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Optimal Power Allocation for OFDM-Based Cognitive Radio with Improved Genetic Algorithm (IGA)

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***Abstract*-The power allocation is a very important factor in OFDM based cognitive radio. In current trend of research focus on the maximization of power allocation for the transmission of user data. For the maximum utilization of power used various optimal and sub optimal process are used. In optimal and suboptimal used under layer, over layer and joint under layer and over layer model in cognitive radio. During the transmission, induction of interference is a major issue inside of the primary user. For the minimization of interference value used improved genetic algorithm. The improved genetic algorithms reduce the value of interface and achieve the maximum throughput of the transmission. The proposed algorithm deal in concern of dual threshold values for the selection of fairness in cognitive radio users. The proposed algorithms simulated in MATLAB environments and measure some standard parameters against joint methods of OFDMA. The proposed algorithms give very fair result, instead of previous models of cognitive radio.**

Keywords - Cognitive Radio, OFDM, PU, SU, IGA, power Allocation, adaptive

I. INTRODUCTION

The demand of high date rate transmission in wireless network depends on the proper utilization of dedicated frequency. The proper utilization of frequency enhanced the performance of wireless network. Due to certain geographical condition the process of frequency utilization is compromised [1,2]. For the enhancement of this process used cognitive radio. A Cognitive radio (CR) network is a technology in which a frequency band used by one or multiple primary user in a primary network can be operated by a secondary user's network which consists of one or multiple secondary user [3]. To guaranty high transmission of the Primary User (PU) and to maximize the transmission rate of the secondary users is one of the most crucial roles in a Cognitive radio system [5,6].

Orthogonal frequency division multiplexing (OFDM) is a promising tech for cognitive radio systems. With OFDM, the SU can smoothly flexible fill the spectral gaps left unused by PUs. It also can determine its location; sense spectrums of other devices, and change in frequency, adjust output power and even alter transmission parameters and characteristics. It can fulfill the SUs communication needs without altering the FCC rules. Cognitive radio mainly works on three tasks including: Radio scene analysis in which CR can detect spectrum holes, lightly used band, interference and Channel state estimation, in which CR determines the channel capacity and the state of the channel; Spectrum management, in which CR makes the spectrum sharing efficient [7,8,9]. The CR design is a featuring new method of radio design philosophy which involves smoothly sensing the vacant spectrum and then determining the transmission characteristics (e.g., symbol rate, power, bandwidth, latency) of a group of secondary users based on the behavior of the users to whom the spectrum has been licensed (PU). The current trend of research focus on power and subcarrier allocation in OFDM/OFDMA based cognitive radio. The various algorithms related to optimal power allocation and carrier allocation is proposed such as under layer and overlayer.

In this paper proposed the optimal power allocation methods for cognitive radio networks using an improved genetic algorithm. The improved genetic algorithms is dual constraint fitness function for the grouping of fairness constraints for the transmission of data and reduces the value of interference during the transmission of primary user[11.12]. The rest of the paper describes as in section II discusses the related work in tabular form. In section III. Discusses the problem formulation. In section IV discusses the system model. In section V discuss the proposed algorithms. In section VI discuss the experimental result and finally discuss conclusion and future work.

II. RELATED WORK

In this section discuss the related work in the field of power allocation techniques in cognitive radio network. The most of authors increase the maximum transmission rate of data. The process of work describes here as tabular form.

