Volume: 12 Issue: 06 Pages: 4793-4799(2021) ISSN: 0975-0290

Adaptive Resource Optimization for Cognitive Radio Networks

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ABSTRACT

In cognitive radio network, the spectrum sensing finds either the channel is occupied or idle, the problem is assigning the unused channels of the primary user (PU) to the secondary users in an efficient manner is most challenging issue. In this work, we investigates the above issue and proposed an adaptive resource allocation to the secondary users in terms of channel allocation and power allocation. The proposed work intelligently handles both frequency and space efficiently without affecting the quality of service (QoS) of the primary user. We considered both underlay and overlay spectrum access, based on that resource allocation is carried out in an efficient manner. The maximum transmitted data rate of the secondary user (SU) obtained is 225Kbps determined by using Shannon channel capacity theorem. The proposed work also shows the effectiveness of the simulation in terms of energy efficiency up to 8.25 x 10^5 bits/Joule.

Keywords - **Resource allocation, Cognitive radio, OFDM, data rate, energy efficiency.**

Date of Submission: Jun 07, 2021 Date of Acceptance: Jun 25, 2021

I. INTRODUCTION

Wireless communication on an open shared medium require wireless technologies to cooperate and share the spectrum in a non-interference manner [1]. Due to an enormous increase in wireless technology leads to huge demand in spectrum. To overcome this issue, cognitive radio (CR) provides solution to spectrum scarcity where the licensed primary users (PUs) will share the unused spectrum to secondary users (SUs). The cognitive radio operates at IEEE 802.22 standards under the regional area network. The spectrum range for cognitive radio is 54-862MHZ.

Cognitive radio networks (CRNs) utilize the unused licensed spectrum in radio environments to establish network communications. It enhances the utilization of available radio frequency spectrum and interference is minimized with other users. Generally, the allocated primary users (PUs) spectrum is underutilized both in terms of time and space. The FCC has reported the temporal and geographical utilization of spectrum ranges between 15% to 85% [2]. Reusing of fixed spectrum to unlicensed users are not allowed which leads to spectrum scarcity for wireless applications. Besides spectrum scarcity it can also be used for secured communication because CR search for unused spectrum and switches the channels like frequency hop spread spectrum[3-6].

Fig. 1 shows the basic cognitive cycle with four main functions: spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility. The spectrum sensing is to discover the status of the spectrum by sensing the white space or unused spectrum by the primary users (PU). In spectrum decision, the primary user's unused and best available channels are selected and decision is made to allocate the unused channel to the secondary users. The spectrum sharing, coordinate to access the white space or unused spectrum with other users. Finally, in spectrum mobility, the secondary users (SUs) immediately evacuate the used primary channel when licensed user is detected in the network.

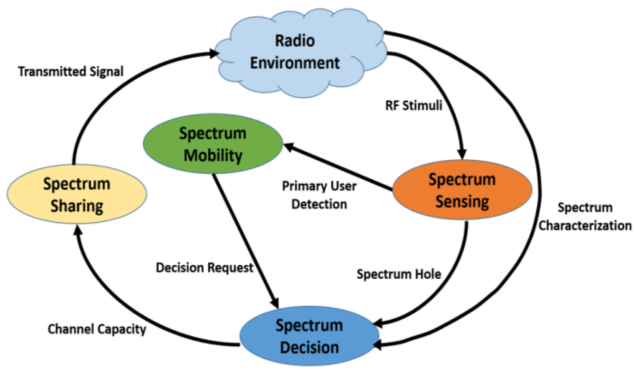

Figure 1. Cognitive radio module [7]

Traditionally, spectrum cannot be utilized by unlicensed users when the spectrum is not used by licensed users. The development of cognitive radio allows to utilize the spectrum effectively by unlicensed users by maintaining interference level minimum to the primary users (PU) [8]. Based on spectrum policies of primary system, the dynamic spectrum access can be broadly classified as overlay, underlay and hybrid spectrum access. In the overlay spectrum access, the SUs can access the channel only when PU is not utilizing the channel [9]. In underlay spectrum access, the SUs can share the spectrum along with the PU by transmitting below the interference temperature [10]. The management of interference

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between secondary users (SU) and the primary users (PU) plays an important role in the resource allocation. To protect the primary system, from interference caused by SUs, it must be below to a threshold in either average or instantaneous sense [11].

