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Throughput Optimization of Parallel Sensing and Energy Harvesting Cognitive Radio Network

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ABSTRACT

In cognitive radio, throughput of secondary user (SU) will depend on spectrum sensing performance and available power of secondary user to transmits data. As the secondary user dissipates energy for spectrum sensing operation and to maintain cooperation among multiple SUs can results in reduction of transmission power. To compensate this energy, an energy harvesting technique has introduced in cognitive radio by which SU can harvest energy from primary (PU) signal and this harvested energy will be utilized to transmit its data and increases the lifetime. In a traditional Energy Harvesting Cognitive Radio Network (EHCRN), SU can perform sensing and harvesting in separate slots which decrease the transmission time of secondary user results in reduction in throughput. To enhance the throughput of secondary user, a parallel operation of spectrum sensing and energy harvesting has been discussed. This parallel operation results in reduction of energy consumption and increases harvested energy that makes more energy to be available for transmission, which results in an increase of SU throughput. Simulation results using MATLAB shows that the proposed Parallel Sensing and Energy Harvesting CRN have improved the throughput compared to Traditional Energy Harvesting CRN and are analyzed with different parameters.

1. INTRODUCTION

CRN nodes can be classified as primary (licensed) users (PUs) and secondary (cognitive or unlicensed) users (SUs). PU has absolute liberty to access the particular licensed spectrum band, whereas SU detects unutilized chunks of spectrum momentarily through its PU and opportunistically utilize them [1]. CRN enables unlicensed users for exploiting the spatially and/or temporally under-utilized spectrum by communicating over the licensed bands. CRNs is an overlay network with dynamic spectrum access where SU should have spectrum sensing capability for sensing whether there is presence of PU before transmission, thereby provide spectrum efficiency and improves network performance [2].

Spectrum sensing is a procedure of identifying the unused spectrum portions by continuous monitoring of primary user and make use of the free spectrum by unlicensed users. During the data transmission, unlicensed user senses the licensed user continuously. If the presence of licensed user is noticed, CR must free up the transmission to minimize the interference to PU [3]. The performance of sensing is affected by probability of false alarm and probability of detection. Spectrum efficiency is improved by lowering the probability of false alarm and increasing probability of detection. Energy detection is an optimum choice of spectrum sensing if the prior knowledge of PU is not available. If a severe fading occurs, the performance of energy detection reduces. Hence, to increase the spectrum sensing efficiency a cooperative spectrum sensing technique has been introduced which permits number of SUs to detect the presence of PU and transmits data to a fusion centre to make a collective decision [4, 5]. There is an agreement between throughput of SU and sensing time, SU throughput maximizes at on optimum sensing time [6]. Spectrum efficiency is upgraded by involving cooperative spectrum sensing [7].

The SU transmission efficiency is affected by energy of SUs. Energy harvesting technique has introduced to enhance the transmission efficiency of SU. When the PU transmission is in progress, SU will harvest the energy [8]. SU can harvest the RF energy from the PU signal when it transmits its data [9-12]. By jointly distributing transmission power and time, SUs energy consumption of SU can be minimized.

The mentioned contributions are listed in the paper:

• An energy-harvesting supported CRN mode has analyzed, which can divide the frame structure of CRs into three sections, sensing, harvesting and data transmission. Transmission energy of SU is increased by harvested energy and hence throughput of SU is enhanced.

• An energy-harvesting supported CRN with parallel action of spectrum sensing and energy harvesting namely Parallel Sensing and Energy Harvesting CRN (PSEHCRN) has proposed.

The remaining paper contributions are as mentioned: section 2 investigates spectrum utilization of SU and the circuit of an energy-harvesting model. In section 3, frame structure of energy harvesting based CRN with energy detection is described; section 4 describes the optimization of spectrum sensing and energy harvesting through parallel functioning. Experimental results will explain in section 5 and section 6 describes the conclusion.

2. SPECTRUM UTILIZATION OF CR USER

CR user is used to continuously monitor the presence of PU and only utilizes the spectrum during free portions to transmit its data. If the PU reappears again, SU has to quit its transmission in order to avoid any harmful interference to the PU transmission as given in Figure 1.

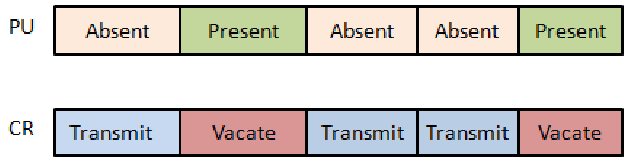

Figure 1. Spectrum utilization of CR user

The busy state and idle state of PU is modelled with probabilities given below Eq. (1) [13]:

$$P_B(t) = \frac{1}{a} exp^{-\frac{t}{a}}; P_I(t) = \frac{1}{b} exp^{-\frac{t}{b}} \quad (1)$$

where, *a* and *b* are average values presence and absence of PU respectively.

