Aggregation-Aware Resource Allocation for Cognitive Radio Networks

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Abstract—**In this paper, we investigate the dynamic spectrum aggregation and allocation problem in multiuser orthogonal frequency division multiplexing (OFDM)-based cognitive radio (CR) networks. We first study a spectrum aggregation (SA)-based spectrum assignment algorithm, which enables secondary users (SUs) to gather multiple spectrum fragments into one channel to support high bandwidth requirement, to improve the spectrum utilization efficiency for the considered system. Then we aim to maximize the system capacity of the considered CR network while considering many practical limitations, such as minimal rate requirement of SUs, transmission power budget and interference constraints of the system. Since the formulated optimization task is a challenging mixed integer programming problem that is NP-hard, a user-oriented subcarrier allocation algorithm is introduced to remove the integer constraints and then for a given subchannels assignment, a fast barrier method is developed to tackle the optimal power allocation problem, the key of which is to calculate Newton step with approximate linear complexity instead of $\mathcal{O}(N^3)$ in standard method. Simulation results validate that our algorithm is significantly better than the standard technique and can maximize the sum capacity of the system.**

Index Terms—**Cognitive radio (CR), OFDM, optimization, resource allocation (RA), spectrum aggregation (SA).**

I. INTRODUCTION

Mobile wireless communications industry has witnessed a boom in the traffic data in varies wireless service and applications in the last decade, which leads to the urgent need of spectrum resource. Thus, the scarcity of spectrum resource has drawn accelerating concern in today's wireless networks [1, 2]. Cognitive Radio (CR) can significantly improve spectrum utilization efficiency by conducting the spectrum sharing between primary users (PUs) and secondary users (SUs), which allows SUs to opportunistically access the spectrum holes without causing harmful interference to PUs [3–5]. Orthogonal Frequency Division Multiplexing (OFDM), is widely recognized as a promising modulation technology for CR system due to its high flexibility in radio resource allocation (RA) [6]. There have been many related works on dynamic RA algorithms for OFDM-based cognitive radio networks. In [7], the authors develop an efficient optimal power distribution algorithm with lower complexity, which not only obtains a significant capacity gain but also perfectly satisfies the proportional fairness. In [8, 9], energy consumption issue for OFDM-based CR networks is investigated, where many practical constraints are taken in to consideration to maximize the energy efficiency of the considered system. In [10], a quality of experience (QoE)-based RA algorithm is investigated, in which subjective metrics to evaluate network performance is introduced.

However, the above works are based on contiguous spectrum assignment algorithms, in which each of the orthogonal subchannels consist of only one spectrum fragment while those small spectrum fragments whose bandwidth are too small to afford the transmission demand can not be fully utilized. This inevitably leads to low spectrum utilization and becomes a crucial challenge which blocks the further development of wireless communications. Spectrum aggregation (SA), which aims to gather discrete spectrum fragments to support high bandwidth requirement of users, is deemed as a promising technology to address the challenges mentioned above and can be implemented by discontinuous orthogonal frequency division multiplexing (DOFDM) [11, 12]. Specifically, DOFDM is an advanced technology which can make the discrete spectrum fragments be accessed simultaneously by a single radio and then make them be aggregated into one channel [13] so as to satisfy the transmission bandwidth requirement. Nevertheless, since the limitations of hardware, not all vacant fragments can be aggregated. Only the discontinuous bands within maximum aggregation span (MAS) can be aggregated by SUs.

In this paper, we study the aggregation-based RA technique in the downlink of multiuser OFDM-based cognitive radio networks, in which we try to maximize the sum capacity of the considered system while quantifying the maximum spectrum utilization. We mainly make the following contributions:

- With the help of discontinuous spectrum access, we propose aggregation based spectrum assignment, the small spectrum fragments could be aggregated and further utilized, which can dramatically improve the spectrum utilization efficiency.
- We propose an efficient RA algorithm, the complexity of which has a significant advantage over the standard convex optimization technique. Thus, it is quite applicable in practical systems.

