Journal of information and
communication convergence engineering
http://jicce.org

J. Inf. Commun. Converg. Eng. 15(2): 79-84, Jun. 2017

Regular paper

Throughput Maximization for Cognitive Radio Users with Energy Constraints in an Underlay Paradigm

Van-Hiep Vu and Insoo Koo*, *Member, KIICE*

School of Electrical Engineering, University of Ulsan, Ulsan 44610, Korea

Abstract

In a cognitive radio network (CRN), cognitive radio users (CUs) should be powered by a small battery for their operations. The operations of the CU often include spectrum sensing and data transmission. The spectrum sensing process may help the CU avoid a collision with the primary user (PU) and may save the energy that is wasted in transmitting data when the PU is present. However, in a time-slotted manner, the sensing process consumes energy and reduces the time for transmitting data, which degrades the achieved throughput of the CRN. Subsequently, the sensing process does not always offer an advantage in regards to throughput to the CRN. In this paper, we propose a scheme to find an optimal policy (i.e., perform spectrum sensing before transmitting data or transmit data without the sensing process) for maximizing the achieved throughput of the CRN. In the proposed scheme, the data collection period is considered as the main factor effecting on the optimal policy. Simulation results show the advantages of the optimal policy.

Index Terms: Cognitive radio, Data collection period, Energy constraints, Maximizing throughput, Optimal policy

I. INTRODUCTION

In cognitive radio network (CRN) [1, 2], to avoid interference with the operation of the primary users (PUs), the cognitive radio users (CUs) often follow one of two paradigms, underlay or overlay paradigms. In the overlay paradigm, the CU is allowed to access the channel only when the PU signal is absent. The underlay paradigm allows the CU to access to the licensed channel, if the interference causes the PU to be below a given threshold.

Due to the limited power supply, energy efficiency becomes an essential part of cognitive radio users and it attracts many researchers such as in [3, 4]. In the CRN, a longer sensing time may consume more energy and reduce the transmission time in a time-slotted manner, which degrades the achieved throughput of the CRN. Therefore, spectrum sensing does not always provide better throughput to the CRN. Most previous studies that have investigated how to improve energy efficiency of the CRN consider spectrum sensing as a requirement before data transmission [5, 6]. The optimal sensing time for maximizing throughput is presented in [6]. In [7, 8], the scheme for finding an optimal action policy, including sleeping to save energy or active (i.e., perform spectrum sensing) to take an opportunity to transmit data, is proposed. The proposed scheme applies the partially observable Markov decision process (POMDP) [9, 10] to determine that optimal action policy.

In most previous works, the data collection period (i.e., within the period, the data needs to be transmitted to the receiver) was not considered to decide the action for energy efficiency. However, the data collection period is common

Received 11 May 2017, **Revised** 23 May 2017, **Accepted** 01 June 2017
***Corresponding Author** Insoo Koo (E-mail: iskoo@ulsan.ac.kr, Tel: +82-52-259-1249)
School of Electrical Engineering, University of Ulsan, 93, Daehak-ro, Nam-gu, Ulsan 44610, Korea.

Open Access http://doi.org/10.6109/jicce.2017.15.2.79 print ISSN: 2234-8255 online ISSN: 2234-8883

in real world applications. For example, talking or alarm data require immediate transmission; and environment information such as location, humidity and temperatures require being transmitted within a certain period. In this paper, we consider the data collection period as a main factor for determining an optimal operation policy in order to maximize the throughput of the CRN with energy constraints in an underlay paradigm. We classify the operations of the CRN as two types: spectrum sensing before data transmission and data transmission without spectrum sensing. It is expected that the proposed scheme will provide the CRN an improved throughput in comparison with conventional systems.