In our proposed work, the resources are allocated to the secondary users (SUs) in an energy efficient by adaptively switching the channel and adjusting power allocation is processed according to the availability of free white-space channels and mutual interference. The proposed adaptive resource allocation method in compared with overlay spectrum access minimize the total power consumption with achievable date rate.

Apart from Section 1, the rest of the paper is organized as follows: section 2 discusses the related literature work carried in resource allocation in CRN. Section 3 explains the system model and section 4 presents the adaptive resource allocation to secondary users. Matlab simulation results are discussed in section 5. Finally, section 6 summarizes the conclusion of our proposed work.

II. LITERATURE REVIEW

In this literature section, different resource allocation techniques was reviewed in which secondary user utilize the spectrum of the primary user leads to degrade the performance of the cognitive radio system in underlay interms of interference, data rate and power. We briefly discussed few techniques in this section.

J. Zou *et.al.*, [12] demonstrated dynamic sharing the primary users spectrum to secondary users by using overlay, underlay and hybrid spectrum access schemes. The multiple secondary users (SUs) transmit data through a common relay to improve the optimal power allocation in CRN. Yongjun Xu *et.al.*, [13] analyzed the drawback of adaptive power control in an underlay CRN in presence of multiple secondary users (SUs) and primary users. Since the optimal power allocation does not provide guaranteed QoS in presence of imperfect channel, so to maximize throughput of secondary users under individual power constraints, signal to interference noise ratio (SINR) constraints of secondary users and interference temperature constraints of primary users are considered in modeling robust adaptive power control under multiple uncertainties.

Xue *et.al.*, [14] proposed a resource allocation framework to optimize both power and channel allocation by adopting different spectrum access schemes based on secondary users (SUs) locations. The proposed framework utilizes the spectrum efficiently to avoid unnecessary spectrum sensing under minimum power consumption. The drawback of this algorithm is only underlay spectrum is considered for spectrum sensing. G. Bansal *et.al.*, [15] investigated power allocation problem of an OFDM based hybrid system in which it outperforms both overlay and underlay system to achieve better transmission rates with less BER. S. Wang *et.al.*, [16] presented barrier-based method to achieve optimal resource allocation in OFDM by considering practical limitations of heterogeneous cognitive radio network such as different traffic demands, imperfect spectrum sensing, limited transmission power of secondary users etc. The authors exploited the overall capacity of cognitive radio systems under different traffic demands of the users and interference constraints. S. Wang *et.al.*, [17] investigated an energy efficient resource management in OFDM based CRNs based on channel uncertainties between primary and secondary users. Generally, secondary user transmitters have perfect knowledge about channel gains of primary user receivers. But in this work author considered, the lack of co-operation from primary users leads to insufficient channel gain measurement. So to reduce the channel uncertainty, author assumed to estimate the channel state of base stations in a periodical manner through feedback signal obtained from each users.

In [18] the author proposed an efficient spectrum monitoring among base stations with low signaling overheads to estimate sub-channel activity index of primary users. The aggregated sub-channel activity index is used to allocate optimal power and sub-channels to the secondary base station. Kayalvizhi *et.al.*, [19] discussed bisectional algorithm to estimate the optimal channel gain from cognitive transmitter to carry out spectrum sharing of primary system. Swati parmar *et.al.*, [20] implemented Moth Flame Optimization (MFO) method to achieve high transmission rate using power assignment. Mohammadi *et.al.*, [21] presented Autonomous and Distributed Underlay Dynamic Spectrum Access to predict the effect of transmission for the nearest primary base station based on that secondary user choose the modulation order and throughput.

From the above literature survey, it has been found that many authors are working in adaptive resource allocation techniques in cognitive radio networks. In this paper, we focused cognitive base station to make decisions rapidly to adapt their resource allocation to SUs energy efficiently according to the changing environment.