If the PU spectrum is free, SU can make its transmition. In some cases PU again reappears in the spectrum with probability P_r during transmission time T_r and given in Eq. (2):

$$P_r = \int_0^{T_r} P_I(t)dt = 1 - exp^{-\frac{T_r}{b}} \quad (2)$$

2.1 Model of energy harvesting

RF systems will support to transmit energy from one point to another. The generated RF power from the base station is transmits through the channel and harvest the energy at the harvesting node. The energy harvesting process is shown in Figure 2. An energy harvesting circuit consists of SU base station, band pass filer, rectifier and LPF. The BPF is used to filter RF signal to the correct frequency. Rectifier transforms the RF signal to DC signal. DC power is derived by passing DC signal through low pass filter and is reserved in battery [14].

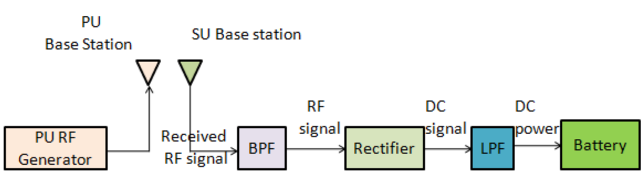

Figure 2. Process of energy harvesting

For diode rectifier, diode will conduct in reverse direction for voltage less than reverse break down voltage Vbr. The voltage across diode V_o in terms of reverse break down voltage is given in Eq. (3):

$$V_o = \frac{V_{br}}{2} \quad (3)$$

The maximum dc power P_{DCmax} is given by Eq. (4):

$$P_{DCmax} = \frac{V_{br}^2}{4R_L} \quad (4)$$

where, R_L is load resistance.

The DC power P_{outDC} across R_L is given in Eq. (5):

$$P_{outDC} = \frac{V_{outDC}^2}{R_L} \quad (5)$$

where, the V_{outDC} is DC output voltage across R_L.

Energy harvester efficiency ϑ is given by Eq. (6), where P_{inEH} is input power of harvester:

$$\vartheta = \frac{P_{outDC}}{P_{inEH}} \quad (6)$$

3. FRAME STRUCTURE OF ENERGY HARVESTING BASED CR

3.1 Traditional frame structure CR

Traditional cognitive radio user performs spectrum sensing and data transmission. The process of making use of the spectrum whenever the user required is mentioned as dynamic spectrum access (DSA) which improves the channel efficiency. Traditional cognitive radio frame structure consists of two slots, sensing slot and transmission slot [15]. Frame structure of CR user of T duration as given in Figure 3. In sensing slot CR user senses the existence of PU for the duration of τ. If PU is not utilizing spectrum then SU can transmits its data during transmission slot for the period of (T-τ).

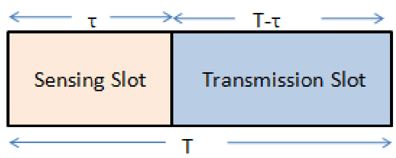

Figure 3. Frame structure CR user

3.2 Energy harvesting cognitive radio network

Spectrum scarcity is the major problem of wireless communications; it can be overcome by cognitive radio networks. Data transmission of SU depends on sensing performance, which depends on sensing parameters and residual energy of SU [16]. Energy harvesting cognitive radio networks (EHCRN) will improve the residual energy of SU will guarantee the SU data transmission [17].

Frame structure of EHCRN consists of three slots: sensing slot, harvesting slot and data transmission slot is mentioned in Figure 4. SU senses the presence of PU in sensing slot and harvests energy from PU RF energy in harvesting slot. If spectrum is free, SU will make its transmission during the data transmission slot [18, 19].

If the duration of frame is T, the sensing time slot is τ and the harvesting time slot is $\tau 1$. Then data transmission time slot is $Td = T - \tau - \tau 1$.

Spectrum sensing is performed by energy detection, which does not require any priori knowledge of PU. The process of energy detection is described in the following Figure 5.

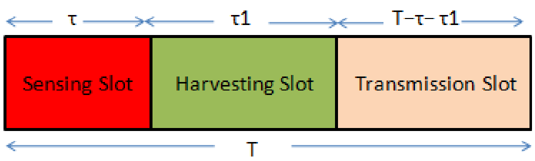

Figure 4. Traditional frame structure of EHCRN

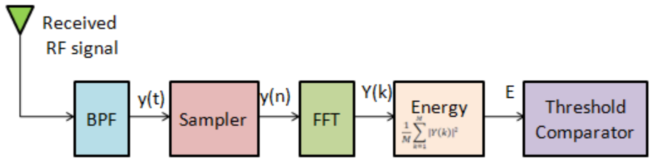

Figure 5. Energy detection process

The collected signal by antenna is passed by BPF then through the sampler with sampling frequency f_s to obtain the samples $y(n)$. The $y(n)$ Discrete Fourier Transform values $Y(k)$ are calculated by FFT. The energy E of PU can be calculated by summing the squared magnitude of $Y(k)$ and is compared in threshold comparator with a value λ.