Et al.	Author	Title & Publication	Approach	Index Term
[1]	Gaurav Bansal, Md. Jahangir Hossain, Vijay K. Bhargava and Tho Le-Ngoc	Subcarrier and Power Allocation for OFDMA-Based Cognitive Radio Systems with Joint Overlay and Underlay Spectrum Access Mechanism, IEEE, 2013	The optimal scheme can be highly complex, they also discussed a low-complexity suboptimal subcarrier-and-power-allocation scheme. The selected numerical results show that a significant gain in terms of total achievable transmission rate can be obtained over an USAM or an OSAM.	• Cognitive radio • Convex optimization • Orthogonal frequency division multiple access • Over layspectrum access, power and rate adaptation • Underlay spectrum access
[2]	Ratnesh Kumbhkar, Gokul Sridharan, Narayan B. Mandayam, Ivan Seskar and Sastry Kompella	Design and Implementation of an Underlay Control Channel for NC-OFDM-Based Networks, IEEE, 2017	The control channel operates in one of two modes. The first mode aids timing and frequency recovery through a two-step process, while the second mode is used for control data transmission. To enable multiple access, the p2p links use orthogonal pseudo-noise (PN) sequences. The discussed control channel is implemented on USRPs in the ORBIT testbed using GNU Radio.	• Noncontiguous-OFDM • Control channel design • Frequency offset estimation • Timing recovery • PN sequences
[3]	Muhammad Amjad, Mubashir Husain Rehmani and Shiwen Mao	Wireless Multimedia Cognitive Radio Networks: A Comprehensive Survey, IEEE, 2017	They present a comprehensive survey of WMCRNs. Various multimedia applications supported by CRNs, and various CR-based wireless networks are surveyed. They highlight the routing and link layer protocols used for WMCRNs. They cover the quality-of-experience (QoE) design and security requirements for transmitting multimedia content over CRNs.	• Cognitive radio network (CRN) • Multimedia communication • Secondary users • Primary users • Quality-of-service • Quality-of-experience.

[4]	Ubaid Ullah Khan, Naqqash Dilshad, Mubashir Husain Rehmani and Tariq Umer	Fairness in Cognitive Radio Networks: Models, Measurement Methods, Applications, and Future Research Directions, Journal of Network and Computer Applications, 2016	They provide a comprehensive survey of fairness, including measuring parameters, fairness models, fairness issues and discussion on different schemes discussed in the literature. They furthermore present common issues, challenges and future research directions for CRNs in fairness perspective.	• Cognitive Radio Networks (CRNs) • Fairness, Spectrum Sensing • Proportional Fairness • Jian's index.
[5]	Muhammad Amjad, Fayaz Akhtar, Mubashir Husain Rehmani, Martin Reisslein and Tariq Umer	Full-Duplex Communication in Cognitive Radio Networks: A Survey, IEEE, 2017	They survey the spectrum sensing approaches and security requirements for FD-CRNs. They also survey major advances in FD medium access control protocols as well as open issues, challenges, and future research directions to support the FD operation in CRNs.	• Cognitive radio network (CRN) • full-duplex (FD) communication • spectrum sensing • self-interference suppression (SIS).
[6]	Shweta Pandit and G. Singh	An overview of spectrum sharing techniques in cognitive radio communication system, Springer, 2015	They have technically overviewed the state-of-the-art of the various spectrum sharing techniques and discussed their potential issues with emerging applications of the communication system, especially to enhance the spectral efficiency.	• Cognitive radio • Dynamic spectrum access • Opportunistic spectrum access • Wireless communication • Spectrum sharing • Spectrum sensing
[7]	Helin Yang, Chen Chen and Wen-De Zhong	Cognitive Multi-Cell Visible Light Communication with Hybrid Underlay/Overlay Resource Allocation, IEEE, 2018	They investigate the unique optical constraints of transmitters in our discussed C-VLC system, and further discussed a flexible hybrid underlay/overlay resource allocation approach to maximize the sum rate of SUs for the multi-cell C-VLC system, which is very different from radio frequency (RF) communication systems.	• Visible light communication (VLC) • cognitive radio • overlay/underlay spectrum access • resource allocation
[8]	Ajmery Sultana, Lian Zhao and Xavier Fernando	Efficient Resource Allocation in Device-to-Device	Thetransmission rate of the D2D users is optimized while	• Cognitive radio • Device-to-device communication