III. SYSTEM MODEL

The system model consists of primary base station (PBS) and cognitive base station (CBS) each one. Assume the system model of K^{th} secondary user (SU) communicating with CBS and PBS in uplink and downlink respectively. For each SUs there is a worst case PU as shown in Fig.2. For the worst case scenario, all the primary users lie within the coverage range of primary base station are protected in long term from the transmission of secondary users.

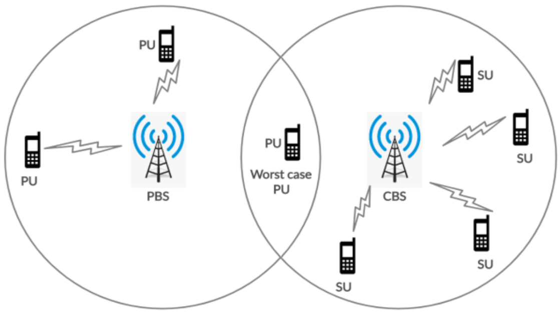

Figure 2. Cognitive radio system coexisting with primary system

The spectrum of primary base station is divided into M sub-channels each have same bandwidth with no spectrum sensing error. To neglect the mutual interference among the secondary users each sub-channel is allocated to one SU. The resource allocation exhibits an adaptive structure, enabling diverse spectrum access when the SUs fall into various service region.

IV. ENERGY EFFICIENT ADAPTIVE RESOURCE ALLOCATION

In this section, an energy efficient adaptive resource allocation is investigated. Fig. 3 elaborates adaptive resource allocation to the secondary users depending on interference. The spectrum of primary user is divided into N sub-channels of equal bandwidth with each sub-channel experiencing flat fading. It is also assumed that there is no spectrum sensing error, and hence, the case of imperfect sensing is out of the scope. The power control plays an important role in energy-efficient communication to prolong the lifetime of the network based on PU channel is shared with SU. The data rate at which SU can transmit and the energy efficiency for each of the SUs are determined. The data rate and energy efficient of the SUs are determined by adapting resource allocation to secondary users depending on interference.

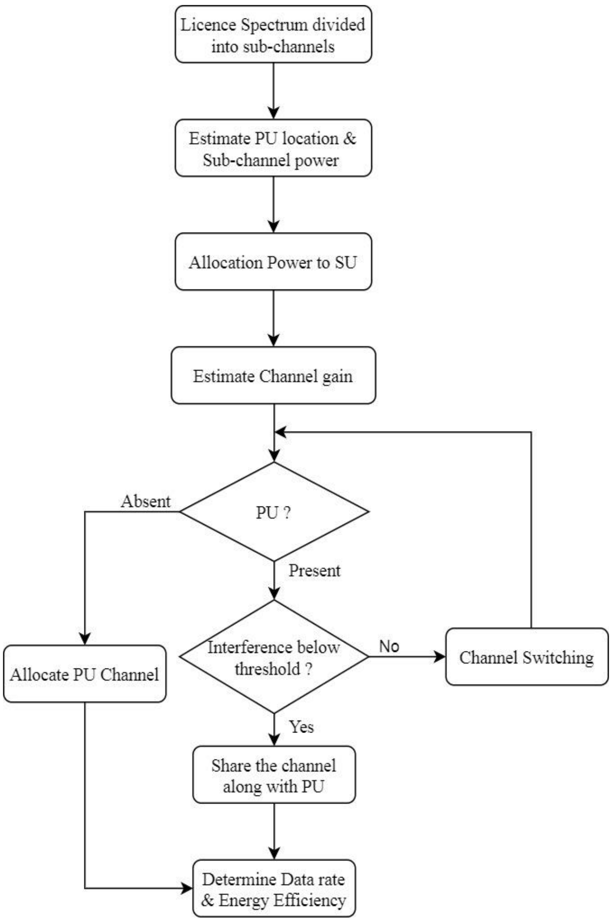

Figure 3. Flowchart of Adaptive Resource Allocation to Secondary Users

Power allocation to PU: The licensed spectrum of 1.5MHz and it is divided into 12 sub-channels. Each sub-channel bandwidth is 125KHz. The power allotted for the primary base station (PBS) is 50W. On determining the transmission power for the PBS, power for the primary user on the sub-channel can be estimated. The power for the primary users on each sub-channels is estimated by calculating the total path loss. The radio signal path loss is determined by using (1)

$$PL(dB) = 10\,log\left(\frac{P_t}{P_r}\right) = -10\,\log\left(\frac{\lambda^2}{4\pi^2 d^2}\right) \quad (1)$$