If $E \geq \lambda$, the PU is present and is denoted by H_1 with probability $P(H_1)$, if not absent of PU is detected and is denoted with H_0 with probability $P(H_0)$.

The detected signal $y(n)$ is processed with binary hypothesis as in Eq. (7):

$$y(n) = \begin{cases} w(n), H_0 \\ h(n)x(n) + w(n), H_1 \end{cases} \tag{7}$$

where, n=1, 2, ..., M; $w(n)$ is AWGN noise of variance σ_n^2, $h(n)$ is gain of channel between the PU and the SU and $x(n)$ is PU signal.

The energy E of detected signal $Y(k)$ is calculated by Eq. (8):

$$E = \frac{1}{M}\sum_{k=1}^{M} |Y(k)|^2 \tag{8}$$

where, k=1, 2, ..., M and $M=\tau f_s$ is the number of the sampling nodes with calculated energy E follows the Normal distribution follows Eq. (9):

$$E \sim \begin{cases} N\left(\sigma_n^2, \frac{\sigma_n^4}{M}\right), H_0 \\ N\left((1+\gamma)\sigma_n^2, \frac{(1+\gamma)^2\sigma_n^4}{M}\right), H_1 \end{cases} \tag{9}$$

where, $N(m, \sigma_n^2)$ is the Normal distribution of average value m, variance σ_n^2 and γ is PU SNR.

The performance measures of detection probability (P_d) and false alarm probability (P_f) can depend on sensing time and threshold values and are calculated by utilizing on the below Eq. (10) and Eq. (11):

$$P_f(\tau, \lambda) = P\left(E > \frac{\lambda}{H_0}\right) = Q\left(\left(\frac{\lambda}{\sigma_n^2} - 1\right)\sqrt{\tau f_s}\right) \tag{10}$$

$$P_d(\tau, \lambda) = P\left(E > \frac{\lambda}{H_1}\right) = Q\left(\left(\frac{\lambda}{\sigma_n^2} - \gamma - 1\right)\sqrt{\frac{\tau f_s}{(\gamma+1)^2}}\right) \tag{11}$$

where, $Q(x)$ is the Q function described as Eq. (12):

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} \exp\left(-\frac{z^2}{2}\right)dz \tag{12}$$

CR user transmits data if it detects PU is free with probability $(1 - P_f)P(H_0)$. Even, the SU transmits data if the PU wrongly find out the absence of licensed user with probability $(1 - P_d)P(H_1)$, which creates harmful interference to the transmission of the PU. The interference power P_{int} must be less than the maximum allowable interference power I_{max} of PU and is given by Eq. (13):

$$P_{int} = P_t h^2 (1 - P_d)P(H_1) \leq I_{max} \tag{13}$$

where, P_t is the power transferred by original signal. The detection probability lower limit is given by Eq. (14):

$$P_d \geq P_d^{low}$$

where,

$$P_d^{low} = 1 - \frac{I_{max}}{P(H_1)P_t h^2} \tag{14}$$

The false alarm probability written in terms of P_d^{low} as Eq. (15):

$$P_f(\tau) \geq Q\left(Q^{-1}\left(P_d^{low}\right)(\gamma + 1) + \gamma\sqrt{\tau f_s}\right) \tag{15}$$

If the $P(H_1)$ is the PU presenting probability, the obtained energy of CR during harvesting time τ_1 is described as Eq. (16):

$$E_h = \vartheta\left(P(H_1)P_s h^2 + \sigma_n^2\right)\tau_1 \tag{16}$$

where, P_s is PU signal power.

In a battery, harvested energy E_h is stored and is utilized for SU transmission in transmission slot and the improvement in the transmission power is described as Eq. (17):

$$\Delta P(\tau_1) = \frac{\vartheta\left(P(H_1)P_s h^2 + \sigma_n^2\right)\tau_1}{T} \tag{17}$$

The data transmission time of SU is T-τ-τ1 with transmission probability $(1-P_f)P(H_0)$ and by using Shannon-Hartley theorem transmission rate is calculated as Eq. (18):

$$C = B\log\left(1 + \frac{\left(P_t + \Delta P(\tau_1)\right)g^2}{\sigma_n^2}\right) \tag{18}$$

where, B is bandwidth of channel and g is gain between SU and FC. The average throughput of SU is described by Eq. (19):

$$R(\tau, \tau_1) = \frac{T - \tau - \tau_1}{T}\left((1 - P_f)P(H_0)\right. \times B\log\left(1 + \frac{\left(P_t + \Delta P(\tau_1)\right)g^2}{\sigma_n^2}\right) \tag{19}$$