II. SYSTEM MODEL

We consider a PU network, which is assumed to operate in a time-slotted manner, and a CRN with a pair of CUs, a CU transmitter (CUtx) and a CU receiver (CUrx). The system model is shown in Fig. 1. The probabilities of absence and presence of the PU signal are defined as p_0 and p_1, respectively. In this paper, we assume that the distance between the CUtx and CUrx is small compared to the distance between the CUtx and the PU receiver (PUrx), and then the CUtx is able to adjust its transmission power in order to not affect the PU link while still delivering data to the CUrx. This means that the CRN follows the underlay paradigm for the operations.

The CUtx is powered by a battery with a capacity E_c in units of energy and always has data to transmit to the CUrx. However, the CUrx only accepts the incoming data within a data collection period n_{s_r}. We define e_s and e_t as the energy consumed for spectrum sensing and data transmitting in a time unit, respectively. The transmission energy e_t is the energy that the CUtx spends to transmit data in order to maintain the received signal-to-noise ratio (SNR) level (SNR_{CU}) at the CUrx.

The CUtx utilizes an energy detector to monitor the activity of the PU. The Gaussian noise is considered in the sensing channel. When the number of sensing samples is relatively large (e.g., $M \geq 200$), the received signal energy xE from the detector can be closely approximated as a Gaussian random variable under both hypotheses of the PU signal [11]. So that, we have,

$$xE \sim \begin{cases} \mathrm{N}(M, 2M) & H_0 \\ \mathrm{N}(M(\gamma+1), 2M(2\gamma+1)) & H_1 \end{cases}, \quad (1)$$

where γ is the signal-to-noise ratio (SNR) of the sensing channel between the CUtx and the PU transmitter (PUtx), M is the number of samples over a sensing interval, H_0 and H_1 are the absence and presence hypothesis of the PU signal, respectively.

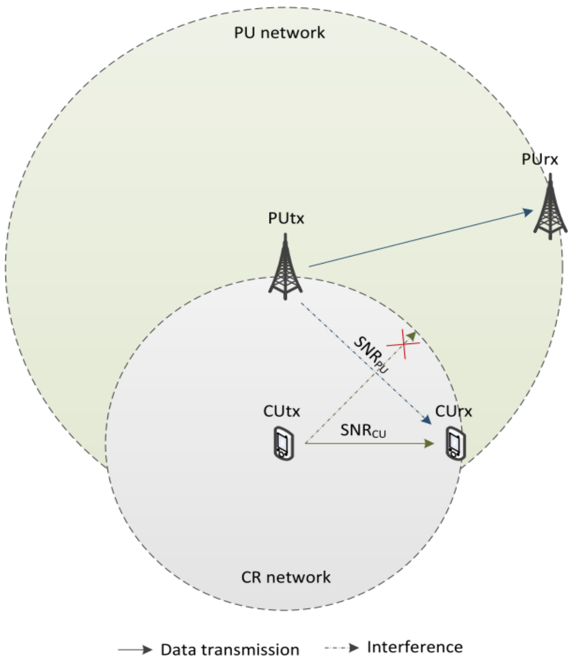

Fig. 1. System model of the proposed scheme.

According to the received signal energy xE, the decision on the PU status can be made as follows:

$$\begin{cases} G = 1(\text{the PU signal is presence}), & \text{If } xE \geq \lambda \\ G = 0\ (\text{the PU signal is presence}), & \text{otherwise}, \end{cases} \quad (2)$$

where λ is the energy threshold for a local decision.

The sensing performance of the CUtx can be evaluated by the probability of detection (p_d) and the probability of false alarm (p_f), which are given, respectively, as [11]:

$$p_d = Q\left(\frac{\lambda - M(\gamma+1)}{\sqrt{1M(2\gamma+1)}}\right), \quad (3)$$

and

$$p_f = Q\left(\frac{\lambda - M}{\sqrt{2M}}\right). \quad (4)$$

When the CUtx transmits data and the PU is absence, the CUtx-CUrx link can achieve the throughput

$$C_0 = \log_2(1 + SNR_{CU}), \quad (5)$$

where SNR_{CU} is the SNR in the CUtx-CUrx link.