Where d is the distance between the transmitter and the receiver, P_t is the transmission power of the user and P_r is the receiver power of the user. The transmitting power for the PU using sub channels is estimated by

$$P = P_{PBS} - PL \quad (2)$$

The primary user (PU) worst-case location lies at the intersection of the PBS boundary region. The worst case primary user location ($PUL_{worst\text{-}case}$) is calculated by using equation (3)

$$PUL_{worst-case} = D_k - R_1 \quad (3)$$

where, D_k denotes the distance between k^{th} secondary user and the primary base station and R_1 is radius of primary base station (PBS).

Power allocation to SU: The power allocation to each secondary user sub-channel depends on the utilization of the spectrum by the primary user. The power allocation to each sub-channels is based on the presence or absence of the primary users. When the secondary user share the channel along with PU then the SU has to transmit with lesser power, because it will cause interference to the PU if it operates above to the interference temperature. The power allocated for the secondary sub-channel which is not utilized by the primary user can be allocated with more power than the power allocated for a network on overlay. The power allocated for the un-occupied channel (P_{uo}) for the primary user is expressed in (5)

$$\beta = \theta(Gi + Fi) + Gi * Fi * \lambda \quad (4)$$

$$P_{uo} = \sqrt{\frac{1}{2\theta * Gi * Fi}\left(-\beta + \sqrt{(\beta)^2 - \frac{4\theta * Gi * fi(\theta - Gi)\lambda}{2}}\right)} \quad (5)$$

The power allocation for the occupied channel (P_O) by the primary user i.e. primary user utilizing the spectrum, can be determined by (7)

$$\gamma = \theta(G_i + F_i) \quad (6)$$

$$P_O = \sqrt{\frac{1}{2\theta * Gi * Fi}\left(-\gamma + \sqrt{(\gamma)^2 - \frac{4\theta * Gi * fi * \theta}{2}}\right)} \quad (7)$$

where F_i and G_i are determined using (8,9) respectively and it depend on the channel gain between SU and CBS. The average channel gains between two systems from A to B, i.e., L_{AB} obtained based on path-loss attenuation model

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d−r for a distance *d* with exponent *r*, *i.e.*, $L_{AB} = d_{AB}-r$, where d_{AB} is distance between the transmitter and receiver system.

$$Fi = \frac{h_i^{SS}}{P_P h_i^{SS} + \sigma^2} \quad (8)$$

$$\mathrm{Gi} = \frac{\mathrm{h_i^{SS}}}{\sigma^2} \quad (9)$$

$$\theta = 1 + \mu \quad (10)$$

Where,$h_{i,k}^{ss}$ is gain of the channel for i^{th} sub-channel from the k^{th} secondary user to CBS, σ^2 is noise power on each sub channel at the PBS, h_i^{PS} is gain of the channel on i^{th} sub channel from PBS to CBS, P_P is transmit power of the PBS and μ is non-negative Lagrange multiplier. The value $\mu \geq 0$ and after optimization of the value using convex optimization the Lagrange multiplier value is 0.78.

Channel allocation to SU

The channels allotted for the secondary users based on the transmission power allotted on the i^{th} sub-channel for the k^{th} secondary user (SU) with lesser interference level. The average channel gain on the i^{th} sub-channel for the k^{th} secondary user (SU) to the worst case PU and channel allocation indicator should be less than the interference temperature expressed in (11)

$$\rho_{i,k} P_{i,k} L_{i,k}^{SP} \leq I_i^{max} \quad (11)$$

$$\rho_{i,k} P_{i,k} \leq 0 \quad (12)$$

where $P_{i,k}$ is transmission power allocated on i^{th} sub-channel for k^{th} SU, I_i^{max} is quality threshold of i^{th} sub-channel for the primary user, $L_{i,k}^{SP}$ is average channel gain on the i^{th} sub-channel from k^{th} secondary user to the worst case PU location and $\rho_{i,k}$ is channel allocation indicator *(i.e.)* if the value is 1 it represent the allocation of the i^{th} sub channel for k^{th} secondary user.

$$\sum_{k=1}^{K} \rho_{i,k} \leq 1, \rho_{i,k} \in \{0,1\} \forall k, i \quad (13)$$

Determination of resource allocation

The resource allocation to the secondary user (SU) is determined in terms of two parameters : data rate and energy efficiency.

