An OFDM Multi-user Spectrum Resource Allocation Algorithm Based on Joint Access Mechanism

Fulai Liu, Dandan Zhang, Ling Yue, Fan Gao, Ruiyan Du

Engineer Optimization & Smart Antenna Institute, School of Computer Science and Engineering
Northeastern University, Qinhuangdao, China
fulailiu@126.com, zdd_0303@126.com

Abstract—**Aiming at the problem of spectrum resource allocation of multi-cognitive users in CR-OFDM systems, this paper proposes a joint subcarrier and power allocation method based on access mechanism. In addition, the cognitive user's interference to the primary user communication is defined as the opportunity interference constraint. The algorithm first allocates subcarriers, takes into account the different communication needs of each cognitive user in the allocation, and introduces an on-demand allocation scale factor to ensure the fairness of spectrum resource allocation. Then, when the subcarrier allocation is completed, add a power lower bound constraint to each subcarrier allocated by the cognitive user, through a ladder algorithm to complete the power allocation optimization of the subcarrier finally. Simulation results show that the proposed algorithm not only ensures the fairness of capacity allocation among cognitive users but also guarantees the communication quality of each user. In addition, the proposed algorithm is more suitable for practical application background due to the introduction of opportunities to interfere with constraints.**

Keywords-OFDM; spectrum resource allocation; multi-user; power Allocation

I. INTRODUCTION

This Cognitive radio (CR) can detect the surrounding wireless communication environment in real time to obtain information such as idle spectrum and interference temperature, and can provide a comprehensive analysis of this information. Besides, CR can allocate spectrum resources by user requirements and effectively control transmission power, which creating a new situation for efficient use of spectrum resources and sharing of spectrum resources. As one of the key technologies of CR, spectrum allocation refers to the specified number of access to the communication system and the corresponding Quality of Service (QoS) requirements, and the process of assigning spectrum resources to certain users by certain policies. Orthogonal Frequency Division Multiplexing (OFDM) [1] technology is a relatively mature wireless transmission technology, which has superior performance such as high frequency utilization and anti-multipath. At the same time, it also supports a flexible frequency selection scheme, which is currently recognized as a modulation technology that is easy to implement spectrum resource control, and can flexibly allocate wireless resources. Therefore, combining CR with OFDM technology can fully utilize the channel adaptability of OFDM technology and the dynamics of allocation to allocate subcarriers, thereby efficiently managing spectrum resources.

At present, related research on multi-user resources allocation in OFDM-based Cognitive Radio (CR-OFDM) systems has appeared at home and abroad. For example, [2-3] comprehensively consider cognitive users of real-time and non-real-time service types. However, they ignore the fairness of cognitive users or do not consider spectrum sensing that is not completely accurate or does not give the rate requirement of cognitive users. [4] improves the total capacity of the cognitive system as much as possible while satisfying the user's proportional rate demand. However, there is a significant difference in capacity between the proposed algorithm and the optimal algorithm. [5] considers the fairness between cognitive users and uses a two-step method for subcarrier and power allocation, but the article does not consider the opportunity constraint problem. In [6-7], considering that it is difficult to accurately estimate channel state information of network in actual scenarios, the cognitive user's interference constraint condition for the primary user are expressed as an opportunity interference constraint. [8] proposes a distributed resource allocation mechanism that can compromise the fairness and utilization of spectrum resource allocation. [9-10] proposes a corresponding Hungarian algorithm for the relevant spectrum allocation problem of subcarrier pairing and power allocation to ensure optimal power allocation, but the literature does not consider the opportunity constraint problem in combination with actual channel conditions. To meet the requirements of sub-network service quality, this paper expresses the interference constraints that cognitive users need to satisfy the primary users as opportunity-constrained planning, and at the same time guarantees the fairness of capacity allocation among cognitive users, the joint access mechanism is proposed a subcarrier and power allocation optimization algorithm on a CR-OFDM model.

II. SYSTEM MODEL AND MULTI-OBJECTIVE OPTIMIZATION PROBLEM FORMULATION

In the multi-user spectrum resources allocation model based on CR-OFDM, the working frequency band of the Secondary User (SU) may cover the licensed spectrum of multiple Primary User (PU) systems. As shown in Fig.1, the PU defines a protection area and requires that the transmission power of the SU is less than a threshold I_ℓ^{PU} for any potential PU receiver in the protection area. In this paper, a joint subcarrier and power allocation algorithm using Joint Overlay and Underlay Spectrum Access Mechanism is studied and designed. The primary and secondary users can occupy the same frequency band at the same time.