3.3 Throughput optimization of SU

By jointly optimizing sensing and harvesting times, the SU average data transmission rate will increase which maximizes the throughput. It can be achieved by maintaining P_d above the minimum value and as mentioned in Eq. (20):

$$\max_{\tau,\tau_1} R(\tau,\tau_1) \quad (20a)$$

$$s.t\ P_d \geq P_d^{low} \quad (20b)$$

$$\tau + \tau_1 \leq T \quad (20c)$$

$$\tau \geq 0\ and\ \tau_1 \geq 0 \quad (20d)$$

Since Q-function decreases monotonically, from Eqns. (10) and (11), both probability of detection Pd and probability of false alram Pf decreae with increasing threshold λ. The throughput of SU will maximize by decreasing P_f and P_d, until Pd reaches its lower limit i.e., $P_d = P_d^{low}$. Throughput R can be re written as Eq. (21):

$$R(\tau,\tau_1) = \frac{T-\tau-\tau_1}{T} \left(1 - Q(Q^{-1}(P_d^{low})(\gamma+1) + \gamma\sqrt{\tau f_s}\right)P(H_0) \times Blog(1 + \frac{(P_t + \Delta P(\tau_1))g^2}{\sigma_n^2}) \quad (21)$$

Throughput R of SU is function of sensing time (τ) and harvesting time (τ_1), so optimization depends on two parameters. Sub optimal solution can be obtained by fixing each parameter once. By fixing harvesting time (τ_1), sub optimal solution about τ can be obtained as follows Eq. (22):

$$\max_{\tau} R(\tau) = \frac{T_1-\tau}{T} \left(1 - Q(Q^{-1}(P_d^{low})(\gamma+1) + \gamma\sqrt{\tau f_s}\right)P(H_0) \times Blog(1 + \frac{(P_t + \Delta P(\tau_1))g^2}{\sigma_n^2}) \quad (22)$$

where, $T_1 = T - \tau_1$ and $0 \leq \tau \leq T_1$.

Sub optimal solution about harvesting time (τ_1) is obtained by fixing the sensing time (τ) and can be given as Eq. (23):

$$\max_{\tau_1} R(\tau_1) = \frac{T_2-\tau_1}{T}\left(1 - Q(Q^{-1}(P_d^{low})(\gamma+1) + \gamma\sqrt{\tau f_s}\right)P(H_0) \times Blog(1 + \frac{(P_t + A\tau_1)g^2}{\sigma_n^2}) \quad (23)$$

where, $T_2 = T - \tau$ and $A = \frac{\vartheta(P(H_1)P_s h^2 + \sigma_n^2)}{T}$.

4. PARALLEL SENSING AND ENERGY HARVESTING COGNITIVE RADIO NETWORK (PSEHCRN)

In a traditional cooperative cognitive radio network with N SUs and one Fusion centre (FC) All the SU s will perform the sensing and harvesting individually and sends result of sensing to FC. Based on collective information of SUs, FC will conclude presence of PU.

A Parallel Sensing and Energy Harvesting Cognitive Radio Network (PSEHCRN) have been proposed in this paper, where N SUs will divide in to two sets. First set, namely, sensing group, will perform cooperative sensing operation and transmits the sensed information to FC. Second set, harvesting group, SUs having highest priority to transmit data are placed in harvesting group are perform the harvesting of RF energy, collects the results of sensing from the FC and transmits data if the PU is absent as conveyed in Figure 6.

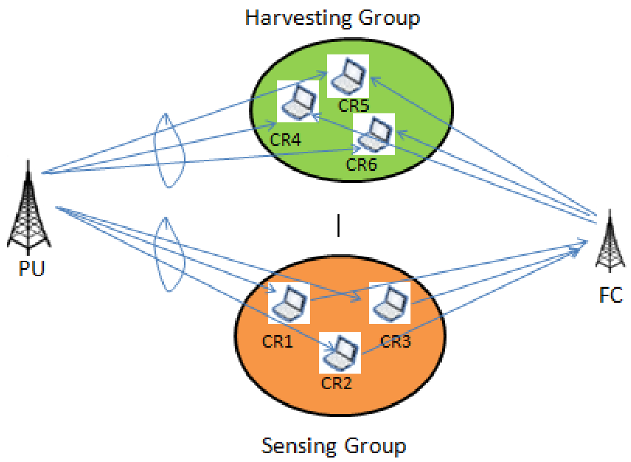

Figure 6. Model of PSEHCRN structure

4.1 Frame structure of SU

The frame structures of SU in sensing group consist of two slots: sensing and reporting slot. In sensing slot, it senses the presence of licensed user for duration of τ and reports to the FC in reporting slot, a single bit sensing information of 1 or 0 will report to FC for presence or absence of PU in reporting slot for duration of τ_r through sensing link is given in Figure 7. Then FC will take a collective decision based OR rule, in which decision of FC is 1 i.e., PU present if any one of SU will send its report as 1. The execution process of OR decision rule for two SUs is shown in Table 1.

