Aadptive Subcarrier Allocation for Multiple Cognitive Users over Fading Channels

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Keywords: Cognitive Radio Network; Adaptive subcarrier allocation; Fading channels; Subcarrier efficiency function; Rate adaptive criterion; Computational complexity

Abstract. In Cognitive Radio Network (CRN), where Primary User (PU) and multiple Secondary Users (SUs) wish to communicate with their corresponding receivers simultaneously over fading channels, spectrum utilization and efficient resource allocation are both significant points for CRN. Interference between PU and SUs should be eliminated in order to realize spectrum sharing. Multi-user resource allocation with the target of maximizing the spectral efficiency of SUs and satisfying the proportional rate constraint between SUs are proposed under the conditions of total SU interference constraint. An adaptive low-complexity suboptimal algorithm for subcarrier and power joint allocation is presented based on Rate Adaptive (RA) criterion, where adaptive subcarrier allocation is performed by assuming equal power distribution, while each subcarrier is assigned in accordance with subcarrier efficiency function. Moreover, linear water-filling algorithm for power allocation is applied within each subcarrier. Simulation results indicate that, with the proposed adaptive subcarrier allocation, spectral efficiency of multiple SUs is superior to traditional subcarrier power joint allocation algorithm. Low computational complexity and adaptive features make it available for implementation.

Introduction

Scarce are the spectrum resources for new wireless services and low is the spectrum utility for licensed spectra, which motivates the development of Cognitive Radio (CR) technique recently. CR systems have been proposed to efficiently exploit the overall spectrum by allowing Secondary Users (SUs) to opportunistically access to the dedicated spectra that have been assigned to Primary Users (PUs), where SUs are allowed to transmit and receive data over portions of spectra when PUs are inactive, demanding that the SUs be invisible to PUs [1]. To fulfill the invisibility requirements, SUs need to sense the spectrum, and this involves some sort of spectral analysis [2]. A significant number of recent researches have aimed at optimizing systematic scheduling by utilizing the available network resource intelligently. *i. e.*, adaptive subcarrier, power and bit joint allocation with the purpose of achieving multi-user diversity to improve system spectral efficiency [3,4,5]. According to different optimization objectives, joint resource allocation algorithm usually implement many optimal algorithm for different objectives, such as water-filling, greedy or iterative algorithms, which has large computational complexity but do not suitable to practical distributed cognitive network with multiple SUs.

The above observation motivates us to design a practical resource allocation strategy with adaptive features based on Cognitive Orthogonal Frequency Division Multiplexing (C-OFDM) modulation. Recently, multi-carrier modulation (MCM) has been recognized as potential candidates for the Physical Layer (PHY) of CRN [6,7]. Because MCM could overcome frequency selective fading by transforming the fading channel into equivalent parallel flat fading channels, we propose an adaptive subcarrier power joint allocation algorithm for multiple SUs in Cognitive OFDM. Due to the Quality of Service (QoS) of PUs should not affected by SUs, the interference between PUs and SUs should below a threshold, that is, the total transmit power of SUs is limited to guarantee the QoS of PUs [7,8]. Hence, efficient resource allocation based on opportunistic spectrum access for multiple SUs is the promising issue in CRN.

System Model and Power Constrains

As illustrated in Fig. 1, we consider spectrum sharing CRN with a pair of PU and multiple pairs of SUs, each with their transceivers respectively. In this model, PU Transmitter (PUT) communicates with PU Receiver (PUR) via the licensed spectrum band while each SU Transmitter (SUT) also wishes to send information to their corresponding SU Receiver (SUR) opportunistically at the same band [6,7]. In this coexistence of primary and secondary network, channel between each SUT and PUR is defined as interfering channel, while the one between each SUT and its corresponding SUR is denoted as cognitive channel. We assume a total of K cognitive users in C-WSN sharing N subcarriers and the total bandwidth is B. Then $|g_{k,n}|^2$ and $|h_{k,n}|^2$ denote the interfering channel and cognitive channel of the k-th SU with the n-th subcarrier respectively. In the condition of Rayleigh fading channel, we assume that perfect Channel State Information (CSI) could be available at each SUT, and channel noise from PUT to each SUR can be considered as AWGN for SUR [5]. Furthermore, we suppose the k-th SUT could adjust its transmission power $P_{k,n}$ at the n-th subcarrier.