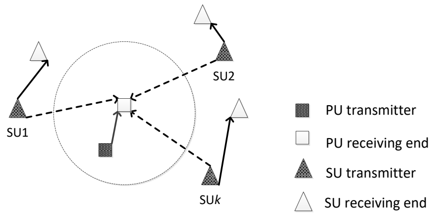

Figure1. System model

Assuming that the cognitive transmitter is in the ideal Nyquist pulse, the power spectral density of subcarrier can be expressed as $\phi_k(f)=p_k T_S(\sin\pi f T_S/\pi f T_S)^2$, in which T_s is the symbol period of OFDM and p_k is the power allocated to the subcarrier k, Define the spectral distance factor as $f(d_{k,\ell})=T_s\int_{d_{k,\ell}-\Delta f/2}^{d_{k,\ell}+\Delta f/2}(\sin\pi fT/\pi fT)^2 df$. Hence, the total interference generated by the cognitive user using the assigned subcarriers to the receiver of the primary user $\ell(\ell\in\mathcal{S}_{\mathrm{U}})$ can be expressed as

$$I_\ell^{\mathrm{PU}}=\left|h_\ell^{\mathrm{SP}}\right|^2\sum_{u=1}^{K}\sum_{k=1}^{Z}\rho_{u,k}p_{u,k}f(d_{k,\ell}),\ \ell\in\mathcal{S}_{\mathrm{U}} \tag{1}$$

where $d_{k,\ell}$ denotes the spectral distance between the CR subcarrier K and the ℓ primary user subcarrier, $p_{u,k}$ is the transmit power of the cognitive user u on the subcarrier k, and h_ℓ^{SP} stands for the cognitive the complex fading coefficient between the transmitter and the primary user ℓ receiver pair, $\rho_{u,k}$ is the carrier occupancy coefficient. The constraint that the cognitive user needs to satisfy the interference generated by the $\ell\,(\ell\in\mathcal{S}_{\mathrm{U}})$ underlay subcarrier is expressed as an opportunistic interference constraint, in order to maximize channel capacity; this paper proposes optimization problems and constraints as follows

$$\begin{aligned}
&\max_{p_{u,k}\rho_{u,k}}\Delta f\sum_{u=1}^{K}\sum_{k=1}^{Z}\rho_{u,k}\log_2\Big(1+\frac{\left|h_{u,k}^{\mathrm{SS}}\right|^2 p_{u,k}}{\sigma^2+J_{k,u}}\Big)\\
&\text{s.t. C1: }\Pr\left(I_\ell^{\mathrm{PU}}\le I_{\mathrm{th}}^{(\ell)}\right)>a,\ \ell\in\mathcal{S}_{\mathrm{U}}\\
&\qquad \text{C2: }\sum_{u=1}^{K}\sum_{k=1}^{Z}\rho_{u,k}p_{u,k}\le P_{\mathrm{T}}\\
&\qquad \text{C3: }\sum_{u=1}^{K}\rho_{u,k}=1,\ \rho_{u,k}=\{0,1\}\\
&\qquad \text{C4: }R_1:R_2:\cdots:R_K=\beta_1:\beta_2:\cdots:\beta_K
\end{aligned} \tag{2}$$

Where C1 represents the opportunistic interference constraint, $I_{\mathrm{th}}^{(\ell)}$ denotes the maximum interference threshold of the cognitive user occupying the subcarrier ℓ to the primary user; C2 represents the total transmit power constraint of the cognitive system, P_{T} stands for the cognition the total transmit power of the system; C3 indicates that each subcarrier can only be occupied by only one cognitive user, but one cognitive user can occupy multiple different subcarriers; C4 represents the scale factor of capacity demand of the cognitive user, it guarantees different QoS requirements for cognitive users.