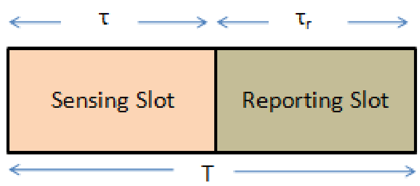

Figure 7. Frame structure of SU in sensing slot

Table 1. OR decision rule

SU1	SU2	OR Decision
Absent (0)	Absent (0)	Absent (0)
Absent (0)	Present (1)	Present (1)
Present (1)	Absent (0)	Present (1)
Present (1)	Present (1)	Present (1)

The frame structures of SU in harvesting group consist of three slots: harvesting slot, collecting slot and transmission slot is given in Figure 8. Individual SU will perform harvesting in first slot, a single bit sensing information of 1 or 0 will collected from FC for presence or absence of PU in collecting slot for duration of τ_h. The transmission of SU data will be taken in third slot, if the FC detects that PU is absent. Each SU will send its data with harvested and SU energy.

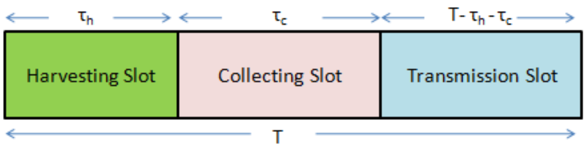

Figure 8. Frame structure of SU in harvesting slot

4.2 Analysis of PSEHCRN

The CRN with N number of SUs, where set of M SUs will perform sensing and (N-M) are performing harvesting. The performance of CRN with parallel sensing and harvesting will depends on false alarm probability and detection probabilities and described as Eq. (24) and Eq. (25):

$$\emptyset_f = 1 - (1 - P_{fi})^M \tag{24}$$

$$\emptyset_d = 1 - (1 - P_{di})^M \tag{25}$$

where, P_{fi} and P_{di} are the i^{th} SU false alarm and detection probabilities.

By fixing the probability of detection $\emptyset_d = P_d^{low}$ false alarm probability is denoted as Eq. (26):

$$\emptyset_f(\tau_h) = 1 - \left(1 - Q(Q^{-1}(1 - P_d^{low})^{\frac{1}{M}}\right)(\gamma + 1) + \gamma\sqrt{\tau_h f_s}))^M \tag{26}$$

where, τ_h is harvesting time.

The total energy harvested from the (N-M) SUs is given by Eq. (27):

$$E_h^{'}(\tau_h) = \vartheta(N - M)(P(H_1)P_s h^2 + \sigma_n^2)\tau_h \tag{27}$$

The resulting power improvement in transmission is given by Eq. (28):

$$\Delta P(\tau_h) = \frac{E_h'(\tau_h)}{T} = (N - M)K\tau_h \tag{28}$$

where, $K = \frac{\vartheta(P(H_1)P_s h^2 + \sigma_n^2)}{T}$.

After (N-M) SUs harvesting energy, the total transmission power of SU is shown in Eq. (29):

$$P_t' = P_t + (N - M)K\tau_h \tag{29}$$

The transmission rate of SU is described by Eq. (30):

$$R'^{(\tau_h, N-M)} = \frac{(T - \tau_h - \tau_c)N}{T}(1 - P_{f,i})^M P(H_0) \times Blog(1 + \frac{(NP_t + (N - M)K\tau_h)g^2}{N\sigma_n^2}) \tag{30}$$

4.3 Throughput optimization of SU

The average throughput of SU will improve by jointly optimizing the sensing time and number of SUs of sensing group with constraints probability of detection is above the minimum value, l=N-M is described by Eq. (31):

$$\max_{\tau_h, l} R(\tau_{h,} N - M) \tag{31a}$$

$$\text{s.t. } \emptyset_f \le \alpha, \emptyset_d \ge P_d^{low} \tag{31b}$$

$$E_h + E_b \ge P_i T + P_c T \tag{31c}$$

$$P_i \ge 0, i = 1,2 \ldots l \tag{31d}$$

where, E_h is harvested energy, E_b battery initial energy P_i is transmission power of ith SU, P_c is power required for operation of circuit and T is the frame time duration.

Optimum throughput is achieved by fixing M value at $\emptyset_d = P_d^{low}$ by fixing M and is given by Eq. (32):

$$R'(\tau_h) = \frac{(T - \tau_h - \tau_c)N}{T} \left(1 - Q(Q^{-1}(1 - (1 - P_d^{low})^{\frac{1}{M}}\right)(\gamma + 1) + \gamma\sqrt{\tau_h f_s}))^M P(H_0) \times Blog(1 + \frac{(NP_t + (N - M)K\tau_h)g^2}{N\sigma_n^2}) \tag{32}$$

5. SIMULATION RESULTS

Throughput of EHCRN is analysed with different parameters that are sensing time, harvesting time and primary user SNR for performing sensing and harvesting individually and parallel. The SUs throughput with sensing time (τ) and harvesting time (τ_1) are shown in Figure 9.

