2] H. He, G. Y. Li, and S. Li, "Adaptive Spectrum Sensing for Time-Varying Channels in Cognitive Radios," *IEEE Wireless Communications letters*, Vol. 2, No. 2, pp. 1-4, 2013.

[3] H. Shokri-Ghadikolaei, Y. Abdi, and M. Nasiri-Kenari, "Learning-Based Spectrum Sensing Time Optimization in Cognitive Radio Systems," *Proc. Telecommunications (IST)*, pp. 249-254, 2012.

[4] R. Deng, S. He, J. Chen, and J. Jia, "Energy-Efficient Spectrum Sensing by Optimal Periodic Scheduling in Cognitive Radio Networks," *IET Communications*, Vol. 6, No. 6, pp. 676-684, 2012.

[5] H. N. Pham, Y. Zhang, P. E. Engelstad, T. Skeie, and F. Eliassen, "Energy Minimization Approach for Optimal Cooperative Spectrum Sensing in Sensor-Aided Cognitive Radio Networks," *Proc. Wireless Internet Conference (WICON)*, 2010.

[6] T. Syed, and G. Safdar, "History assisted Energy Efficient Spectrum Sensing for Infrastructure based Cognitive radio Networks," *IEEE Transactions on Vehicular Technology*, 2016, doi: 10.1109/TVT. 2016. 2585763.

[7] F. Awin, E. Abdel-Raheem, and M. Ahamdi, "Designing an Optimal Energy Efficient Cluster-based Spectrum Sensing for Cognitive Radio Networks," *IEEE Communications Letters*, Vol. 20, No. 9, pp. 1884-1887, 2016.

[8] Y. Pei, Y. C. Liang, K. C. Teh, and K. H. Li, "Energy-Efficient Design of Sequential Channel Sensing in Cognitive Radio Networks: Optimal

Sensing Strategy, Power Allocation, and Sensing Order," *IEEE Journal on Selected Areas in Communications*, Vol. 29, No. 8, pp. 1648-1659, Sep. 2011.

[9] L. Luo, and S. Roy, "Efficient Spectrum Sensing for Cognitve Radio Networks via Joint Optimization of Sensing Threshold and Duration," *IEEE Transactions on Communications*, Vol. 60, No. 10, pp. 2851-2860, Oct. 2012.

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