On the other hand, when the CUtx transmits concurrently with the PUtx, the signal that the CUrx receives from the PUtx will be considered as noise. In this case, the CUtx-CUrx link can achieve the throughput

$$C_1 = \log_2\left(1 + \frac{SNR_{CU}}{1 + SNR_{PU}}\right), \quad (6)$$

where SNR_{PU} is the SNR in the PUtx-CUrx link.

It can be seen that the appearance of the PU signal may reduce the achieved throughput of the CUtx-CUrx link, meaning that C_1 is always smaller than C_0.

III. AN OPTIMAL POLICY FOR CU OPERATION

In this section, we consider the data collection period as the main factor for deciding an optimal operation policy of the CRN. The operations of the CRN will be classified into two types. First, the CUtx performs spectrum sensing; if the sensing result is “the PU signal is absent”, the CUtx will transmit data; otherwise, the CUtx will keep silent and wait for the next time slot. The first operation type may avoid a collision with the PUtx, making energy use more efficient. However, it must wait for a free time slot to transmit data that may take a long time, allowing the data collection period to potentially end. Second, the CUtx transmits data immediately during the entire time slot without a sensing process. This operation type may guarantee to transmit data within a short data collection period, but collisions with the PU network may occur, which reduces the received SNR at the CUrx. This may result in the achieved throughput of the CRN being reduced. In this paper, we propose a scheme to determine an optimal policy for CU operations that can maximize the total achieved throughput of the system during the data collection period.

We define the operations of the CR network as $\Theta \in \{SS\_DT, DT\}$, where $\Theta = SS\_DT$ is the first operation type; the CUtx performs spectrum sensing before deciding to transmit data or not, and $\Theta = DT$ is the second operation type; the CUtx transmits data in whole time slot without sensing process. According to the operation types, the CR network can achieve different throughput and consume different energy.

A. The First Operation Type: The CU Performs Spectrum Sensing before Deciding Transmit Data or Not (Θ = SS_DT)

If the CR network executes this operation type, it will achieve the average throughput as

$$TH(SS\_DT) = \left(\frac{T - t_s}{T}\right)\left(C_0(1 - p_f)p_0 + C_1(1 - p_d)p_1\right), \quad (7)$$

where T is length of a time slot, t_s is the sensing time, p_0 and p_1 are the probability of absence and presence of the PU signal, respectively.

The average energy consumption can be given as,

$$E(SS\_DT) = e_s t_s + e_t t_t\left((1 - p_f)p_0 + (1 - p_d)p_1\right), \quad (8)$$

where $t_t = T - t_s$ is the transmission time.

The expected lifetime (i.e., the maximum number of time slots that the CR network can be powered by the battery) of the CR network can be computed as,

$$ns(SS\_DT) = \frac{E_c}{E(SS\_DT)}. \quad (9)$$

B. The Second Operation Type: The CU Transmits Data in whole Time Slot without Sensing Process (Θ = DT)

In this operation type, the CR network transmits data in whole time slot T. Therefore, the average throughput will be given as

$$\mathrm{TH}(DT) = C_0 p_0 + C_1 p_1. \quad (10)$$

The average energy consumption can be given as

$$E(DT) = e_t T. \quad (11)$$

Subsequently, the expected lifetime of the CR network can be computed as

$$ns(DT) = \frac{E_c}{E(DT)}. \quad (12)$$

C. Problem Formulation

Due to the data collection period of the CR network, only the data arrives the CUrx within n_{s_r} time slots is eligible. Other data arrival late will not be accepted. Therefore, the total achieved throughput of the CR network for the first operation type and second operation type can be given, respectively, as

$$R(SS\_DT) = TH(SS\_DT)(\mathrm{I}(ns(SS\_DT), n_{s\_r})n_{s\_r} + \mathrm{I}(n_{s\_r}, ns(SS\_DT))ns(SS\_DT)), \quad (13)$$

and

$$R(DT) = TH(DT)(\mathrm{I}(ns(DT), n_{s\_r}) n_{s\_r} + \mathrm{I}(n_{s\_r}, ns(DT)) ns(DT)), \quad (14)$$

where *I(a, b)* is defined as,

$$I(a,b) = \begin{cases} 1, & \text{if } a \geq b \\ 0, & \text{otherwise.} \end{cases} \quad (15)$$

The optimal policy of the CU operation can be determined as

$$\Theta_{opt} = \underset{\Theta \in \{SS\_DT, DT\}}{\arg\max} \left(R(\Theta) \middle| E_c, e_t, p_0, n_{s\_r} \right). \quad (16)$$

The solution of the optimization problem in Eq. (16) can be found by using numerical method [12].