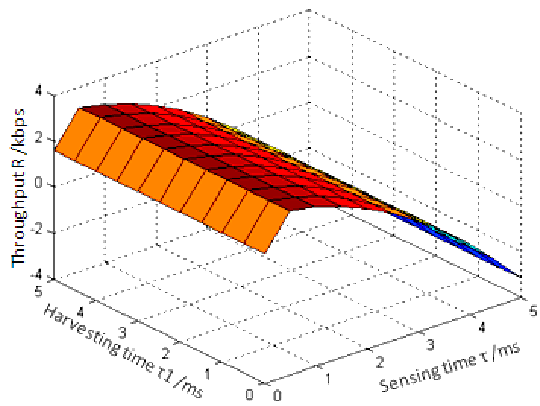

Figure 9. Throughput of SU with sensing and harvesting-time

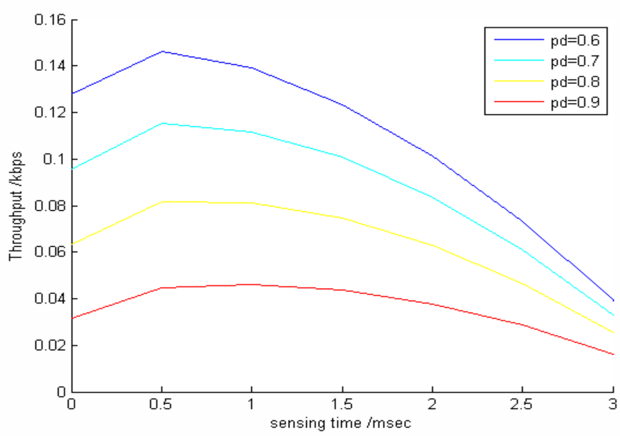

Figure 10. Sensing time Vs throughput of SU

As the sensing time τ increases, (T-τ-τ1) decreases which in turn decreases the throughput of SU. Figure 10 indicates that the SUs throughput for different probability of detection, as Pd increases spectrum utilization of PU increases there by throughput of SU decreases.

Figure 11 shows that the harvesting energy is increases as the harvesting time of SU increases.

