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Optimal Sensing and Transmission of Energy Efficient Cognitive Radio Networks

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Abstract

The issue of spectrum scarcity can be alleviated by the cognitive radio technology with efficient spectrum sensing and allocation of free spectrum bands. In Cognitive Radio Networks energy efficiency improvement is the state of art now days. This paper considers the case of primary user protection from cognitive user transmission to optimize the energy efficiency. The parameters of optimal design problem are sensing, transmission time and transmission power. A Sub Optimal Iterative Search Algorithm is proposed to maximize efficiency by optimizing sensing time and transmitting time. Simulation results exhibits substantial improvement in energy efficiency compared to the recent algorithms.

Keywords Cognitive radio networks · Sensing time · Transmission time · Transmission power · Energy efficiency

1 Introduction

Cognitive Radio solves the spectrum paucity problem, by opportunistic transmission and dynamic spectrum allocation scheme [1]. In Cognitive Radio Networks (CRNs) Cognitive User (CU) utilizes the licensed spectrum dynamically if the spectrum is temporally vacant [2]. In the spectrum sensing CU detects the primary user's (PU) presence or absence and accordingly access the vacant spectrum of PU. If the presence of the PU is detected, SU should postpone its transmissions. In practical CRNs, energy efficiency (EE) concept is very essential. Both sensing and transmission time exhibit a great impact on the EE of CRNs. An increased transmission time increases the throughput but it also enhanced

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interference to PU and loss probability of data. Also, increased sensing time results in high consumption of energy but improved detection accuracy. However, if sensing time is too short, it will give high false alarm probability [3, 4]. In this paper single node CRN is considered. Many techniques for the sensing and detection are available in the research. It may be classified as energy detection, matched-filter detection, detection based on cyclostationarity, waveform based detection, covariance, Eigen value, wavelet and spectral estimation. Among all the above given methods energy detection is often used due to its less complexity and non prior information type detection [5–8].

Some latest researchers are working on the EE in CRNs. In, [9] the transmission time and sensing time both are optimized separately. In [10, 11], author proposed optimum sensing time and transmission time in frequency—flat fading environment. In [12], sub optimal algorithm is proposed to get the optimum sensor. In [13] authors reflected the joint optimization of sensing time and transmission power to improve EE. Literature [14] [15], optimize either the detection threshold or sensing time to maximize EE. Many researchers have focused on the optimization of either the transmission parameter or the sensing parameter to improve the throughput of the CRNs [16–19].

Based upon the inspiration of past research, this paper jointly optimizes the transmission power, sensing time and transmission time considering single CR user environment. Here, sensing time and transmission time are considered as the variables of the problem. One of the CR quality metrics, false alarm probability has also been taken into account. Further interference to the PU by the CU is also considered. The optimal transmission time, sensing time and sensing power with respect to energy efficiency is exhibited. The main features of this paper are as follows:

Energy efficiency is maximized with respect to sensing time by calculating optimal sensing time mathematically. Afterwards, transmission time is optimized and the optimized value of transmitting time is calculated. Lastly, proposed algorithm is applied to get the maximized EE by using the above optimized sensing and transmission time.

The organization of paper is given as follows:

The system model of single PU and single CU is shown in Sect. 2. The problem formulation is given in Sect. 3 and its solution in Sect. 4. Results, their interpretation & comparisons are presented in Sect. 5. Conclusions and future scope of the paper are summarized in the Sect. 6.

2 System Model

In this paper, single PU and single CU cognitive radio network is considered, which indicates that only one secondary/cognitive node is used to detect presence or absence of PU. The time frame of this network includes sensing time and transmission time. For the duration T, SU node will detect availability of PU channel. Here, the time frame T is given by, $T = t_s + t_{tr}$, where, t_s and t_{tr} are the sensing time and transmission time, respectively. After each time frame T, the presence or absence of PU is detected and accordingly PU channel is occupied by the CU. However, during CU transmission, the channel can be reoccupied by the PU again causing interference to the CU signal. Hence, the interference resulted by PU reoccupation has also been taken into account. The probability of PU interference during the CU transmission time t_{tr}, can be given by the following equation [20]:

$$P_I(t_{tr}) = 1 - \exp\left(\frac{-t_{tr}}{a_0}\right) \tag{1}$$

where, P_I is the interference probability, a_1 and a_0 are the mean values of busy and idle time of PU signal which is exponentially distributed.