In order to evaluate complexity of the proposed scheme, we mentioned that the proposed scheme needs to calculate the expected throughput of the first and second operations while the conventional scheme which just fixes the operation as the first or second one without any mathematical cost. Hence, if it is assumed that the complexity of the conventional scheme is $O(N)$, the complexity of the proposed scheme will be $O(N+2)$.

IV. SIMULATION RESULTS

In this section, we present the simulation results to prove the efficiency of the proposed scheme. The performances of the first operation type, the second operation type and the random policy are also shown for references. The random policy will randomly perform the second operation type with the probability p_0. We consider SNR of the CUtx-CUrx link as SNR_{CU} = 10 dB, and the interference of the PUtx-CUrx link will be SNR_{PU} = 10 dB.

Fig. 2 shows the total achieved throughput of the considered schemes according to the probability of absence (p_0) of the PU signal. Actually, all of the schemes have better performance when p_0 increases. It can be seen that the random policy is the worst scheme with the least total achieved throughput. On the other hand, the proposed scheme has the best performance. When p_0 is low (i.e., $p_0 \leq$ 0.4), the second operation type can obtain a higher total achieved throughput than that of the first operation type. However, when $p_0 \geq 0.4$, the first operation type obtains better performance.

Fig. 3 shows the effects of the data collection period (n_{s_r}) on the total achieved throughput of the schemes. When the CR network has a longer time to transmit data (i.e., a higher data collection period n_{s_r}), it may have chance to improve the total achieved throughput with the same capacity of battery (E_c).

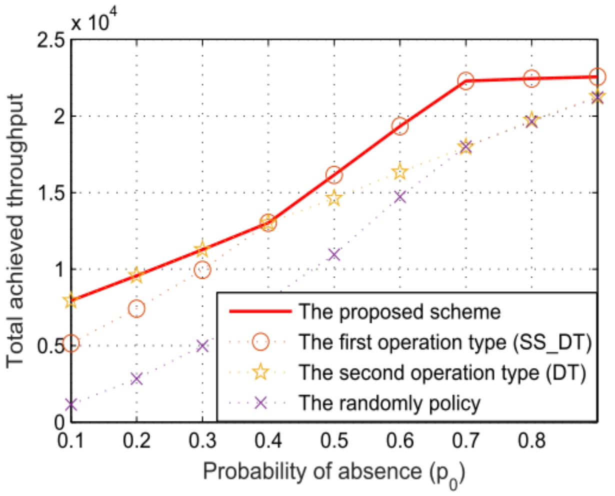

Fig. 2. Total achieved throughput versus the probability of absence (p_0) when E_c=400, e_s=1, e_t=3 and n_{s_r}= 10000.

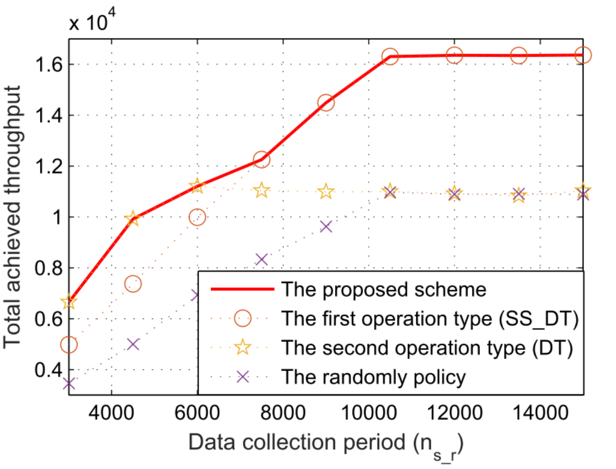

Fig. 3. Total achieved throughput versus the data collection time (n_{s_r}) when E_c=400, e_s=1, e_t=3 and p_0=0.5.