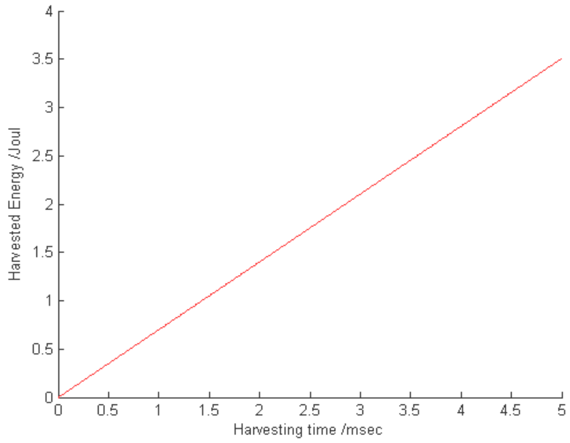

Figure 11. Relation between harvesting time and harvesting - energy

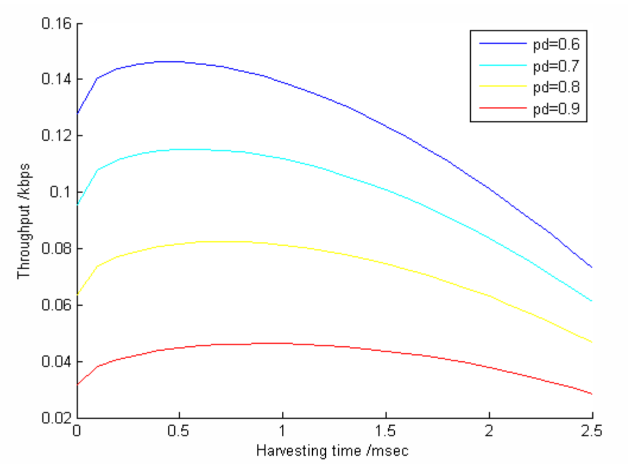

Figure 12. Throughput Vs Harvesting time

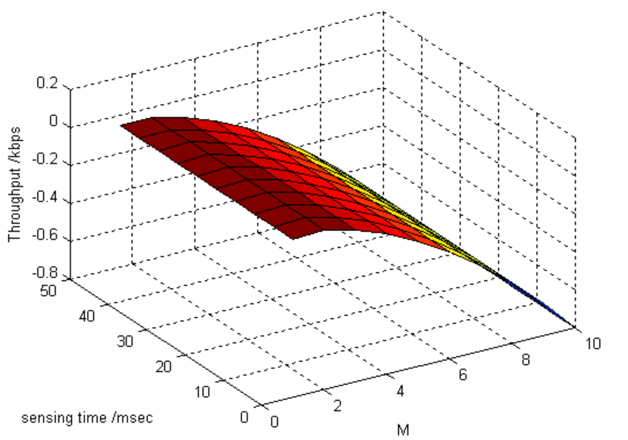

Figure 13. Throughput with sensing and number of Sus

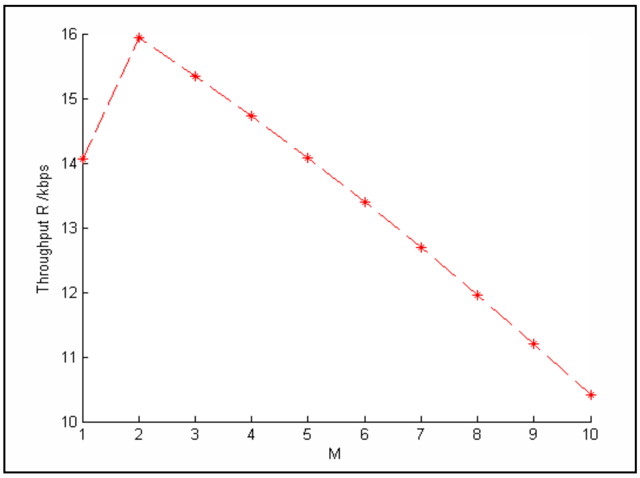

Figure 14. Number of SUs in sensing Vs throughput

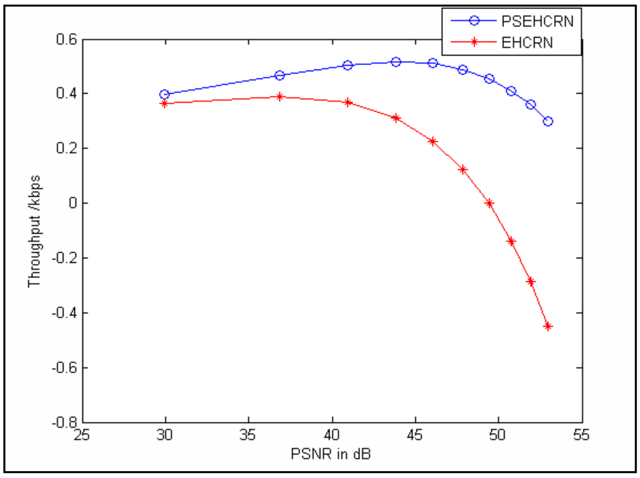

Figure 15. PSNR Vs Throughput of PSEHCRN

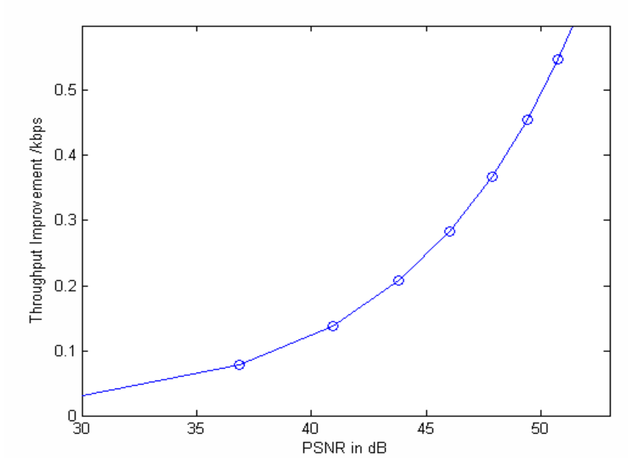

Figure 16. PSNR Vs Throughput improvement

The relation between the throughputs of SU with harvesting time for different probability of detection is shown in Figure 12. Initially as increasing the harvesting time will increases harvesting energy of SU then in turn increases throughput and reach maximum value. Data transmission time of SU decreases as the harvesting time increase which decreases the throughput of SU.

Throughput of CRN is analyzed with number of SUs under sensing operation with sensing time and is shown in Figure 13. The throughput of CRN reduces with number of SUs under sensing is increases which results in reduction in number of SUs in harvesting which reduces the harvesting energy and is shown in Figure 14.

Figure 15 indicates the performance of throughput of CRN with PSNR for EHCRN and PSEHCRN. Parallel operation of sensing and harvesting in PSEHCRN will increases the throughput compare to the traditional EHCRN, and the improvement in throughput of CRN is shown in Figure 16.

6. CONCLUSION

In this paper, parallel operation of sensing and energy harvesting of PSEHCRN have proposed. The frame structure of traditional EHCRN and PSEHCRN are analyzed. Optimum throughput of traditional cognitive radio network is obtained and analyzed with different parameters. Throughput of PSEHCRN with M number of SUs has discussed with various parameters. Throughput of CRN with parallel sensing and energy harvesting is increased as compared to traditional energy harvesting.