The probability density functions of PU occupied and vacant channels are expressed as $x_1(t)$ and $x_0(t)$ and given by the following equations, respectively:

$$x_1(t) = \frac{1}{a_1} \exp\left(-\frac{t}{a_1}\right) u(t) \tag{2}$$

$$x_0(t) = \frac{1}{a_0} \exp\left(-\frac{t}{a_0}\right) u(t) \tag{3}$$

Based upon the busy time and idle time the respective probability of PU busy and idle state can be given by:

$$P_{bu} = \frac{a_0}{(a_0 + a_1)} \tag{4}$$

$$P_{id} = \frac{a_1}{(a_0 + a_1)} \tag{5}$$

The quality metrics in cognitive radio can be specified by two types of probabilities: *Probability-of-false alarm*, *Probability-of-detection*, denoted as $P_f(t_s)$ and $P_d(t_s)$ respectively. These two probabilities depend upon the sensing time and detection threshold. Here, in this paper we assume detection threshold as implicit variable. Now, as per detection of PU signal by the CU, four scenarios can be considered. First, the probability of correct detection of PU signals absence, $P_{id}(1 - P_f(t_s))$. This means correct detection of vacant PU channel. Second, the probability of correct detection of PU signals presence, $P_{bu}P_d(t_s)$. This gives the correct detection of occupied PU channel. Third, the probability of wrong detection of PU absence, $P_{id}P_f(t_s)$. This implies the false detection of PU idle state. In the fourth scenario busy state of PU signal is falsely detected & the probability is given as $P_{bu}(1 - P_d(t_s))$. In the first case the probability that PU signal again uses the channel along with the transmission of CU is already given in Eq. (1). However, other definition of PU interference is also given in the literature [21]. In the scenario second and fourth, there is no CU data transmission exists and hence there is no interference produced on PU transmission.

3 Problem Formulation

The main objective of this paper is to optimize the sensing time and transmission time to increase the number of bits transmitted per frame so as to achieve maximum energy efficiency. This problem also considers the interference occurred due to PU signal to CU transmission. Also, the EE with respect to transmission power is shown by the graphs. Here, in this part, first the total energy consumed is calculated and then the total number of bits transmitted.

3.1 Energy Consumed

The total energy consumed is calculated depending upon the total power for a given time. In this model, the sensing power and transmitting power are considered for the duration of t_s and t_{tr}.

The total energy consumption can be calculated for the four scenarios within a time frame. It is shown as follows:

$$E_T = P_s t_s + P_t t_{tr}\left(P_{id}\left(1 - P_f\left(t_s\right)\right) + P_{bu}\left(1 - P_d\left(t_s\right)\right)\right) \tag{6}$$

where E_T is the total energy consumed, P_s and P_t are the sensing power and transmission power respectively.

3.2 Total Throughput

In this model, Additive White Gaussian Noise (AWGN) channel is considered, hence the total number of bits transmitted for duration of t_{tr} is given by $t_{tr}R$. Considering the four scenarios, successful data transmission can be occurred in the first scenario only if PU does not return again. In this model, whole frame is to be transmitted for a successful transmission.

The total throughput of the CR system:

$$R_T = RP_{bu}t_{tr}\left(1 - P_f\left(t_s\right)\right)\left(1 - P_I\left(t_{tr}\right)\right) \tag{7}$$

3.3 Energy Efficiency

The energy efficiency (EE) of the single CRN can be calculated as follows [22, 23]:

Energy Efficiency (EE) = Total throughput/Energy consumed

$$\zeta = \frac{R_T}{E_T} = \frac{RP_{bu}t_{tr}\left(1 - P_f\left(t_s\right)\right)\left(1 - P_I\left(t_{tr}\right)\right)}{P_s t_s + P_t t_{tr}\left(P_{id}\left(1 - P_f\left(t_s\right)\right) + P_{bu}\left(1 - P_d\left(t_s\right)\right)\right)} \tag{8}$$

where ζ is the energy efficiency, R_T is the total throughput and E_T is total energy consumed. To maximize EE, the problem for optimal sensing time and transmission time with varying transmission power can be formulated as:

$$\begin{aligned} &\max.\ \zeta_{\text{Power}}(t_s, t_{tr}) \\ &s.t.\ t_{s0} \le t_s \le t_{s1} \\ &t_{tr0} \le t_{tr} \le t_{tr1} \\ &P_d\left(t_s\right) \ge P_{d0} \\ &P_I\left(t_{tr}\right) \le \alpha_1 \end{aligned} \tag{9}$$

where P_{d0} is set to 0.9 as the target *Probability-of-detection*, considering IEEE 802.22 standard and α_1 is the maximum interference level that occur in case of mis-detection, to the PU by the transmission of CU. The *Probability-of -false alarm* for the energy detection based sensing can be defined as:

$$P_f\left(t_s\right) = Q\left(\sqrt{\left(2\gamma_{pu} + 1\right)}Q^{-1}\left(P_{d0}\right) + \gamma_{pu}\sqrt{t_s f_s}\right) \tag{10}$$

where f_s is the sampling frequency and γ_{pu} is the PU SNR due to CU data transmission. If we increase the sensing time then $P_f\left(t_s\right)$ will decrease. Therefore, to make $P_f\left(t_s\right)<0.5$, the sensing time must satisfy the condition of $t_s>(\frac{Q^{-1}(P_{d0})(\sqrt{(2\gamma_{pu}+1)}}{\gamma_{pu}\sqrt{f_s}})^2$. Hence, the lower limit for sensing time will be $t_{s0}=(\frac{Q^{-1}(P_{d0})(\sqrt{(2\gamma_{pu}+1)}}{\gamma_{pu}\sqrt{f_s}})^2$. Next, for the transmission time, the lower and upper limits can be calculated based upon the interference constraint α_0. Hence, to fulfill this requirement the transmission time can be maximized as $t_{tr1}=-a_0\log\left(1-\alpha_1\right)$.

Now, the EE maximization problem can be rewritten as:

$$\begin{aligned} &\max.\ \zeta_{\text{Power}}(t_s,t_{tr}) \\ &\text{s.t.}\ t_{s0}\le t_s\le t_{s1} \\ &t_{tr0}\le t_{tr}\le t_{tr1} \end{aligned} \tag{11}$$

4 Solution of the Problem

In the preceding part of the paper, we suggest the solution of the stated problem given in Sect. 3. The main parameters for the considered problem are, sensing time, transmission time and transmitting power. To solve the maximization problem first the relationship of energy and time is formed and then the problem is solved. The values of sensing and transmission time to maximize EE are calculated and then iterative optimal algorithm is proposed.

Step 1 Take the partial differentiation of $\zeta_{\text{Power}}\ (t_s,t_{tr})$ with respect to t_s and put it to zero keeping fix t_{tr}.

$$\frac{\partial}{\partial\left(t_s\right)}\left(\zeta\left(t_{tr},t_s\right)\right)=\frac{\partial}{\partial\left(t_s\right)}\left(\frac{RP_{bu}t_{tr}\left(1-P_f\left(t_s\right)\right)\left(1-P_I\left(t_{tr}\right)\right)}{P_st_s+P_tt_{tr}\left(P_{id}\left(1-P_f\left(t_s\right)\right)+P_{bu}\left(1-P_d\left(t_s\right)\right)\right)}\right)=0 \tag{12}$$

Let us take $P_f(t_s)$ as P_f, $P_d\left(t_s\right)$ as P_d and $P_I\left(t_{tr}\right)$ as P_I for simplicity in Eq. (12). Now, the above equation is equivalent to:

$$\begin{aligned} P_sP_f-\left[t_{tr}P_{id}\left(1-P_d\right)P_t+P_st_s\right]P_f'-P_s=0 \\ t_s^{opt}=-\frac{1}{P_f'}-\frac{t_{tr}P_{id}\left(1-P_d\right)P_t}{P_s}+\frac{P_f}{P_f'} \end{aligned} \tag{13}$$