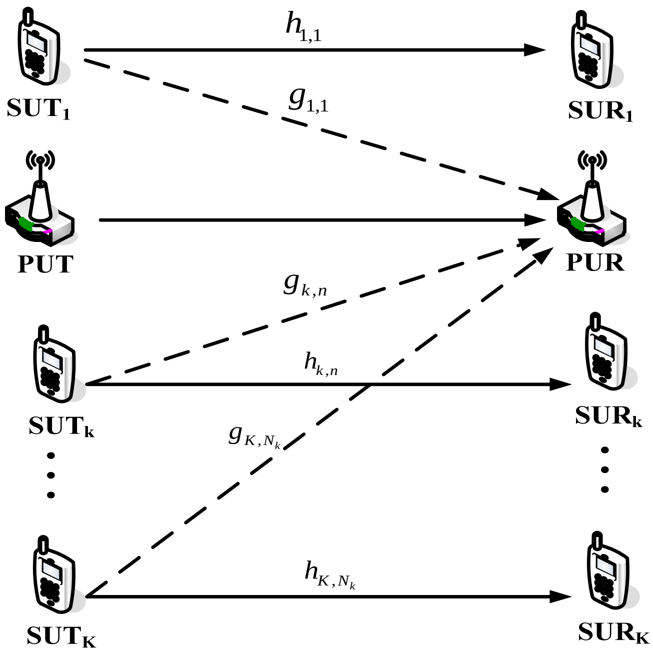

Fig. 1 System model of a pair of PU and multiple pairs of SUs

In the case of K pairs of SU transceiver, we set K SUTs' total transmit power P_{SU} as the interference power constraint within the bandwidth B. Then the k-th SU cognitive channel achievable rate can be expressed as

$$\begin{aligned} R_k &= \frac{B}{N}\sum_{n=1}^{N_k}\log_2(1+\frac{|h_{k,n}|^2 P_{k,n}}{\sigma_{k,n}^2\Gamma}) \\ &= \frac{B}{N}\sum_{n=1}^{N_k} b_{k,n} \end{aligned} \tag{1}$$

where the k-th SU has N_k subcarriers, $P_{k,n}$ indicates the transmitted power of the k-th SU at the n-th subcarrier, and $\sigma_{k,n}^2$ denotes the noise power of the k-th SU in the n-th subcarrier, which includes the interference generated by PUT and the random noise, and $b_{k,n}=\log_2(1+\frac{|h_{k,n}|^2 P_{k,n}}{\sigma_{k,n}^2\Gamma})$ is the bits of the k-th SU at the n-th subcarrier. The k-th SU's spectral efficiency can be regarded as the sum of the bits allocated in the assigned subcarriers [9,10]. Mathematical model of adaptive subcarrier power joint optimization can be written as

$$\begin{cases} \arg \max\limits_{P_{k,n},\rho_{k,n}\in[0,1]} R_{\text{total}} = \sum\limits_{k=1}^{K} \rho_{k,n} R_k \\ \text{s.t.} \quad \begin{cases} \sum\limits_{k=1}^{K}\sum\limits_{n=1}^{N_k} \left|g_{k,n}\right|^2 P_{k,n} \le P_{\text{SU}} \\ R_1 : R_2 : \cdots : R_K = r_1 : r_2 : \cdots : r_K \\ \sum\limits_{k=1}^{K} \rho_{k,n} = 1, \quad \rho_{k,n} \in \{0,1\} \end{cases} \end{cases} \tag{2}$$

where K is the total number of SUs, N is the total number of subcarriers, and $\rho_{k,n}$ only be either 1 or 0, indicating whether subcarrier n is used by the k-th SU or not. $\{r_k\}_{k=1}^{K}$ denotes a set of predetermined values that are used to ensure proportional fairness among SUs. In this condition, we also regard the maximum achievable rate of multiple SUs with adaptive subcarrier power joint allocation scheme [11,12].

Adaptive Subcarrier Allocation Algorithm

Our proposed suboptimal subcarrier power joint allocation scheme has two independent parts. One is subcarrier allocation, the other is power allocation. Subcarrier allocation is performed by assuming equal power distribution, while each subcarrier is assigned to SU in accordance with the best subcarrier efficiency function, which improves the fairness between different SUs. After subcarrier allocation, we use adaptive linear water-filling algorithm to inject power at each subcarrier. Although this algorithm is suboptimal to traditional capacity maximization algorithm, it could reduce the whole scheme's computational complexity efficiently.

Firstly, we consider adaptive subcarrier allocation algorithm, which satisfies the proportional rate constraint between SUs. Each SU chooses the available subcarrier that has large subcarrier efficiency value, but do not choose the subcarrier that with high SNR. Subcarrier efficiency function is shown as below

$$\beta_{k,n} = \frac{b_{k,n}}{\sum\limits_{m=1}^{K} b_{m,n}} \tag{3}$$

where $b_{k,n}$ denotes bits of the k-th SU at the n-th subcarrier illustrated in Eq. (1). Eq. (3) can be viewed as the ratio of the assigned bits at the n-th subcarrier and the whole bits of the n-th subcarrier.