III. Resource Allocation Algorithm

A. *Subcarrier Allocation Algorithm*

The optimization problem (2) is to maximize the total transmission rate of the cognitive user, and define the metric as follows

$$\Delta_{u,k}=\left|h_{u,k}^{\mathrm{SS}}\right|^2\Big/(\sigma^2+J_{k,u}) \tag{3}$$

The subcarrier sequence set defined for the cognitive user u in the cognitive system is Ω_u^{fair} .Based on the above discussion, it is clear that the proposed subcarrier allocation algorithm for CR-OFDM systems can be summarized and presented with pseudo-codes as follows

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Algorithm: Subcarrier Assignment Algorithm

- Initialization: $\mathrm{A}=\{1,2,\cdots,Z\}$ and $\Omega_u^{\mathrm{fair}}=\varnothing$, Set $u=1$ and $R_{u,k}=0$ at the same time
- Iteration:
  1） Compute $\overline{\Delta_{u,k}}$ for all $k\in A$ according to (3); find the k^* that maximizes the $\overline{\Delta_{u,k}}$ value， where $k^*=\arg\max(\Delta_{u,k})$;
  2） Assign k^* to u , update $\Omega_u^{\mathrm{fair}}=\Omega_u^{\mathrm{fair}}\bigcup\{k^*\}$, and compute R_{u,k^*} according to equation (2);
  3） Let $u=u+1$ and if $u>K$ go to step 4) otherwise go to steps 1)-2);
  4） If $\mathrm{A}\neq\varnothing$ find the u with the largest difference in capacity on the allocated k , where $u^*=\arg\max(R_u-\sum_{k\in\Omega_u^{\mathrm{fair}}}R_{u,k})$;
  5） For u^*, assign the remaining K to it according to steps 1)-2). Repeat step 4)-5) until all u and K are assigned.

B. *Subcarrier Power Allocation Algorithm*

Assuming that the channel fading amplitude gain h_ℓ^{SP} is a Rayleigh distribution obeying the known parameter λ_ℓ, $\left|h_\ell^{\mathrm{SP}}\right|^2$ is an exponential distribution obeying the parameter λ_ℓ^2 . Therefore, the interference constraint can be expressed as $1-\exp\left(-I_{\mathrm{th}}^{(\ell)}\Big/2\lambda^2\sum_{u=1}^{K}\sum_{k=1}^{Z}\rho_{u,k}p_{u,k}f(d_{k,\ell})\right)\ \ge\ a,\ \ell\in\mathcal{S}_{\mathrm{U}}$, which can be reformulated as $\sum_{u=1}^{K}\sum_{k=1}^{Z}\rho_{u,k}p_{u,k}f(d_{k,\ell})\le I_{\mathrm{th}}^{(\ell)}\big/2\lambda^2(-\ln(1-a)),\ \ell\in\mathcal{S}_{\mathrm{U}}$.

Then the subcarrier allocation is performed, the set of subcarriers Ω_u assigned to each user has been determined, and the optimization problem described in the optimization problem (2) can be simplified to the following form

$$\max_{p_{u,k}} \sum_{u=1}^{K}\sum_{k\in\Omega_u} \log_2\Big(1+\frac{\left|h_{u,k}^{\mathrm{SS}}\right|^2 p_{u,k}}{\sigma^2+J_{k,u}}\Big)$$

$$\text{s.t. } \sum_{u=1}^{K}\sum_{k\in\Omega_u} p_{u,k} f(d_{k,\ell}) \le \frac{I_{\mathrm{th}}^{(\ell)}}{2\lambda^2(-\ln(1-a))},\ \ell\in\mathcal{S}_{\mathrm{U}}; \qquad (4)$$

$$\sum_{u=1}^{K}\sum_{k\in\Omega_u} p_{u,k} \le P_{\mathrm{T}};\ p_{u,k}\ge P_{\mathrm{L}}; R_1:R_2:\cdots:R_K=\beta_1:\beta_2:\cdots:\beta_K;$$

This paper uses the ladder allocation algorithm for research. The ladder formula assigns power based on the distance between the subcarrier and the main user band. First, equal power allocation to the underlay subcarrier can be expressed as $p_{\ell}^{\mathrm{sub,un}} = P^{\mathrm{un}}, \ell\in\mathcal{S}_{\mathrm{U}}$; then the power allocated to the overlay subcarriers is distributed in a stepwise manner, and the step size of the steps is fixed. The power allocated to the overlay subcarrier can be expressed as follows

$$p_n^{\mathrm{sub,ov}} = P^{\mathrm{ov}}\times i_n, n\in\mathcal{S}_{\mathrm{O}} \qquad (5)$$

where $i_n \triangleq \lfloor \Delta n/\Delta f \rfloor$, in which Δn denotes the spectral distance between the n overlay subcarrier and the nearest primary user band. Here, introducing a design factor x, the mathematical relationship between the power P^{ov} allocated to the overlay subcarrier closest to the primary user band and the power P^{un} assigned to the underlay subcarrier is $P^{\mathrm{ov}} = x\times P^{\mathrm{un}}$. The algorithm of subcarrier power allocation is summarized as follows