The derivative of *Probability-of -false alarm* in the Eq. (13) $P_f'\left(t_s\right)$ can be expressed as:

$$P_f'\left(t_s\right)=-\frac{1}{\sqrt{2\pi}}\frac{\gamma_{pu}\sqrt{f_s}}{2\sqrt{t_s}}\exp\left[-\frac{1}{2}(Q^{-1}(P_{d0})\left(\sqrt{\left(2\gamma_{pu}+1\right)}+\gamma_{pu}\sqrt{t_sf_s}\right)\right] \tag{14}$$

Here, for the range of sensing time $t_{s0}\le t_s\le t_{s1}$ $P_f\left(t_s\right)$ is decreasing and $P_f'\left(t_s\right)$ is increasing and negative, therefore $P_f\left(t_s\right)$ is convex function and $P_f''\left(t_s\right)$ is positive [9].

Step 2 Take the partial differentiation of $\zeta_{\mathrm{Power}}\left(t_s, t_{tr}\right)$ with respect to t_{tr} and put it to zero keeping fix t_s:

$$\frac{\partial}{\partial\left(t_{tr}\right)}\left(\zeta\left(t_{tr}, t_s\right)\right)=\frac{\partial}{\partial\left(t_{tr}\right)}\left(\frac{RP_{bu}t_{tr}\left(1-P_f\right)\left(1-P_I\right)}{P_st_s+P_tt_{tr}\left(P_{id}\left(1-P_f\right)+P_{bu}\left(1-P_d\right)\right)}\right)=0$$

$$\frac{RP_{id}\left(1-P_f\right)\exp\left(-\frac{t_{tr}}{a_0}\right)\left[-(P_{id}\left(1-P_f\right)+P_{bu}\left(1-P_d\right))P_tt_{tr}^2-P_st_st_{tr}+a_0P_st_s\right]}{a_0\left(P_st_s+\left(P_{id}\left(1-P_f\right)+P_{bu}\left(1-P_d\right)\right)P_tt_{tr}\right)^2}=0 \tag{15}$$

By solving the Eq. (15), we get:

$$t_{tr}^{opt}=\frac{P_st_s-\sqrt{P_s^2t_s^2+4a_0P_tP_s\left[P_{id}\left(1-P_f\right)+P_{bu}\left(1-P_d\right)\right]t_s}}{-2P_t\left[P_{id}\left(1-P_f\right)+P_{bu}\left(1-P_d\right)\right]} \tag{16}$$

Equation (16) gives the optimum value of transmission time. Here, for the range of $0<t_{tr}<t_{tr}^{opt}$, the EE shows a unique ζ_{max} value. If we further increase the value of transmission time, say, $t_{tr}>t_{tr}^{opt}$ then $\frac{\partial}{\partial\left(t_{tr}\right)}\left(\zeta\left(t_{tr}, t_s\right)\right)<0$, hence for the range of $0<t_{tr}<t_{tr}^{opt}$, $\zeta\left(t_{tr}, t_s\right)$ has a unique maximum value for each fixed t_s.

Step 3 Optimization Algorithm

An iterative algorithm is proposed to maximize the energy efficiency by calculating the optimization problem. Energy efficiency can be calculated by using this algorithm. Here, in this Sub Optimal Iterative Search Algorithm (SOISA), EE, sensing time and transmission time are represented as $\zeta(k)$, $t_s(k)$ and t_{tr} (k) for kth iteration. For the initialization purpose, let EE, transmitting & sensing time are considered as zero. In this algorithm, the EE is calculated by Eq. (8). Afterwards, the iteration will start with k + 1. If the difference of (k + 1) th iteration and kth iteration is less than ΔE then the iteration process will stop. Herein, ΔE is pre decided fix value.