		Communication using Cognitive Radio Technology, IEEE, 2017	simultaneously satisfying five sets of constraints related to power, interference, and data rate, modeling D2D users as cognitive secondary users in an OFDM environment and analyzed using Lagrange formulation. Furthermore, a two-stage approach is considered to allocate the radio resources efficiently.	• Power allocation • geometric water-filling • Adaptive subcarrier allocation
[9]	T. Abirami and R. Gayathri	A Survey on Efficient Power allocation for OFDM – Based Cognitive Radio Systems, Journal of Chemical and Pharmaceutical Sciences, 2016	They present the different types of algorithms that are used to get better the allocation power in OFDM-based Cognitive Radio (CR) Systems.	• Power allocation • Cognitive radio, OFDM • Energy efficiency • Spectrum Management.
[10]	Tong Xue, Xiaodai Dong and Yi Shi	Resource Allocation Strategy for Multi-user Cognitive Radio Systems: Location-Aware Spectrum Access, IEEE, 2015	The discussed scheme intelligently utilizes frequency and space opportunities, avoids unnecessary spectrum sensing and minimizes the overall power consumption while maintaining the quality of service of a primary system.	• Cognitive radio, energy efficiency • Resource al-location • Location-aware strategy • OFDM
[11]	Jun Peng, Shuo Li, Chaoliang Zhu, Weirong Liu, Zhengfa Zhu and Kuo-chi Lin	A joint subcarrier selection and power allocation scheme using variation inequality in OFDM-based cognitive relay networks, wireless communications and mobile computing, 2016	A non-cooperative game model is discussed to maximize the system throughput by jointly optimizing subcarrier selection and power allocation.	• Cognitive relay networks • Subcarrier selection • Power allocation • Variational inequality • OFDM
[12]	B. Vidhya and PL. Diana Joycy	An Efficient Subcarrier and Power Allocation Scheme for OFDM based Cognitive Radio Networks Considering Channel Sensing Errors, Journal of VLSI Design and Signal Processing, 2016	Sub carrierand power allocation for OFDM based cognitive radio network for joint overlay and underlay spectrum access mechanism (JOUSAM) with channel sensing error is discussed.	• Cognitive radio • OFDM, joint overlay and underlay spectrum access mechanism • Channel sensing error • Subcarrier allocation • Power allocation

[13]	Stefano Buzzi, Chih-Lin I, Thierry E. Klein, H. Vincent Poor, Chenyang Yang and Alessio Zappone	A Survey of Energy-Efficient Techniques for 5G Networks and Challenges Ahead, arXiv, 2016	This survey provides an overview of energy-efficient wireless communications; reviews seminal and recent contribution to the state-of-the-art, including the papers published in this special issue, and discusses the most relevant research challenges to be addressed in the future.	• Energy efficiency • 5G • Resource allocation • Dense networks, massive MIMO • Small cells, mmWaves • Visible-light communications, Cloud RAN • Energy harvesting • Wireless power transfer
[14]	Gozde Ozcan, M. Cenk Gursoy and Jian Tang	Spectral and Energy Efficiency in Cognitive Radio Systems with Unslotted Primary Users and Sensing Uncertainty, arXiv, 2017	The optimal power control policy which maximizes the EE of the secondary users or maximizes the average throughput while satisfying a minimum required EE under average/peak transmit power and average interference power constraints are derived.	• Cognitive radio, collision constraints • energy efficiency • Interference power constraint • Optimal frame duration • Optimal power control • Probability of detection • Probability of false alarm • Renewal processes • Throughput • Un slotted transmission
[15]	Kanchan Tripathi and Jitendra Kumar Mishra	A survey of cooperative spectrum sensing in cognitive radio network", International Journal of Master of Engineering Research and Technology, 2018	A comprehensive survey on the CRN communication paradigm in SGs, including the system architecture, communication network compositions, applications, and CR-based communication technologies. One of the great challenges of implementing spectrum sensing is the hidden terminal problem, which occurs when the cognitive radio is shadowed, in severe multipath fading or inside buildings with high penetration loss, while a primary user (PU) is operating in the vicinity.	• Cognitive Radio, Spectrum Sensing • Cognitive Radio Frontend • Signal Processing • Techniques for Spectrum Sensing • Signaling Overhead • Dynamic Network • Allocation Schemes • Signaling Overhead