Data rate:

The data rate at which each secondary user transmits has to be determined based on the Shannon channel capacity. The maximum transmission rate achieved over a transmission channel in the presence of noise is defined in (14)

$$C = B \log_2(1 + \tfrac{S}{N}) \quad (14)$$

where, C is channel capacity, B is bandwidth of the spectrum and S/N is signal to noise ratio.

The data rate at which secondary users are estimated by using (15) where $R_k \geq R^{min}\ \forall k$.

$$\mathrm{R_k} = \sum_{i \in A} \rho_{i,k} C\left(\frac{P_{i,k} h_{i,k}^{SS}}{\sigma^2}\right) + \alpha^{(k)} \sum_{i \in N} \rho_{i,k} C\left(\frac{P_{i,k} h_{i,k}^{SS}}{\sigma^2 + P_p h_i^{PS}}\right) \quad (15)$$

Where $\alpha^{(k)}$ the spectrum sharing indicator of k^{th} SU, R^{min} is minimum resource allocation for secondary user, $P_{i,k}$ represents transmit power allocated on the i^{th} sub-channel for the k^{th} secondary channel, ρ represents the channel allocation, $h_{i,k}^{SS}$ is the channel gain obtained on the i^{th} sub-channel from the k^{th} secondary user to CBS, $h_i^{PS}$is channel gain obtained on the i^{th} sub-channel from PBS to CBS and $R^{min}$is the minimum resource allocation to secondary user.

Energy efficiency:

The energy efficiency $E^{(k)}$ of k^{th} system can be obtained by estimating the actual data rate and the power allocated to the secondary user expressed in (16)

$$\mathrm{E}^{(k)} = \frac{R_{act}^{(k)}}{\sum_{i \in A^{(k)} \cup N^{(k)}} P_{i,k}} \ (\mathrm{Mb/s/W}) \quad (16)$$

Where *N* is the set of occupied sub-channels, *A* is the set of unoccupied sub-channels and $R_{act}^{(k)}$ is actual data rate of the k^{th} secondary user.

V. Simulation Results

In this section, employing MATLAB computer simulation, the performance of energy efficient adaptive resource allocation was evaluated. The data rate at which the secondary user transmits and energy efficient of each SUs are presented. From the obtained results it is found that our proposed energy efficient adaptive resource allocation achieves better channel allocation and power allocation to SU with optimum data rate. The simulation scenario of a primary base station (PBS) and the cognitive base station (CBS) are shown in Fig. 4 and the simulation parameters are shown in Table 1.

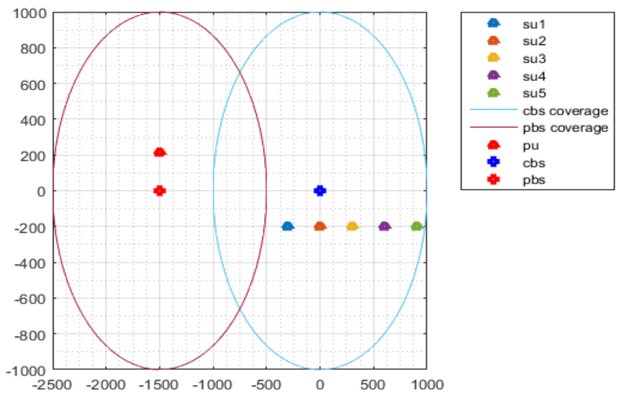

Figure 4. Simulation Scenario

The simulation setup consists of PBS and CBS and each are separated at a distance 1500m. The radio coverage of each BS is 1000m. We deployed 5 secondary users in the radio rage of CBS. Each SUs are deployed in a linear manner separated at a distance of 300m. The bandwidth of the PBS system is considered as 1.5MHz, where channels are sub-divided into 12 with each channel has a bandwidth of 125KHz. The path loss between the transmitter and the receiver is affected by Rayleigh fading and large-scale path loss where path loss exponent *r* considered as 3. The maximum transmit power of the SU should not exceed 2 Watts. The power allocated for the primary system is 5w.