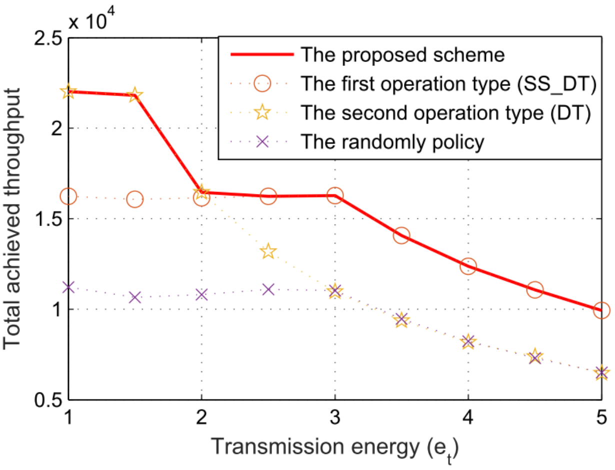

Fig. 4. Total achieved throughput versus transmission energy (e_t) when E_c=300, e_s=1, p_0=0.5 and n_{s_r}= 10000.

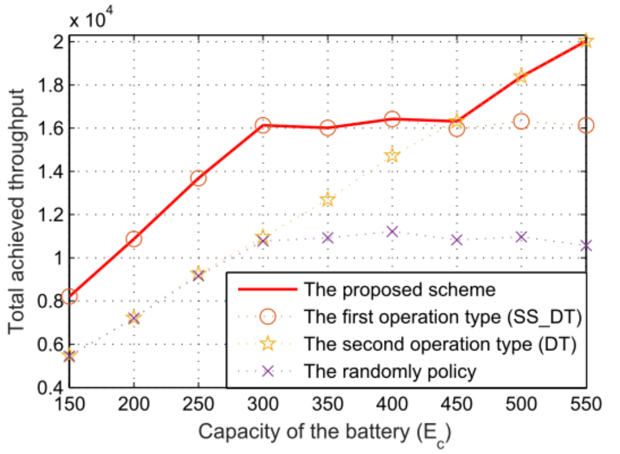

Fig. 5. Total achieved throughput versus capacity of the battery (E_c) when e_s=1, e_t=3, p_0=0.5 and n_{s_r} = 10000.

The higher n_{s_r} (i.e., $n_{s\_r} \geq 7000$) gives better performance to the first operation type in comparison with the second type. On the other hand, the second operation type obtains better performance than the first type when $n_{s\_r} < 7000$.

The relations between transmission energy (e_t) and the total achieved throughput is shown in Fig. 4. Higher transmission energy may reduce the total achieved throughput of the schemes. However, the proposed scheme always has the best performance in comparison with the other considered schemes.

The capacity of the battery (E_c) strongly effects on the performance of the schemes, which is shown in Fig. 5. A higher E_c may help the network to obtain higher throughput. Among the first and the second operation types, the first one achieves better performance when $E_c < 450$, otherwise the second one is better.

V. CONCLUSION

In this paper, we proposed a scheme to find an optimal policy for CU operation to maximize the achieved throughput in a certain data collection period of the CR network. The optimal policy can choose an operation type for the CU including sensing before transmitting data or transmitting data without sensing process. The data collection period plays a main role in switching between the first and second operation type of the CU. The proposed scheme also considers the effects of the capacity of the battery, the condition of the data channel and the probability of absence of the PU signal on the optimal policy. The simulation results shows that adaptive switching between the first and second operation type can help the proposed scheme achieve the outstanding performance.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation (NRF) of Korea funded by the MEST (No. NRF-2014R1A1A2005378).