III. PROBLEM FORMULATION

We use Pt to denote the OFDM block's total power constraint and Pi is the allocated signal power on the ith subcarrier. Hence the optimal power allocation problem can be expressed by

$$\begin{cases} pi\}_{i=1}^{N} \sum_{i=1}^{N} \text{wi} \log(1+|hi|^2 \text{Pi}) \\ subject\ to: 0 \le Pi \le Si, \forall i; \\ \sum_{i=1}^{N} pi \le pt \\ Fj \le Gj, \forall j \end{cases} \quad \ldots\ldots\ldots.(1)$$

Where N is the total number of subcarriers and J=1……………..M; and M is the total number of sub channel , $.Fj = \sum_{i=mj}^{mj+1-1} pi$ is the power allocated to the jth subchannel and mj is the index of the first subcarrier and mj+1-1 is the index of the last subcarrier in the j^{th} sub channel[13,14].

IV. SYSTEM MODEL

In the CR system based on OFDM, the frequencies that SU can access to may overlay some licensed frequencies allocation algorithm takes not only the transmitter power constraint into consideration, but also the interference constraint. We consider the resource allocation of a CR system with one PU and M (m=1,2,…..M) SUs, but the proposed algorithm can be extended to situations with several Pus. Because we choose underlay as the spectrum access techniques, PU and SUs can access the same frequency at the same time [1,2,3]. As depicted in the figure, the available bandwidth is W Hz and is divided into K(k=1,2,…..K) subcarriers each of which occupies Δf=W_s Hz. The PU occupies W_P Hz among the total bandwidth. Since PU may not employ OFDM, the mutual interference (MI) between PU and SUs is necessary to be considered. The PU receiver locates randomly in a circle of protective field and within the area the interference cannot exceed the threshold l_th.

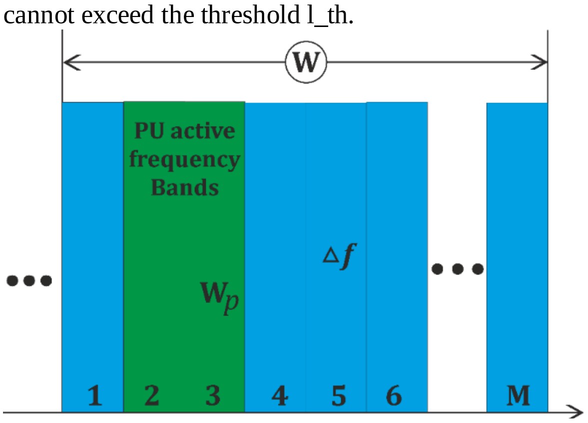

Figure 1 Primary User active frequency band diagram.

The power spectral density (PSD) of the kth subcarrier is modeled as

$$\Phi_k(f) = T_s\left(\frac{Sin\ (\pi f T_s)}{\pi f T_s}\right)^2 \ldots\ldots\ldots\ldots\ldots..(1)$$

The T_s is the symbol duration. The interference to the PU introduced by the k th subcarrier of m^{th} SU is

$$I_{m,k}(d_k, P_{m,k}) = P_{m,k} \int_{d_k - \frac{W_p}{2}}^{d_k + \frac{W_p}{2}} |g_{m,k}|^2 \Phi_k(f) df \ \ldots\ldots\ldots\ldots (2)$$