Table 1. Simulation Parameters

Parameters	Values
PBS radius	1000m
CBS radius	1000m
Primary User (PU)	1
Secondary User (SU)	5
PU Bandwidth	1.5MHz
PU Sub-channel	12
Sub-Channel bandwidth	125KHz
PU accommodated channels	CH6 &10
PBS coordinator	(-1500,0)
CBS coordinator	(0,0)
X coordinator of SU	300m
Y coordinator of SU	200m
Distance between each SU	300m
Transmit power of PBS	5w
Maximum power of SU	2w

Determination of resource allocation:

The power and channel allocation to the individual secondary users is shown in Fig. 5. The power allocation is determined by estimating the channel gain, between individual secondary users (SU) and primary base station (PBS). Similarly, SUs share the channel with PU based on the interference level.

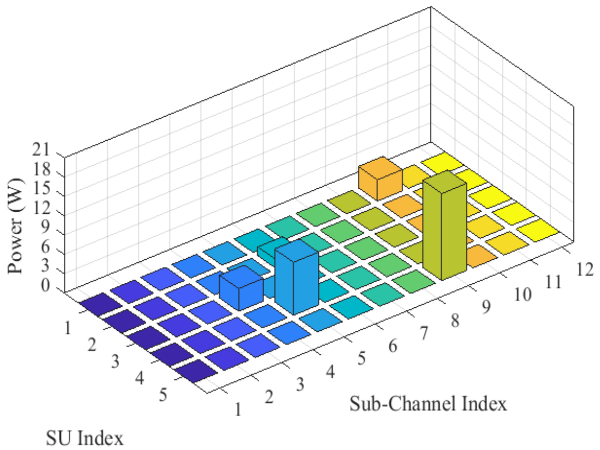

Figure 5. Adaptive Resource Allocation

From the simulation result, the power allocated to the secondary user (SU2) obtained is 1.37 Watts and it is less when compared to the other secondary user because SU2 is closer to the CBS whereas SU5 the power allocated is 13.54 Watts is comparatively high because it is far away from the CBS and it undergoes more channel fading. The channel allocated for each SUs are uniquely allotted by CBS. The channel allocated for SU1, SU2, SU3, SU4 and SU5 are 10, 6, 4, 5 and 9 respectively. Since these channels are not been utilized by the primary user (PU), so secondary users (SUs) can utilize these channel for communication purpose without any power constraints.

Energy efficiency of each SU

The energy efficiency for each secondary user (SU) is determined. Fig. 6 shows comparison of our proposed resource. The proposed adaptive resource allocation is compared with overlay spectrum access method in terms of energy efficiency. The energy efficiency of each secondary users (SU) is determined by the ratio of actual data allocated to the secondary user (SU) to the power allocated to SU. The energy efficiency obtained for SU2 is 8.25 x 10^5 bits/Joule for the proposed adaptive resource allocation whereas for overlay system is 0.77 x 10^5 Kbits/Joule. The proposed method shows higher energy efficiency because it is near to the cognitive base station (CBS) and it adapts to different resource allocation to achieve maximum energy efficiency with minimum power consumption.