The *pseudo-code* for SOISA is shown below:

Algorithm: SOISA algorithm

```
Initialize: k=0, $\zeta(0)$=0, $t_s(0) = (\frac{Q^{-1}(P_{d0})(\sqrt{(2\gamma_{pu}+1)}}{\gamma_{pu}\sqrt{f_s}})^2$, ΔE
    $t_{tr}(0) = 0$, diff = infinite.
While diff >= ΔE.
Set k = k+1.
Compute $t_{tr}(k)$ by using equation (16) with $t_s(k-1)$.
Calculate $t_s(k)$ using (13) with $t_{tr}(k)$ calculated above.
Get $\zeta(k)$ using (8) with $t_s(k)$ and $t_{tr}(k)$ .
diff = $\zeta(t_s(k+1), t_{tr}(k+1))$ - $\zeta(t_s(k), t_{tr}(k))$
Output $\zeta(k)$, $t_s(k)$ and$t_{tr}(k)$.
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5 Results and Discussion

In this section the simulation results obtained after simulation in MATLAB software are shown and have been illustrated through figures. In this research paper many parameters have been considered in the mathematical representation. The parameters used for simulation are shown in Table 1.

Figure 1 depicts the effect of change in transmission power for the SOISA on EE. It can be observed that when transmission power is increased the EE will decrease. For the transmission power (P_t) taken to be 0.1 W, the EE (ζ) is 11.9321 Bits/Hz/Joule. Further increase in transmission power results in very low EE. The reason of this effect is, larger transmission power results in larger loss of throughput because of false alarm. That increases the consumed energy for a longer sensing time.

Figure 2 shows the improvement of the proposed SOISA over exhaustive search method and sub optimal algorithm [10]. In this figure it is shown that at a fix transmission power the EE for the proposed algorithm is highest among all. For a transmission power of P_t=0.1 W the EE for SOISA is 11.9321 W while for exhaustive and sub optimal algorithm it is 7.5092 and 6.5285 respectively. The algorithm gives the optimal values for sensing, transmission time and accordingly EE as 0.0030 s, 0.0749 s and 11.9321 Bits/Hz/Joule respectively. The number of iterations required for the proposed algorithm is, 3 whereas for the sub optimal algorithm number of iteration required is, 5.

Figure 3 exhibits the response of sensing time on the EE for three different values of transmission time. Here, it can be analysed that the EE is maximum for t_{tr}=0.06 s and t_s=0.002 s.