Where d_k, is the spectral distance between the kth CR subcarrier and the PU band, P_(m,k) is the transmit power of the kth CR subcarrier occupied by m th SU and g_(m,k) denotes the channel fading gain in the kth subcarrier between the mth SU transmit and the PU receiver. As to the interference caused by a PU to SUs, we regard it as white gauss noise in the signal processing. We assume that the subcarriers change slowly with time and SU transmits have perfect channel state information (CSI). Then the maximum number of bits during an OFDM symbol transmitted on kth subcarrier of the mth SU is

$$b_{m,k} = \left\lfloor log_2\left(1 + \frac{|h_{m,k}|^2 P_{m,k}}{\Gamma N_0 W_s}\right) \right\rfloor \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(3)$$

Where the symbol $\lfloor \blacksquare \rfloor$ denotes the flooring operation, h_(m,k) is kth channel gain of mth SU, N_0 denotes the noise PSD and Γ is the single noise ratio (SNR) gap which present the SNR difference in Shannon capacity.

The object is to maximize the overall bit rate allocated SUs under the power, interference and fairness constraints. The optimization problem can be formulated as

$$\max \sum_{m=1}^{M} \sum_{k=1}^{K} x_{m,k}\, b_{m,k} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(4)$$

s.t.

$$\sum_{k=1}^{K} x_{m,k} p_{m,k} < P_m, \forall\, m \in \{1, 2, \ldots\ldots, M\} \ldots\ldots\ldots\ldots\ldots.(5)$$

$$\sum_{m=1}^{M} \sum_{k=1}^{K} x_{m,k} p_{m,k} I_{m,k} < I_{th} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(6)$$

$$x_{m,k} \in \{0,1\}, \sum_{m=1}^{M} \sum_{k=1}^{K} x_{m,k} \le 1, \forall k, m \ldots\ldots\ldots.(7)$$

$$R_1 : R_2 : \ldots\ldots\ldots.: R_M \approx \lambda_1 : \lambda_2 : \ldots\ldots\ldots\ldots.. \lambda_M \ldots\ldots(8)$$

Where $x_{m,k}$ is an allocation indicator which indicates whether subcarrier k is allocated to SU m or not. and guarantees that one subcarrier that one subcarrier can only be allocated to at most one SU. P_m is the transmit power constraint of the m th SU while I_{th} the total interference constraint. $R_m = \sum_{k=1}^{K} b_{m,k}$ is the number of bits allocated to SU m. Consider different quality of services (QoS) of SUs, λ_m is defined as the bit weight factor (BWF). $\frac{\lambda_m}{\sum_{i=1}^{M} \lambda_i}$ indicates the percentage of the bits allocated to SU m in total loaded bits. So, the equation (8) satisfied all QoS of all SUs.

V. PROPOSED ALGORITHM

In this section discuss the multi-objective genetic algorithm. The multi-objective genetic algorithm used for the dual selection of fitness constraints for the reduce the complexity of power allocation and maximize the throughput in OFDMA-based CR system. It firstly calculates the incremental power and incremental interference for transmitting one nit of mth SU on the kth subcarrier. Then the CR system chose the most suitable pair which increases the throughput.

1. Selection process

Combined all the fitness constraints function and produces multiple objective functions using the concept of subcarrier of the index.

f(x)=I1.f(x)+⋯.+In.f(x)……………………(1)

Where x is a string, f(x) is a combined fitness function, I is the index of optimal power

2. Elite Preserves policy

In process of execution of the MOGA, a tentative set of praetor optimal solutions is strode and update at every generation.

3. Process steps

Step 1 generates an initial population contain N strings where N is the number of strings in each population.

Step 2

Estimate the values of the objective function for the generated string. Update the tentative set of solution.

Step3

Estimate the fitness value of each string using the random index. The random index selects in terms of pair string for the processing of data.

$$= \frac{f(x) - fmin(i)}{\sum_{x \in I} f(x) - fmin(i)} \dots\dots\dots\dots\dots(2)$$

Where $fmin(x) = min|f(x), x \in I|$

Step 4

For each selected pair, apply a crossover operation to generate two new strings. The N new string are generated by the crossover operation.