The rest of this paper is organized as follows. In Section II,

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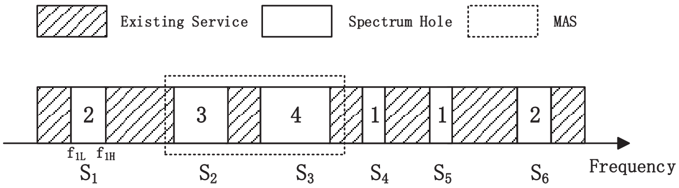


Fig. 1. An example of spectrum fragments. The letters are the labels of the available bands. The numbers are the bandwidths of the bands (MHz).

we illustrate system model and formulate optimization problem. In Section III, subchannel allocation method and optimal power distribution algorithm are proposed. Simulation results and discussions are presented in Section IV and conclusions are drawn in Section V.

II. SYSTEM MODEL

A. Spectrum Aggregation

Consider the downlink of a multiuser OFDM-based CR network with *K* SUs, denoted by $\mathcal{K} = \{1, 2, \ldots, K\}$, sharing spectrum bandwidth with *L* PUs in a licensed system, denoted by $\mathcal{L} = \{1, 2, \ldots, L\}$. Let $B_i(i = 1, 2, \ldots, K)$ indicate the bandwidth requirement of a CR link. There are *M* spectrum fragments, denoted by $\mathcal{M} = \{1, 2, \ldots, M\}$. The whole spectrum range is from $[f_{1L}, f_{MH}]$, and the range of the *m*th band is $[f_{mL}, f_{mH}]$ as shown in Fig. 1. Then we make the following assumptions in this paper: (i) Assume that perfect channel state information (CSI) is available at the transceivers of the SUs and PUs; (ii) Assume that each SU has the same aggregation capability and the MAS is fixed, thus the SUs can only aggregate the spectrum fragments within MAS; (iii) Assume that a period consists of spectrum detection, spectrum allocation and data transmission, in which there are always transmission requests; (iv) Assume that that the status of idle spectrum fragments varies slowly compared to the fast process of performing spectrum allocation [14], so the vacant frequency bands in the CR network is deemed to be fixed.

Assume that in a CR network, the transmission bandwidth requirement is 4MHz. The hatching parts are occupied and the white parts, which are denoted by $\{s_1, s_2, \ldots, s_6\}$ are available spectrum bands as shown in Fig. 1. The MAS is fixed to be 10MHz and all the aggregated spectrum fragments must be within it. With contiguous spectrum assignment, it can only utilize the 4MHz band (s_3) and the other vacant bands are wasted because they are smaller than the demand 4MHz. Obviously, the utilization of the given spectrum is very low. If we could aggregate small fragments into one channel, we could fully utilize those vacant spectrum holes. For example, aggregate s_1 and s_2 or s_4, s_5 and s_6.

Based on the above discussions, we propose an aggregation-aware spectrum assignment for downlink multiuser OFDM-based CR systems. Let C_n indicates channel *n*, whose bandwidth is $| C_n |$ Hz. C_n consists of N_n spectrum fragments. Denote

$$\begin{aligned} F &= \mathop{}\limits_{m=1}^{M} [f_{mL}, f_{mH}], \ f_{mH} < f_{(m+1)L}, \\ C_n &= \mathop{}\limits_{i=1}^{N_n} [f_{nL}^i, f_{nH}^i] \subseteq F, \\ | C_n | &= \sum_{i=1}^{N_n} | f_{nH}^i - f_{nL}^i |, \end{aligned} \tag{1}$$

where $[f_{nL}^i, f_{nH}^i]$ represents the range of the ith spectrum fragment of the nth aggregated subchannel.