Table 1 Simulation parameters

Parameters	P_{d0}	α_q	P_s	R_0	a_0	a_1	B	γ_{pu}
Values	0.9	0.1	0.11 W	10 Mbps	0.65 s	0.35 s	6 MHz	– 20 dB

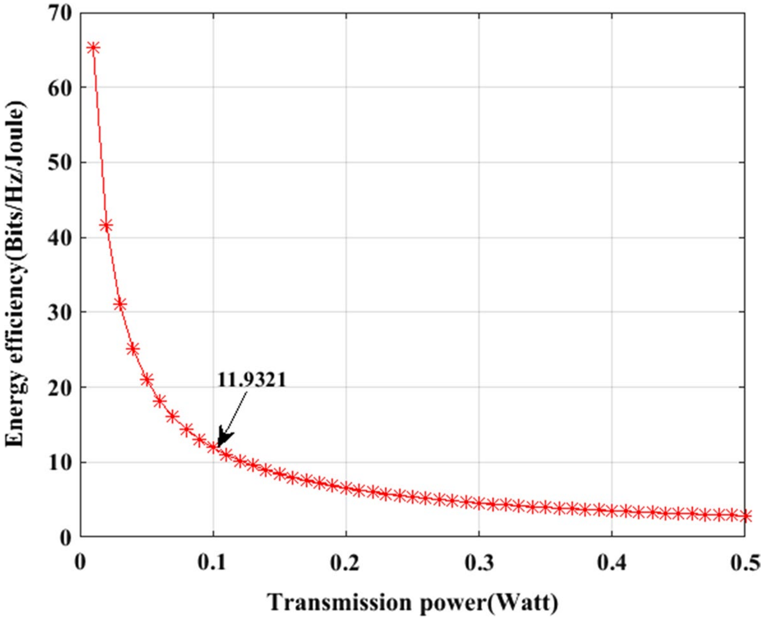

Fig. 1 Energy efficiency versus transmission power for the proposed SOISA algorithm

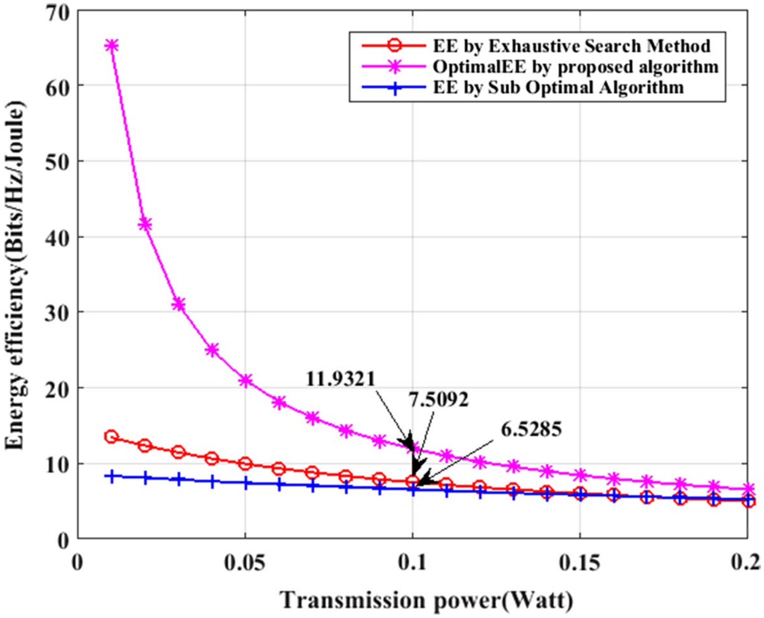

Fig. 2 Comparison of proposed SOISA algorithm with previous algorithms

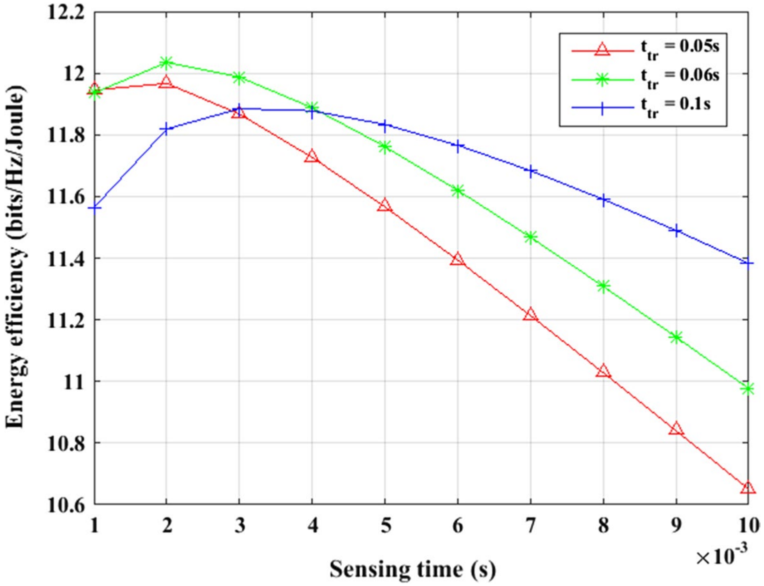

Fig. 3 Energy Efficiency versus sensing time for different transmission times

Initially increase in sensing time results in increase in EE but after the optimal value it starts decreasing. Similarly, EE versus transmission time is shown in Fig. 4. This figure shows that increase in transmission time give rise in EE but after optimal transmission time EE falls

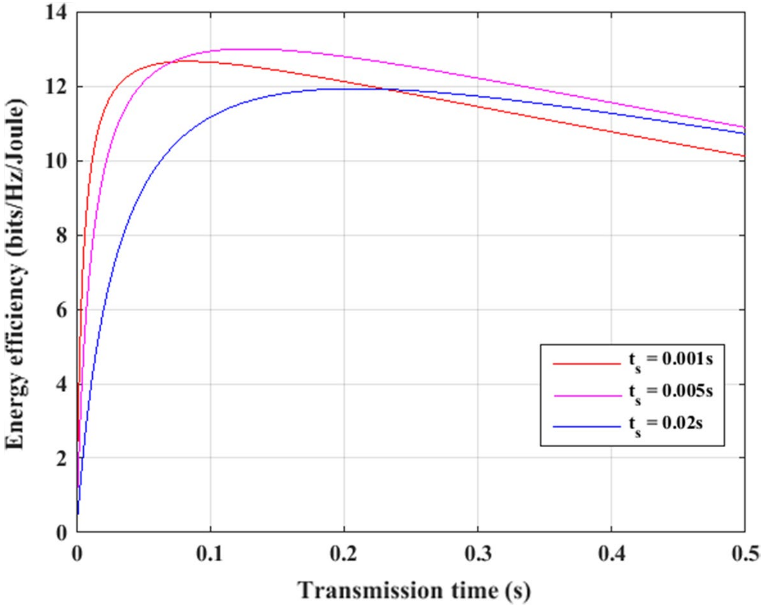

Fig. 4 Energy Efficiency versus transmission time for different sensing times

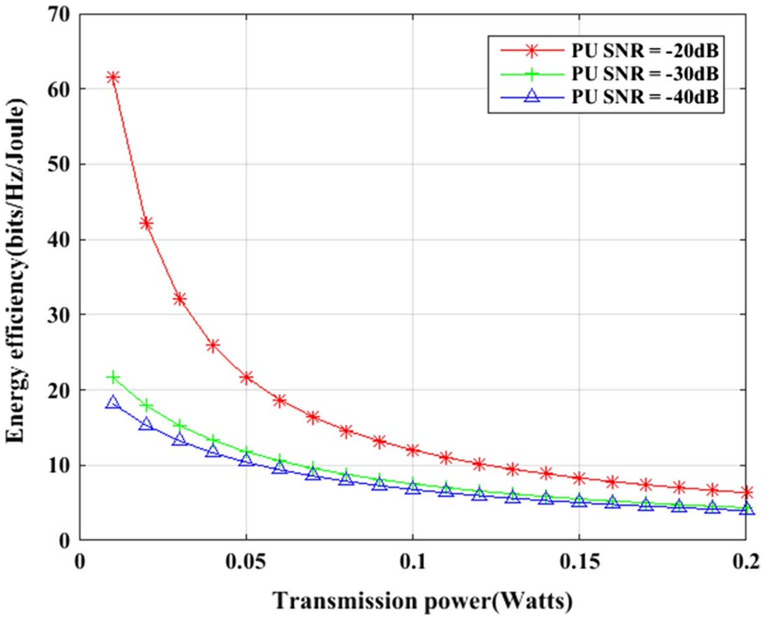

Fig. 5 Energy Efficiency versus transmission power for different signal to noise ratio conditions

rapidly. The three sensing time are taken as 0.001 s, 0.005 s and 0.02 s. Figure 5 indicates the EE plot against transmission power for three different PU SNR conditions. It is observed that decrease in PU SNR largely affects the EE. In this paper PU SNR is considered as −20 dB. Low PU SNR results in poor energy efficiency.

6 Conclusions

The joint optimization of sensing and transmission time for energy efficiency in cognitive radio networks CRNs is represented. A single PU and single CU model to improve EE is considered. The protection of PU from the SU transmission is also taken into account. Simulation results show that for a unique point of both sensing and transmission durations energy efficiency is maximised under the constraint of PU interference probability. Hence, the proposed algorithm shows superiority over sub optimal algorithm and exhaustive search method and outperforms both in terms of efficiency and complexity.

References

1. Mitola, J., & Maguire, G. Q. (1999). Cognitive radio: making software radios more personal. *IEEE Personal Communication Magazine, 6*(4), 13–18.