Step 5

For each bit value of string generated by the crossover operation apply a mutation operation probability.

Step 6

Randomly remove the N population string from the set of pervious sets of N population.

Step 7 if the result-oriented solution is obtained the process is terminated.

The proposed algorithm is a combination of two algorithms one is k-means algorithm and the other is MOGA (multi-objective genetic algorithm). The MOGA algorithm validates the value of the optimal power index and validated the generated optimal power for the processing of data in terms of the optimal power index. The proposed algorithm describes in following steps.

Steps 1 initialization

Set the maximization of power in terms of subcarrier index $\{x^*(i,j) I\ i = 1,2,\dots..,n\ ; j = 1,2,\dots,p\}$ is a subcarrier, n is the number of $x^*$and p is the number of factors of each x^* . $x^*(i,j)$is the evaluation index j of the i-th carrier. For different quantities of each power and different ranges of subcarrier, for the formation of SU used mapping function using equation (1) and (2)

For the estimation of allocation group value used these formula

$$x(i,j) = \frac{(x^*(i,j) - x_{min}(j))}{(x_{max}(j) - x_{min}(j))} \quad (1)$$

For the estimation of interference value during the allocation of power:

$$x(i,j) = \frac{((x_{max}(j) - x^*(i,j))}{(x_{max}(j) - x_{min}(j))} \quad (2)$$

Where $x_{min}(j)$the minimum value of is interferences$j$, and $x_{max}(j)$is the maximum value of interferences$j$.

Step 2 estimates the value of optimal power index $Q(a)$. $\{x(i,j) I\ j = 1,2\dots.,p\}$ is distributed into search space based on a genetic algorithm optimal power to get index values $z(i)$ through distribuation $a = [a(1), a(2), \dots.., a(p)]$ as:

$$z(i) = \sum_{j=1}^{p} a(j)x(i,j), \quad i = 1,2,\dots\dots.n \quad (3)$$

Then, $z(i)$ is the center of optimal power, which required allocation of mapped optimal power space

The evaluation index function of optimal power allocation is determined by$Q(a)$, shown as:

$$Q(a) = S_z D_z \quad (4)$$

Where $S_z$is the standard deviation of $z(i)$; $D_z$is the fitness value; standard deviation $S_z$and local density $D_z$are defined in formula (5):

$$\begin{cases} S_z = \sqrt{\dfrac{\sum_{i=1}^{n}(z(i) - E(z))^2}{(n-1)}} \\ D_z = \sum_{i=1}^{n}\sum_{j=1}^{n}(R - r(i,j))\, u(R - r(i,j)) \end{cases} \quad (5)$$

(1) Defining $d(z(k), z(h))$as the absolute distance between the two optimal power index value

$$d(z(k), z(h)) = \sqrt{(z(k) - z(h))(z(k) - z(h))} = \sqrt{(z(k) - z(h))^2}$$

$k = 1,2,\dots\dots\dots..,N; h = 1,2,\dots\dots\dots..,N$

$N(n \geq N \geq 2)$ is evaluation level number or the optimal power s number and $D_q(q = 1,2,\dots\dots,N)$ is used to describe optimal power distance of group $G_q(q = 1,2,\dots\dots,N)$,

Step 4 Determining constraint established the which gave the constraint conditions s.t. $\sum_{j=1}^{p} a^2(j) = 1$. but it did not specify a value range.

$$\begin{cases} s.t. \sum_{j=1}^{p} a^2(j) = 1 \\ 1 \geq a(j) \geq 0 \end{cases} \quad (7)$$

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Step 5 Optimal power evaluation

The evaluation of an optimal power used formula (3) is used to calculate index values. Sample points which have similar index values are divided into one optimal power.