The problem of the maximization of spectrum utilization efficiency can be formulated as follows,

$$\begin{aligned} & \max \textstyle\sum_{i=1}^{K} x_i \mid B_i \mid \\ s.t. \quad & C_1 : | f_{nL}^i - f_{nH}^j | \leq \mathrm{MAS}, \forall 1 \leq i, j \leq N_n, \forall n \\ & C_2 : C_i \quad C_j = \varnothing, \forall i \neq j, \\ & C_3 : \textstyle\sum_{n=1}^{N} | C_n | \leq | F |, \\ & C_4 : | C_n | \geq B, \forall n, \end{aligned} \tag{2}$$

where x_i is a binary variable representing whether or not the SU *i* is allocated spectrum. MAS is the max span of a channel and *B* is a known constant, indicating the minimal transmission bandwidth; otherwise the node cannot start transmitting.

Then, we propose an efficient spectrum assignment for Eq. (2). The main idea of the algorithm is that the fusion centre (FC) searches the whole spectrum band from the low spectrum band to the high spectrum band. As long as the spectrum fragments is within MAS and meet SUs minimal transmission bandwidth requirement or the spectrum fragment whose bandwidth is greater than MAS, they will be regarded as a suitable aggregated spectrum $C_n, n = \{1, 2, \ldots, N\}$. The spectrum aggregation algorithm is described in Table I.

B. Problem Formulation

After spectrum aggregation in subsection A, we can have *N* aggregated OFDM subchannels which satisfy the minimal transmission bandwidth requirement in the CR system, we denote them as $\mathcal{N} = \{1, 2, \ldots, N\}$. The bandwidth of the *n*th subchannel spans from $f_0 + f_{nL}^i$ to $f_0 + f_{nH}^j$, where f_0 is the starting frequency and $| C_n | = \sum_{i=1}^{N_n} | f_{nH}^i - f_{nL}^i |$ is the bandwidth of the nth aggregated OFDM subchannel. The SUs in the cognitive radio network (CRN) share the licensed bandwidth with the PUs, of which the nominal bandwidth ranges from to f_l to $f_l + W_l$, where f_l and W_l are the starting frequency and the occupied bandwidth of the lth PU, respectively. Denote $h_{k,n}$ as the kth SU 's signal-to-noise ratio (SNR) on the nth subchannel with unit power,

$$h_{k,n} = \frac{g_{k,n}}{\Gamma(N_0 W/N + \sum_{l=1}^{L} I_{k,n}^{PS})}, \tag{3}$$

where $g_{k,n}^{PS}$ is the power gain from a PU's transmitter to the *k*th SU's receiver on the *n*th subchannel while N_0 is the noise power on each subchannel. Γ is the SNR gap and

TABLE I
THE AGGREGATION-AWARE SPECTRUM ASSIGNMENT

Initialization: Set $S = \varnothing$

Step 1: Put the left side of the MAS window at the left side of the first spectrum fragment;

Step 2: Decide within the window, whether the available spectrum fragments can satisfy or can be aggregated to satisfy the demand transmission bandwidth. If yes, denote the first satisfied aggregated spectrum fragments as C_n, $n = 1, 2, \dots, N$, and go to step 3;
Otherwise, go to Step 4;

Step 3: Decide whether the right side of the MAS window locates in the spectrum hole or not. If yes, place the left side of the MAS window at the location of its right side and go to step 2. Otherwise, go to step 4;

Step 4: Decide whether other spectrum fragments exist in high spectrum band. If yes, place the left side of the window at the left side of next spectrum hole and go to Step 2.
Otherwise,stop searching and return the set of all the aggregated spectrum fragments $C = \{C_1, C_2, \dots, C_N\}$.

$I_{k,n}^{PS}$ denotes the interference introduced to the kth SU on the nth subchannel with unit power. Similarly, the interference introduced to the lth PU on the nth subchannel with unit power can be described as $I_{l,n}^{SP}$,

$$I_{l,n}^{SP} = \int_{f_l - f_0 - f_{nU}^i}^{f_l + W_l - f_0 - f_{nU}^i} g_{l,n}^{SP} \phi(f)\, df, \tag{4}$$

where $\phi(f)$ is the power spectrum density (PSD) of each OFDM subchannel.