2. Kaur, K., Rattan, M., & Patterh, M. S. (2013). Optimization of cognitive radio system using simulated annealing. *Wireless Personal Communications, 71*(2), 1283–1296.
3. Zhao, N., Li, S., & Wu, Z. (2012). Cognitive radio engine design based on ant colony optimization. *Wireless Personal Communications, 65*(1), 15–24.

4. Awasthi, M., Kumar, V., & Nigam, M. J. (2017). Energy—efficiency techniques in cooperative spectrum sensing: A survey. *Proceedings of IEEE Computational Intelligence and Communication Technology (CICT)*. https://doi.org/10.1109/CIACT.2017.7977341.
5. Lundén, J., Koivunen, V., & Poor, H. (2015). Spectrum exploration & exploitation for cognitive radio [Recent advances]. *IEEE Signal Processing Magazines*. https://doi.org/10.1109/MSP.2014.2338894.
6. Sharma, S. K., Bogale, T. E., Chatzinotas, S., Ottersten, B., et al. (2015). Cognitive radio techniques under practical imperfections: A survey. *IEEE Communication Surveys & Tutorials, 17*(4), 1858–1884.
7. Haykin, S. (2005). Cognitive radio: Brain-empowered wireless communications. *IEEE Journal on Selected Areas in Communications, 23*(2), 201–220.
8. Lu, L., Zhou, X., Onunkwo, U., & Li, G. Y. (2012). Ten years of research in spectrum sensing and sharing in cognitive radio. *EURASIP Journals on Wireless Communication and Networking, 28,* 1–16.
9. Wu, Y., & Tsang, D. H. K. (2011). Energy-efficient spectrum sensing and transmission for cognitive radio system. *IEEE Communication Letters, 15*(5), 545–547.
10. Shi, Z., Teh, K. C., & Li, K. H. (2013). Energy-efficient joint design of sensing and transmission durations for protection of primary user in cognitive radio systems. *IEEE Communication Letters, 17*(3), 565–568.
11. Awasthi, M., Nigam, M. J., & Kumar, V. (2017). Energy efficient hard decision fusion rules for fading and non-fading environment. In *proceedings of the 2017 IEEE Region 10 Conference (TENCON)*, Malaysia, 2056-2060. https://doi.org/10.1109/tencon.2017.8228199.
12. Monemian, M., Mahdavi, M., & Omidi, M. J. (2016). Optimum sensor selection based on energy constraints in cooperative spectrum sensing for cognitive radio networks. *IEEE Sensors Journal, 16*(6), 1829–1841.