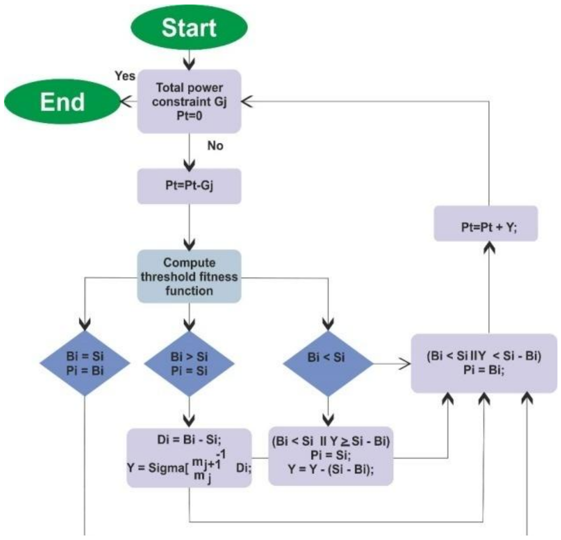

Figure 2 Process block diagram of proposed algorithm.

VI. EXPERIMENTAL RESULT ANALYSIS

The proposed algorithm simulated in MATLAB with given parameter and compare with pervious methods. The values of Ts and Δf have been taken to be 4 µs and 0.3125 MHz, respectively. We assumed that there are K = 4 CR users, N = 8overlay subcarriers, and L = 8 underlay subcarriers. AWGN power per subcarrier σ^2 = 1.2944 × 〖10〗^(-15) W, and the values of interference j_(k,u)= σ^2 (k = 1,2,...,Z).

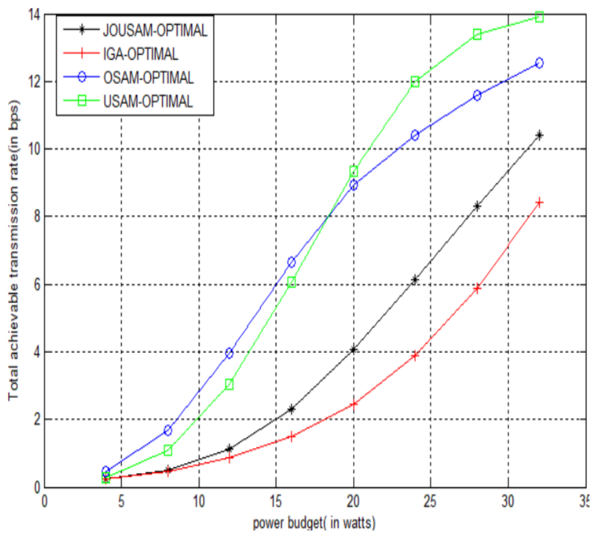

Figure 3 window show that the performance between different techniques.

For a given value of interference threshold I_th^((l))=500 ×σ^2 Wfor all l, we have plotted the total achievable transmission rate of the CR users versus the total power budget for the proposed optimal and -power- allocation schemes for the JOUSAM.

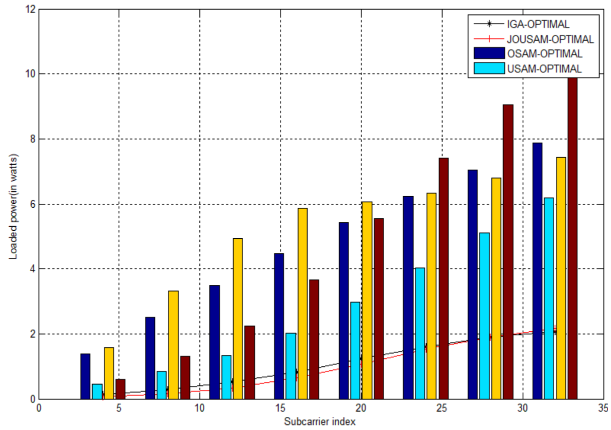

Figure 4 show that the performance between all techniques in our simulation works.