REFERENCES

[1] Y. Hur, J. Park, W. Woo, K. Lim, C. H. Lee, H. S. Kim, and J. Laskar, “A wideband analog multi-resolution spectrum sensing (MRSS) technique for cognitive radio (CR) systems,” in *Proceedings of IEEE International Symposium on Circuit and System (ISCAS)*, Island of Kos, Greece, pp. 4090-4093, 2006.

[2] A. Sahai, N. Hoven, and R. Tandra, “Some fundamental limits on cognitive radio,” in *Proceedings of Allerton Conference on Communications, Control, and Computing*, Monticello, IL, pp. 1-11, 2004.

[3] Z. Shi, T. Tan, K. C. The, and K. H. Li, “Energy efficient cognitive radio network based on multiband sensing and spectrum sharing,” *IET Communications*, vol. 8, no. 9, pp. 1499-1507, 2014.

[4] M. Zhou and X. Zhao, “Energy-efficient power allocation algorithm in cognitive radio networks,” *IET Communications*, vol. 10, no. 17, pp. 2445-2451, 2016.

[5] S. Mao, M. H. Cheung, and V. Wong, “An optimal energy allocation algorithm for energy harvesting wireless sensor networks,” in *Proceedings of IEEE International Conference on Communications (ICC)*, Ottawa, Canada, pp. 265–270, 2012.

[6] Y. C. Liang, Y. Zeng, E. Peh, and A. T. Hoang, “Sensing-throughput tradeoff for cognitive radio networks,” *IEEE Transactions on Wireless Communications*, vol. 7, no. 4, pp. 1326-1337, 2008.

[7] A. Sultan, “Sensing and transmit energy optimization for an energy harvesting cognitive radio,” *IEEE Wireless Communications Letters*, vol. 1, no. 5, pp. 500-503, 2012.

[8] S. Park, J. Heo, B. Kim, W. Chung, H. Wang, and D. Hong, “Optimal mode selection for cognitive radio sensor networks with RF energy harvesting,” in *Proceedings of 2012 IEEE 23rd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, Sydney, Australia, pp. 2155–2159, 2012.

[9] X. Cao and X. Guo, “Partially observable Markov decision processes with reward information,” in *Proceedings of 43rd IEEE Conference on Decision and Control (CDC)*, Nassau, Bahamas, pp. 4393-4398, 2004.

[10] L. P. Kaelbling, M. L. Littman, and A. R. Cassandra, “Planning and acting in partially observable stochastic domains,” *Artificial Intelligence*, vol. 101, no. 1, pp. 99-134, 1998.

[11] J. Ma and Y. Li, “Soft combination and detection for cooperative spectrum sensing in cognitive radio networks,” in *Proceedings of IEEE Global Telecommunications Conference (GLOBECOM)*, Washington, DC, pp. 3139-3143, 2007.

[12] D. P. Bertsekas, *Dynamic Programming and Optimal Control*, 2nd ed. Belmont, MA: Athena Scientific, 2001.

Van-Hiep Vu
received the B.E. degree in Electronics & Telecommunications Engineering from Ton Duc Thang University, Vietnam in 2005 and the bachelor's degree in Business Administration from University of Economy Ho Chi Minh City, Vietnam in 2007. He received Ph.D. degree in Electrical Engineering from the University of Ulsan (UOU), Korea, in 2013, where he is now research fellow. His current research interests include cognitive radio and next generation wireless communication systems.

Insoo Koo
received his B.E. degree from Konkuk University, Seoul, Korea, in 1996, and his M.S. and Ph.D. degrees from Gwangju Institute of Science and Technology (GIST), Gwangju, Korea, in 1998 and 2002, respectively. From 2002 to 2004, he worked with the Ultrafast Fiber-Optic Networks (UFON) Research Center in GIST, as a research professor. For one year from September 2003, he was a visiting scholar at the Royal Institute of Science and Technology, Sweden. In 2005, he joined the University of Ulsan, where he is now a full professor. His research interests include next-generation wireless communication systems and wireless sensor networks.