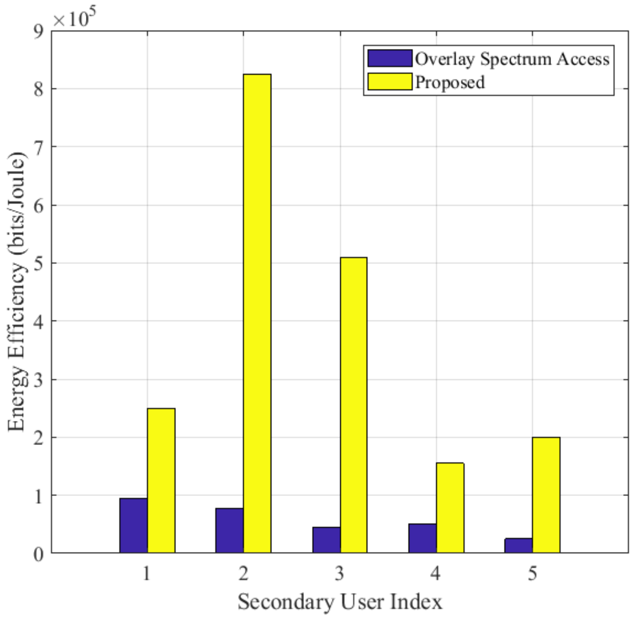

Figure 6. Energy Efficiency of SU

Data rate of each SU

The data rate at which the secondary user is transmitting is shown in Fig 7. The achieved data rate for the Secondary User 2(SU2) is 225 Kbps which is high compared to other SU's because it is near to the cognitive base station (CBS) and the fading is also very minimum. The data rate obtained for SU3 is 140kbps which is little bit away from CBS and fading and path loss also increases when moving away from CBS. The data rate for SU1, SU4 and SU5 are 68kbps, 28kbps and 25kbps respectively. The reason for achieving lesser data rate compared to other SU's is these SUs are far away from cognitive base station, path-loss and fading also increases as the distance increases.

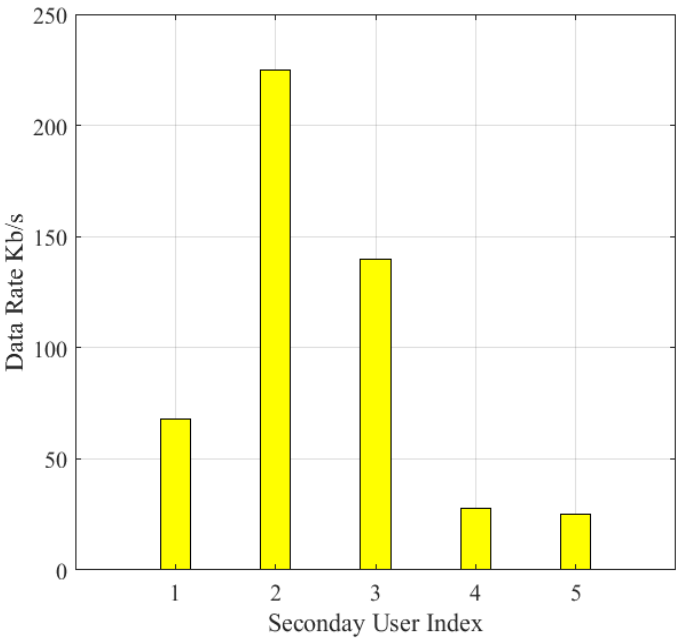

Figure 7. Data rate of each SU

VI. Conclusion

In today's world, the spectrum is becoming more congested leads to slog in spectrum load. The spectrum scarcity and resource allocation are the vital issues to be address in wireless communication. In this work, we addressed resource allocation to the secondary users (SUs) in an energy efficient by adaptively switching the channel and adjusting the power allocation according to the availability of free white-space channels and mutual interference. Our proposed method shows higher energy efficiency of 8.25 x 10^5 bits/Joule and the maximum achievable data rate of secondary users is 225 Kbps. The obtained results conclude that the secondary users utilized the white space of primary users in an efficient manner.

References

[1] S. Pandit, G. Singh, "An overview of spectrum sharing techniques in cognitive radio communication system," *Wireless Network*, 23(2), 2017, 497–518.

[2] Force, S.P.T. Spectrum Policy Task Force Report Et Docket No. 02-135; US Federal Communications Commission: Washington, DC, USA, 2002.

[3] Pickholtz, RL., Schilling, DL., Milstein, LB.: "Theory of spread-spectrum communications-A tutorial," *IEEE Transactions on Communications*, 30(5), 1982, 855–84.

[4] Gopalakrishnan, B., Bhagyaveni, MA.: "Anti-jamming communication for body area network using chaotic frequency hopping," *Healthcare Technology Letters*, 4(6), 2017, 233–237.