Here we can see the performance between subcarrier and load power. We have plotted the power loading profile for various schemes under consideration to depict how much power can be loaded into different subcarriers under various spectrum access mechanisms. For this plotting, we have used I_th^((l))=50 ×σ^2 Wand total power budget P_T= 50 × 〖10〗^(-3) W. These values are chosen such that the total power budget is relatively high and interference constraint becomes the boundary constraint, i.e., the interference-limited scenario.

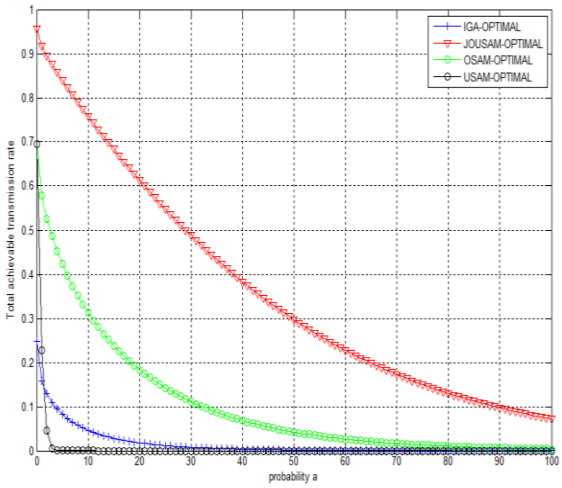

Figure 5 show that the comparative performance of all optimal techniques between probabilities and total achievable transmission rate.

We have varied the probability a threshold and plotted the achievable transmission rate for various schemes under consideration. It can be observed that, for a = 1, the achievable transmission rate is zero as it is impossible that the instantaneous interference remains below threshold Ith with probability 1 while transmitting some power in the CR subcarriers. The achievable transmission rate increases as the value of decreases and vice versa.

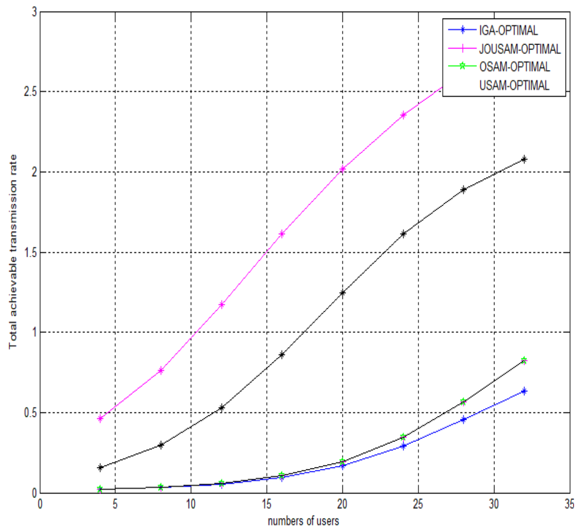

Figure 6 window show that the comparative performance of all optimal techniques between power budget in watts and total achievable transmission rate in bps with using of Matlab tool.

We have compared the maximum transmission rate achieved by the optimal subcarrier-and-power-allocation scheme with that of the subcarrier-allocation scheme with a fairness constraint. We have assumed that there are two CR users in the system with a mean channel fading amplitude gain of -47.91 dB (corresponding path loss of 94.78 dB) for CR user 2 and -52.39 dB (corresponding path loss of 103.73 dB) for CR user 1, respectively. We have assumed that the values of $\beta_1$and $\beta_2$to be 1.

VII. CONCLUSION & FUTURE WORK

In this paper proposed improved genetic algorithm-based power allocation in OFDMA based cognitive radio. The proposed algorithm maximized the rate of transmission in allocating power budget. The proposed algorithms also reduce the interference value of primary user side. These results also showed that the proposed optimal scheme, which has relatively lower operational complexity, provides significant improvements in performance. The proposed optimal scheme can lead to unfairness among CR users in terms of sharing the total transmission rate. In all our work, we used binary interference models and did not account for additive interference. A physical interference model that takes the additivity of interference into account would be more accurate. Running experiments over larger network sizes will draw more realistic conclusions.

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