Algorithm: Subcarrier Power Allocation Algorithm

- Initialization: Allocate the same power to all underlay subcarriers;
- Iteration:

1） compute $P_{(1)}^{\mathrm{un}}$ according to

$$\sum\nolimits_{\ell=1}^{L} p_{\ell}^{\mathrm{sub,un}} + \sum\nolimits_{n=1}^{N} p_n^{\mathrm{sub,ov}} = P_{\mathrm{T}};$$

2） According to the predetermined interference threshold $I_{\mathrm{th}}^{(\ell)}$,compute $P_{(\ell)}^{\mathrm{un}}$ for all $\ell\ (\ell=2,\ldots,L+1)$ according to

$$P_{(\ell+1)}^{\mathrm{un}}\sum_{k=1}^{L} f(d_{k,\ell}) + xP_{(\ell+1)}^{\mathrm{un}}\times\left(\sum_{k=L+1}^{N+L} f(d_{k,\ell})\times i_{(k-L)}\right); = I_{\mathrm{th}}^{(\ell)}\big/2\lambda^2(-\ln(1-a))$$

3） The value of the power P^{un} finally assigned to all underlay subcarriers is determined by equation $P^{\mathrm{un}} = \max\left\{P_{\mathrm{L}}, \min\left\{P_{(1)}^{\mathrm{un}}, P_{(2)}^{\mathrm{un}}, \cdots, P_{(L+1)}^{\mathrm{un}}\right\}\right\}$;

4） Combine the results of step 3) compute P^{ov} for all N according to (5); until the power allocated to each subcarrier is determined.

IV. SIMULATION RESULTS

This section conducts experiments to evaluate the performance of the proposed algorithms. Assuming that the number of OFDM subcarriers is $Z=16$, where the number of overlay subcarriers is $N=8$, and the number of underlay subcarriers is $L=8$. The channel bandwidth of the subcarrier is $\Delta f = 0.3125\mathrm{MHz}$, the symbol period of OFDM is 4 μs , and the number of cognitive users is $K=4$. Assuming that the noise is Additive White Gaussian Noise(AWGN) and the variance is $\sigma^2 = 1.2944\times10^{-15}\mathrm{W}$, the probability of the chance interference constraint of the cognitive user occupying the subcarrier is $a=0.95$, and the sum of the interference caused by the primary user's normal communication to the subcarrier occupied by the cognitive user is $J=\sigma^2$.

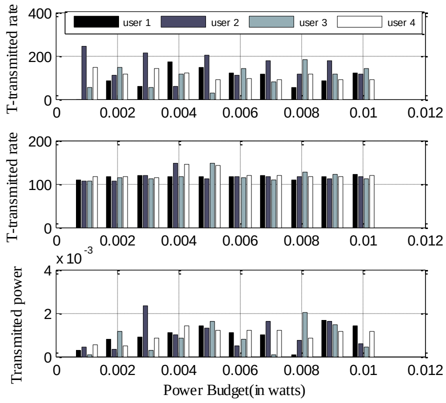

Figure2. User comparison chart based on maximum capacity and proportional fair distribution strategy.

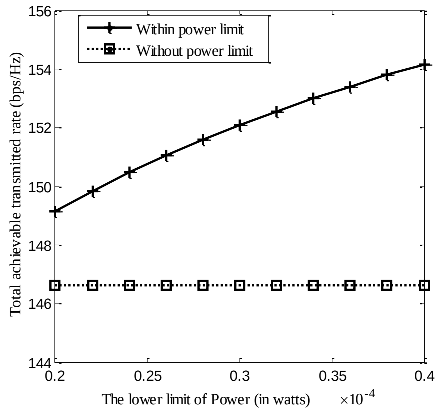

Figure3. The total transmission rate of cognize user 1 under different lower limit of power.