[5] Dhivyadharshini and B. Gopalakrishnan, "Comparative Analysis of FH and CFH Spread Spectrum Under Different Jammers," *2020 International Conference on Communication and Signal Processing (ICCSP)*, Chennai, India, 2020, 1361-136.

[6] G. Asaithambi and B. Gopalakrishnan, "Design of Code and Chaotic Frequency Modulation for Secure and High Data rate Communication," *2021 5th International Conference on Computer, Communication and Signal Processing (ICCCSP)*, 2021, pp. 1-6.

[7] S. Barve, A. Akotkar, A. Chavan, A. Kumar and M. Dhaigude, "Open Source Software Defined Radio Using GNU Radio and USRP," *International journal of scientific and technology research*, 3(5), 2014, 305-308.

[8] J. Mitola, III, "Software radio architecture: A mathematical perspective," *IEEE J. Sel. Areas Commun.*, 17(4) , 2010, 514–538.

[9] Q. Zhao and B. M. Sandler, "A survey of dynamic spectrum access," *IEEE Signal Process. Mag.*, 24(3), 2007, 79–89.

[10] A. Ghasemi and E. S. Sousa, "Fundamental limits of spectrum-sharing in fading environments," *IEEE Trans. Wireless Commun.*, 6(2), 2007, 649–658.

[11] G. Marques, L. M. Lopez-Ramos, G. B. Giannakis, and J. Ramos, "Resource allocation for interweave and underlay CRS under probability of interference constraints," *IEEE J. Sel. Areas Commun.*, 30(10), 2012, 1922–1933.

[12] J. Zou, H. Xiong, D. Wang and C. W. Chen, "Optimal Power Allocation for Hybrid Overlay/Underlay Spectrum Sharing in Multiband Cognitive Radio Networks," *IEEE Transactions on Vehicular Technology*, 62(4), 2013, 1827-1837.

[13] Yongjun Xu, Xiaohui Zhao, "Robust adaptive power control for cognitive radio networks," *Signal Processing IET*, 10(1), 2016, 19-27.

[14] T. Xue, X. Dong and Y. Shi, "Resource-Allocation Strategy for Multiuser Cognitive Radio Systems: Location-Aware Spectrum Access," *IEEE Transactions on Vehicular Technology*, 66(1), 2017, 884-889.

[15] G. Bansal, M. J. Hossain, V. K. Bhargava and T. Le-Ngoc, "Subcarrier and Power Allocation for OFDMA-Based Cognitive Radio Systems With Joint Overlay and Underlay Spectrum Access Mechanism," *IEEE Transactions on Vehicular Technology*, 62(3), 2013, 1111-1122.

[16] S. Wang, Z. Zhou, M. Ge and C. Wang, “Resource Allocation for Heterogeneous Cognitive Radio Networks with Imperfect Spectrum Sensing,” *IEEE Journal on Selected Areas in Communications*, 31(3), 2013, 464-475.

[17] S. Wang, W. Shi and C. Wang, “Energy-Efficient Resource Management in OFDM-Based Cognitive Radio Networks Under Channel Uncertainty,” *IEEE Transactions on Communications*, 63(9), 2015, 3092-3102.

[18] G. C. Deepak, K. Navaie and Q. Ni, “Radio Resource Allocation in Collaborative Cognitive Radio Networks Based on Primary Sensing Profile,” *IEEE Access*, 6, 2018, 50344-50357.

[19] Kayalvizhi, E, and Gopalakrishnan, B, “Estimation of optimal channel gain in cognitive radio networks using bisectional algorithm,” *International Journal of Advanced Networking and Applications*, 11(1), 2019, 4171-4176.

[20] Swati parmar, Keshav Mishra “Moth Flame Optimization Based Maximization Of Transmission Rate For Cognitive Radio Users,” *International Journal of Advanced Science and Technology*, 29(12), 2020, 1845-1851.

[21] F. Shah-Mohammadi, H. H. Enaami and A. Kwasinski, “Neural Network Cognitive Engine for Autonomous and Distributed Underlay Dynamic Spectrum Access,” in *IEEE Open Journal of the Communications Society*, vol. 2, 2021, 719-737.