REFERENCE

[1] Xu, D., Li, Q. (2017). Joint power control and time allocation for wireless powered underlay cognitive radio networks. IEEE Wireless Communications Letters, 6(3): 294-297. https://doi.org/10.1109/LWC.2017.2676102

[2] Bae, Y.H., Baek, J.W. (2016). Achievable throughput analysis of opportunistic spectrum access in cognitive radio networks with energy harvesting. IEEE Transactions on Communications, 64(4): 1399-1410. https://doi.org/10.1109/TCOMM.2016.2533485

[3] Yin, S., Qu, Z., Li, S. (2015). Achievable throughput optimization in energy harvesting cognitive radio systems. IEEE Journal on Selected Areas in Communications, 33(3): 407-422. https://doi.org/10.1109/JSAC.2015.2391712

[4] Tang, Y., Chen, D., Wang, L., Zomaya, A.Y., Chen, J., Liu, H. (2018). Bayesian tensor factorization for multi-way analysis of multi-dimensional EEG. Neurocomputing, 318: 162-174. https://doi.org/10.1016/j.neucom.2018.08.045

[5] Liu, Z., Wang, W., Yuan, Y., Li, X., Guan, X. (2019). Robust power control based on hierarchical game for hybrid access femtocell networks. IET Communications, 13(11): 1607-1614. https://doi.org/10.1049/iet-com.2018.5957

[6] Li, Z., Liu, B., Si, J., Zhou, F. (2017). Optimal spectrum sensing interval in energy-harvesting cognitive radio networks. IEEE Transactions on Cognitive Communications and Networking, 3(2): 190-200. https://doi.org/10.1109/TCCN.2017.2702167

[7] He, Y., Xue, J., Ratnarajah, T., Sellathurai, M., Khan, F. (2016). On the performance of cooperative spectrum sensing in random cognitive radio networks. IEEE Systems Journal, 12(1): 881-892. https://doi.org/10.1109/JSYST.2016.2554464

[8] Li, K.H., Teh, K.C. (2017). Optimal spectrum access and energy supply for cognitive radio systems with opportunistic RF energy harvesting. IEEE Transactions on Vehicular Technology, 66(8): 7114-7122. https://doi.org/10.1109/TVT.2017.2673861

[9] Kishore, R., Gurugopinath, S., Muhaidat, S., Sofotasios, P.C., Dobre, O.A., Al-Dhahir, N. (2019). Sensing-throughput tradeoff for superior selective reporting-based spectrum sensing in energy harvesting HCRNs. IEEE Transactions on Cognitive Communications and Networking, 5(2): 330-341. https://doi.org/10.1109/TCCN.2019.2906915

[10] Yang, Z., Ding, Z., Fan, P., Karagiannidis, G.K. (2015). Outage performance of cognitive relay networks with wireless information and power transfer. IEEE Transactions on Vehicular Technology, 65(5): 3828-3833. https://doi.org/10.1109/TVT.2015.2443875

[11] Wang, Z., Chen, Z., Xia, B., Luo, L., Zhou, J. (2015). Cognitive relay networks with energy harvesting and information transfer: Design, analysis, and optimization. IEEE Transactions on Wireless Communications, 15(4): 2562-2576. https://doi.org/10.1109/TWC.2015.2504581

[12] Singh, K., Moh, S. (2016). A comparative survey of energy harvesting techniques for wireless sensor networks. Advanced Science and Technology Letters, 142: 28-33. http://dx.doi.org/10.14257/astl.2016.142.05

[13] Bhowmick, A., Yadav, K., Roy, S.D., Kundu, S. (2017). Throughput of an energy harvesting cognitive radio network based on prediction of primary user. IEEE Transactions on Vehicular Technology, 66(9): 8119-8128. https://doi.org/10.1109/TVT.2017.2690675

[14] Liu, X., Jia, M., Gu, X. M., Yan, J.H., Zhou, J.J. (2017). Optimal spectrum sensing and transmission power allocation in energy-efficiency multichannel cognitive radio with energy harvesting. International Journal of Communication Systems, 30(5): e3044. https://doi.org/10.1002/dac.3044

[15] Li, Z., Liu, B., Si, J., Zhou, F. (2017). Optimal spectrum sensing interval in energy-harvesting cognitive radio networks. IEEE Transactions on Cognitive Communications and Networking, 3(2): 190-200. https://doi.org/10.1109/TCCN.2017.2702167

[16] Banerjee, A., Maity, S.P. (2017). Residual energy maximization in cooperative spectrum sensing with energy harvesting. In 2017 Twenty-third National Conference on Communications (NCC), Chennai, India, pp. 1-6. https://doi.org/10.1109/NCC.2017.8077064

[17] Bujunuru, A., Tadisetty, S. (2019). Residual energy of energy harvesting cognitive radio networks. International Journal of Engineering and Advanced Technology, 8(6): 1376-1378. https://doi.org/10.35940/ijeat.E7309.088619

[18] Xu, C., Zheng, M., Liang, W., Yu, H., Liang, Y.C. (2017). End-to-end throughput maximization for underlay multi-hop cognitive radio networks with RF energy harvesting. IEEE Transactions on Wireless Communications, 16(6): 3561-3572. https://doi.org/10.1109/TWC.2017.2684125

[19] Zheng, M., Xu, C., Liang, W., Yu, H. (2016). Harvesting-throughput tradeoff for RF-powered underlay cognitive radio networks. Electronics Letters, 52(10): 881-883. https://doi.org/10.1049/el.2015.4418