13. Awin, F. A., Abdel-Raheem, E., & Ahmadi, M. (2017). Joint optimal transmission power and sensing time for energy efficient spectrum sensing in cognitive radio networks. *IEEE Sensors Journal, 17*(2), 369–376.
14. Ergul, O., & Akan, O. B. (2013). Energy-efficient cooperative spectrum sensing for cognitive radio sensor networks. In *IEEE symposium of computer and communication (ISCC)* (pp. 465–469).
15. Peh, E. C. Y., Liang, Y. C., Guan, Y. L., & Pei, Y. (2011). Energy-efficient cooperative spectrum sensing in cognitive radio networks. In *IEEE global telecommunications conference (GLOBECOM 2011)*, IEEE.
16. Wang, Y., Xu, W., Yang, K., & Lin, J. (2012). Optimal energy-efficient power allocation for OFDM-based cognitive radio networks. *IEEE Communication Letters, 16*(9), 1420–1423.
17. Haddad, M., Hayel, Y., & Habachi, O. (2015). Spectrum coordination in energy-efficient cognitive radio networks. *IEEE Transaction on Vehicular Technology, 64*(5), 2112–2122.
18. Awin, F. A., Abdel-Raheem, E., & Ahmadi, M. (2016). Designing an optimal energy efficient cluster-based spectrum sensing for cognitive radio networks. *IEEE Communications Letters, 20*(9), 1884–1887.
19. Hojjati, S. H., Ebrahimzadeh, A., Najimi, M., & Reihanian, A. (2016). Sensor selection for cooperative spectrum sensing in multi antenna sensor networks based on convex optimization and genetic algorithm. *IEEE Sensors Journal, 16*(10), 3486–3487.
20. Li, L., Zhou, X., Xu, H., Li, Y., et al. (2011). Energy-efficient transmission in cognitive radio networks. *IEEE Transactions on Broadcasting, 57*(3), 718–720.
21. Zarrin, S., & Teng, J. L. (2011). Throughput-sensing trade off of cognitive radio networks based on quickest sensing. In *Proceedings of IEEE international conference on communications* (pp. 1–5).
22. Pei, Y., Liang, Y. C., Teh, K. C., & Li, K. H. (2011). 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 Communication, 29*(8), 1648–1659.
23. Awasthi, M., Nigam, M. J., & Kumar, V. (2019). Optimal sensing, fusion and transmission with primary user protection for energy-efficient cooperative spectrum sensing in CRNs. *International Journal of Electronics and Communication (AEU), 98*(2019), 95–105.

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