Fig.2 shows the performance comparison of subcarrier allocation algorithms for four cognitive users under different transmit power budget values. As can be seen from the first figure in Fig.2, for the sub-carrier allocation strategy based on the largest capacity, the cognitive users sometimes have better capacity and can guarantee normal communication. The capacity is small, and even some subcarriers are not allocated capacity, which affects the normal communication of cognitive users. As can be seen from the second figure in Fig.2，the proportional fair allocation strategy based on user fairness allocates the relative average capacity of each cognitive user, mainly because the algorithm considers the fairness of capacity allocation among cognitive users, where $\beta_1 : \beta_2 : \beta_3 : \beta_4 = 1:1:1:1$. The capacity requirements are guaranteed and more stable than the allocation strategy based on the largest capacity.

Fig.3 shows the total transmission rate curve for cognitive user 1 under different power lower limit conditions. It can be seen from the figure that under the premise that the total transmit power allocated to the cognitive user 1 satisfies the constraint condition, as the power lower limit set for the cognitive user increases, the transmission rate of the cognitive user 1 gradually increases, thereby improving. The communication quality of the cognitive user satisfies the communication needs of the cognitive user.

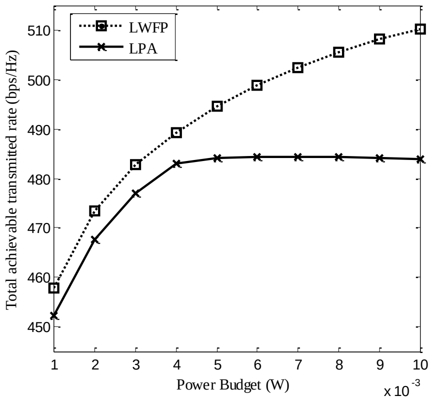

Figure4. Total achievable transmitted rate varying transmitted power budge.

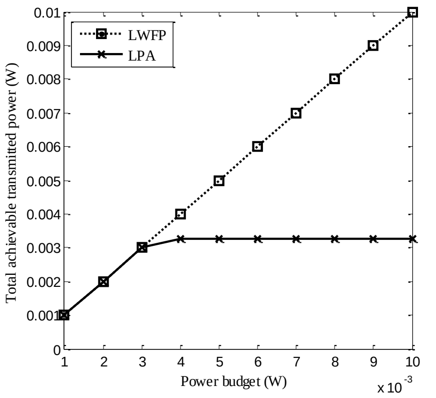

Figure5. Total achievable transmitted power varying transmitted power budge.

Fig.4 and Fig.5 shows the total transmission rate and total transmission power of the two power allocation algorithms under different transmit power budget values. It can be seen from the figure that the total transmission rate of the Power allocation based on Linear Water-Filling(LWFP) algorithm is higher than the ladder algorithm given the same rated transmission power, and more transmission power is required than the ladder algorithm to achieve larger capacity transmission. As the upper limit of the total transmit power of the cognitive system increases, the transmit power required by the cognitive user in the LWFP algorithm is higher than the transmit power required by the cognitive user in the ladder algorithm. As can be seen from equation (1), the more power is allocated to the cognitive user, the greater the interference to the primary system. Therefore, compared to the LWFP algorithm, the ladder algorithm used in this paper has a compromise between capacity and interference.

V. CONCLUSIONS

This paper analyses the problem of spectrum resource allocation in CR-OFDM and proposes a joint subcarrier and power allocation algorithm. The algorithm introduces a proportional allocation factor to allocate sub-carriers to avoid the imbalance of spectrum resource allocation of cognitive users, the algorithm adds a power lower bound constraint to the sub-carriers assigned to each cognitive user, and uses a ladder algorithm to solve the problem of power allocation optimization, complete the power allocation of the subcarriers. The simulation results show that the algorithm significantly improves the spectrum efficiency of the system and ensures the QoS requirements of cognitive users, which reflects fairness. Moreover, the ladder algorithm used in subcarrier power allocation is more suitable for the compromise between capacity and interference than the power allocation algorithm based on linear water injection method, and the complexity is lower. In addition, the algorithm uses the opportunity interference constraint to describe the interference constraints of the cognitive system to the primary user, so the algorithm is more in line with the practical application background.

VI. ACKNOWLEDGMENT

This work was supported by the Natural Science Foundation of Hebei Province (No. F2016501139) and the Fundamental Research Funds for the Central Universities under Grant No. N162304002 and No. N172302002.

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