Suppose N_k denotes the set of subcarriers for the k-th SU, and A is the set including all subcarriers. Then the achievable rate of each SU shown in Eq. (1) is updated by the following specific processes.

- Initialization.
  Set $N_k = \Phi$, $A = \{1,2,\cdots,N\}$, and $R_k = 0$, $k = 1,2,\cdots,K$.
- For $k = 1,2,...,K$, the iteration process is shown as below.
  a) $k = 1$;
  b) Find n, which satisfies $\beta_{k,n} \ge \beta_{k,j}$, for all $j \in A$;
  c) Let $N_k = N_k \cup \{n\}$, $A = A - \{n\}$ and update $R_k = R_k + \log_2(1 + \frac{\left|H_{k,n}\right| P_{\text{SU}}}{N})$, where $H_{k,n} = \frac{\left|h_{k,n}\right|^2}{\sigma_{k,n}^2 \Gamma}$.
- When $A \ne \Phi$, the fairness of subcarrier allocation is presented as follows.
  a) Find k^*, which satisfies $\frac{R_{k^*}}{r_{k^*}} \le \frac{R_i}{r_i}$, for all $1 \le i \le K$;
  b) For the optimal SU k^*, find the subcarrier n^*, which satisfies $\beta_{k^*,n^*} \ge \beta_{k^*,j}$, for $j \in A$;

c) For the found optimal SU k^* and subcarrier n^*, let $N_{k^*} = N_{k^*} \cup \{n^*\}$, $A = A - \{n^*\}$, and update $R_{k*} = R_{k*} + \log_2(1 + \frac{|H_{k^*,n^*}| P_{SU}}{N})$.

d) Continue the above iteration steps until $A = \Phi$.

Then, after subcarrier allocation, adaptive power allocation for each fixed subcarrier is performed with adaptive linear water-filling algorithm, that is, the objection of power injection is the maximization of transmission rate for the k-th SU R_k with the power constraint $\sum_{n=1}^{N_k} |g_{k,n}|^2 P_{k,n} = \frac{N_k}{N} P_{SU}$, where R_k is given in Eq.(1). The flow of adaptive linear water-filling algorithm is just the same as Best to be Better algorithm shown in Ref. [2,7,9], which has much lower computational complexity compared with traditional linear water-filling.

Simulation Results and Discussions

In this section, we present and discuss the simulation results for our proposed adaptive water-filling algorithm. Simulation parameters are referred in Ref. [9,10,12] with cognitive OFDM (C-OFDM) modulation.

Fig. 2 illustrates the same relationship of SU's transmitted power (equals to SU's bit SNR with $N_0 = 1$) and spectral efficiency with $N = 128$, $\mathrm{Pr}_b = 10^{-5}$. It is indicated that, the proposed algorithm also has the best spectral capacity performance. *i.e.*, when SU's SNR is $20\,\mathrm{dB}$, spectral efficiency approaches to $12.5\,\mathrm{bps/Hz}$, the value is much higher than adaptive power allocation algorithm about $2.5\,\mathrm{bps/Hz}$ and linear switch algorithm about $4.5\,\mathrm{bps/Hz}$ respectively. It is also shown that, linear switch algorithm has better performance than adaptive power allocation within low SNR region (namely, $\mathrm{SNR} < 10\,\mathrm{dB}$), while in higher SNR region, adaptive water-filling has its unique advantages. We also find that, subcarrier number influences spectral efficiency significantly, and spectral efficiency could be improved with the increase of subcarrier numbers. *i.e.*, when SU's transmitted power is $20\,\mathrm{dB}$, SU's maximum spectral efficiency with $N = 128$ achieves $12.5\,\mathrm{bps/Hz}$, which is $3.5\,\mathrm{bps/Hz}$ higher than $N = 64$ at the same scenario. It also indicates that, traditional power allocation algorithms are suitable for low subcarrier number region, while the proposed adaptive water-filling algorithm is fit for all situations. Moreover, the computational complexity of the proposed algorithm is lower than traditional ones, which is appropriate for implementation in distributed CRN.