Let $r_{k,n}$ denote SU k's achiveable rate on subchannel *n*, we have

$$r_{k,n} = \frac{W}{N} \log_2(1 + p_{k,n} h_{k,n}), \tag{5}$$

where $p_{k,n}$ is the transmission power allocated to the SU k on subchannel *n*. Then the sum transmission rate of SU k can be described as follows,

$$R_k = \sum_{n=1}^{N} c_{k,n} \frac{W}{N} \log_2(1 + p_{k,n} h_{k,n}), \tag{6}$$

where $c_{k,n}$ is a binary variable with $c_{k,n} = 1$ informing SU k occupies the *n*th subchannel and $c_{k,n} = 0$ otherwise.

Our goal is to maximize the sum capacity of the considered multiuser CR system under the practical constraints including the minimal transmission rates requirement (QoS) of the SUs , the transmission power limit of the system and the interference threshold of the PUs. Thus, we can conclude our optimization problem into the following mathematical formulation,

$$\begin{aligned}
&\max_{p_{k,n}} \textstyle\sum_{k=1}^{K} R_k, \\
s.t.\quad & C_1 : R_k \geq R_{min}, \forall k \in \mathcal{K} \\
& C_2 : \textstyle\sum_{k=1}^{K} \sum_{N=1}^{N} c_{k,n} p_{k,n} \leq P_T, \\
& C_3 : p_{k,n} \geq 0, \forall k \in \mathcal{K}, \forall n \in \mathcal{N}, \\
& C_4 : \textstyle\sum_{k=1}^{K} \sum_{n=1}^{N} c_{k,n} p_{k,n} I_{l,n}^{SP} \leq I_l^{th}, \forall l \in \mathcal{L}, \\
& C_5 : \textstyle\sum_{k=1}^{K} c_{k,n} = 1, \forall n \in \mathcal{N}, \\
& C_6 : c_{k,n} \in \{0, 1\}, \forall k \in \mathcal{K}, \forall n \in \mathcal{N},
\end{aligned} \tag{7}$$

where R_{min} is the rate requirement of SUs, P_T is the power budget of the CR system and I_l^{th} is the interference power threshold of the *l*th PU. C_1 indicates the QoS requirement of SUs. C_2 and C_3 are the transmission power limits while C_4 is the interference constraints. C_5 and C_6 guarantee that each subchannel is allocated to at most one SU.

III. PROPOSED RESOURCE ALLOCATION ALGORITHMS

Note that the existence of the binary variable $c_{k,n}$ makes (7) a mixed binary integer programming problem that can not be solved directly. In this section, we proposed a two-step resource allocation method (subchannel allocation and power distribution) to tackle the optimization problem.

Although optimal subchannel assignment can be obtained by exhaustive search, the exponential increase of the computational complexity prevents its practical application. Thus, a heuristic subchannel allocation method is firsly introduced to remove the integer constraints. As can be seen from Fig. 2, the core idea of our proposed method is that we always allocate SUs the subchannel over which they can achieve the highest possible transmission rate. Besides, a coarse proportional fairness is satisfied in the second round of our method, where we make the user obtaining the minimal rate in the last round has the priority to choose subchannels among the remaining ones. This allocation process terminates until all subchannels are consumed. $\mathcal{K}$ and $\mathcal{N}$ are the set of users and subchannels, respectively. The set of subchannels allocated to user *k* is denoted as Ω_k.

For a given subchannel assignment, the integer constraints (C_5, C_6) in (7) vanish. The optimization problem can be described into the following transformation,

$$\begin{aligned}
&\max_{p_{k,n}} \textstyle\sum_{k=1}^{K} \sum_{n \in \Omega_k} r_{k,n}, \\
s.t.\quad & C_1 : \textstyle\sum_{k=1}^{K} \sum_{n \in \Omega_k} r_{k,n} \geq R_{min}, \forall k \in \mathcal{K} \\
& C_2 : \textstyle\sum_{k=1}^{K} \sum_{n \in \Omega_k} p_{k,n} \leq P_T, \\
& C_3 : p_{k,n} \geq 0, \forall k \in \mathcal{K}, \forall n \in \mathcal{N}, \\
& C_4 : \textstyle\sum_{k=1}^{K} \sum_{n \in \Omega_k} p_{k,n} I_{l,n}^{SP} \leq I_l^{th}, \forall l \in \mathcal{L},
\end{aligned} \tag{8}$$