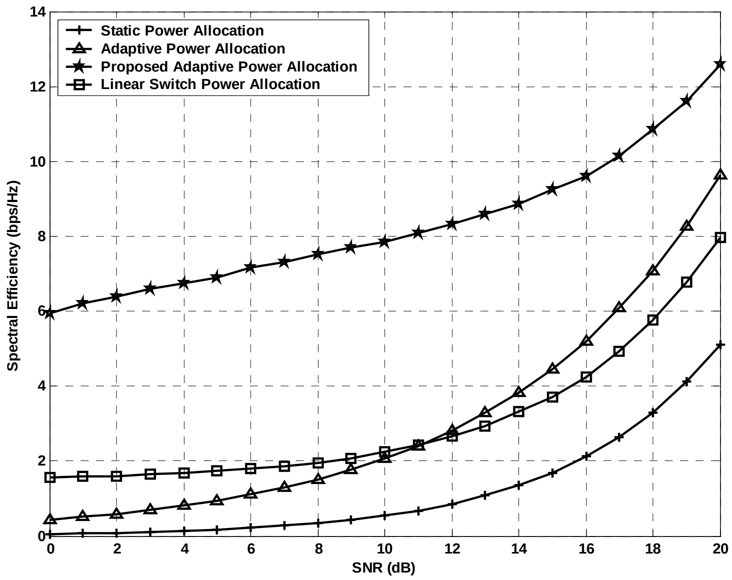

Fig. 2 Relationship of SU's transmitted power and spectral efficiency ($N = 128$, $\mathrm{Pr}_b = 10^{-5}$)

Moreover, relationship of subcarrier numbers and spectral efficiency with SU numbers $K=5$ and the required BER $\Pr_b=10^{-3}$ is shown in Fig. 3. It is illustrated that, the proposed algorithm is superior to average power allocation, and inferior to adaptive capacity maximization algorithm. However, when the whole subcarrier number is fixed as $N=16$, each curve reaches their peak values, which indicates that the increasing of subcarrier number could not enhance total achievable rates in SUs' cognitive channel. Obviously, the theoretical peak results could not be achieved with multiple SU in C-OFDM. Although our proposed resource allocation algorithm performs a little inferior to capacity maximization algorithm, it has low computational complexity and adaptive features, which enables it to be implemented in practical CRN.

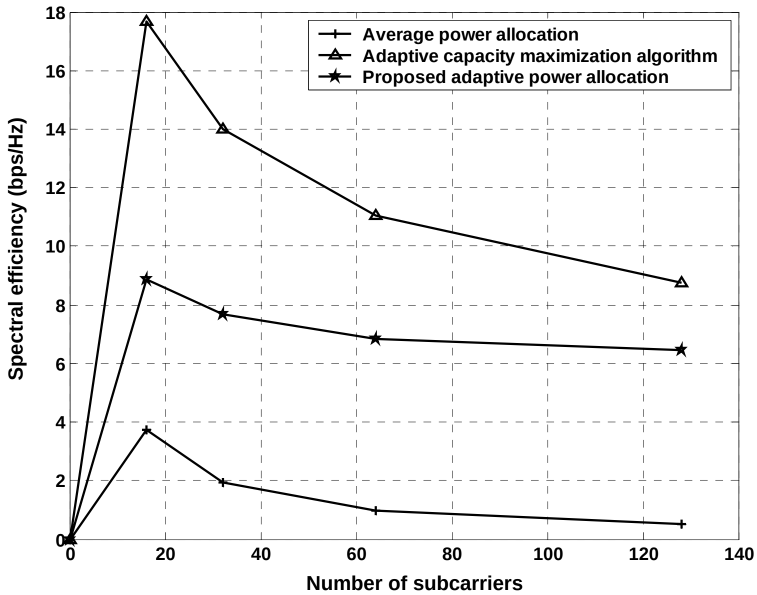

Fig. 3 Subcarrier number and spectral efficiency with $K=5$, $\Pr_b=10^{-3}$ for multiple SUs

Summary

An effective adaptive subcarrier allocation algorithm is presented in CRN with multiple SU underlay spectrum sharing scenario. The proposed subcarrier allocation strategy could directly determine the subcarriers that do not require power allocation by rough estimation of water levels. Hence, computational complexity could be reduced significantly for the proposed scheme. In K SU transceivers scenario, our scheme is composed of subcarrier allocation as well as adaptive linear water-filling algorithm, which is based on RA criterion. Simulations are performed in RA criterion with the condition of SUs' power control. Numerical results confirm our theoretical derivations for different circumstances. It is shown that, for single SU situation, spectral efficiency is superior to traditional subcarrier power joint allocation algorithm, while for multiple SU transceivers scenario, our proposed algorithm performs a little worse than adaptive capacity maximization algorithm, however, computational complexity of the proposed algorithm could be reduced, and its adaptive features and low complexity makes it appropriate for practical application in resource-restrained CRN.

Acknowledgments

This work is supported by National Natural Science Foundation of China (Grant No. 61102066, 61001133), China Postdoctoral Science Foundation (Grant No. 2012M511365, 2011M500999), Scientific Research Project of Zhejiang Provincial Education Department (Grant No. Y201119890), and Zhejiang Provincial Natural Science Foundation of China (Grant No. LY12F01021). Preliminary results of this paper were presented in part at the Proceedings of 2011 the 2nd Asia-Pacific Youth Conference on Communications (APYCC 2011).

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Published by Atlantis Press, Paris, France.