Eq. (8) is easy to be proved as a convex optimization problem since the objective function is convex and all the

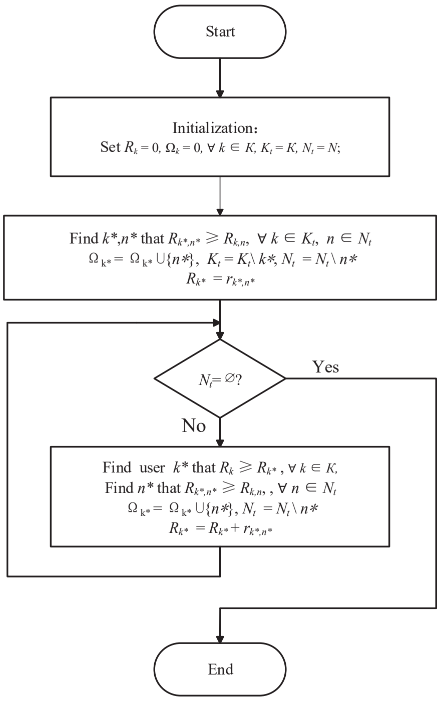


Fig. 2. The flow diagram of Subchannel Allocation

constraints are affine [15]. In general, barrier method, a convenient standard convex optimization technique, is widely used to solve such kind of problems.

The barrier function of (8) is

$$\begin{aligned}\phi(P) = &-\sum_{k=1}^{K}\log\Big(\sum_{n\in\Omega_k}\frac{W}{N}\log_2(1+p_{k,n}h_{k,n}) - R_{min}\Big)\\ &-\sum_{k=1}^{K}\sum_{n\in\Omega_k}\log(p_{k,n}) - \log\Big(P_T - \sum_{k=1}^{K}\sum_{n\in\Omega_k}p_{k,n}\Big)\\ &-\sum_{l=1}^{L}\log\Big(I_l^{th} - \sum_{k=1}^{K}\sum_{n\in\Omega_k}p_{k,n}I_{l,n}^{SP}\Big),\end{aligned} \tag{9}$$

where $P = (p_{1,1}, p_{1,2}, \ldots, p_{K,N})$. Denote

$$f(P) = \sum_{k=1}^{K}\sum_{n\in\Omega_k}\frac{W}{N}\log_2(1+p_{k,n}h_{k,n}),$$

by introducing a parameter *t*, which is related to the accuracy of the solution, the optimal solution of (8) can be approximated by solving the following unconstrained minimization problem,

$$\min \psi_t(P) = -tf(P) + \phi(P). \tag{10}$$

Newton method [15] is generally used to solve the above unconstrained minimization problem with quadratic convergence property. Denote Newton step at *P* as ΔP_{nt}, we have

$$\nabla^2\psi_t(P)\Delta P_{nt} = -\nabla\psi_t(P), \tag{11}$$

where $\nabla^2\psi_t(P)$ is the Hessian and $\nabla\psi_t(P)$ is the gradient of $\psi_t(P)$, respectively. Obviously, the computational complexity of calculating (11) is $O(N^3)$, which is unacceptable for an online application. Thus, an efficient algorithm to quickly compute Newton step is developed.

For simplicity, denote

$$\begin{aligned}f_0 &= P_T - \sum_{k=1}^{K}\sum_{n\in\Omega_k}p_{k,n},\\ f_k &= \sum_{n\in\Omega_k}\frac{W}{N}\log_2(1+p_{k,n}h_{k,n}) - R_{min},\\ g_l &= I_l^{th} - \sum_{k=1}^{K}\sum_{n\in\Omega_k}p_{k,n}I_{l,n}^{SP}.\end{aligned}$$

The gradient of $\psi_t(P)$ is

$$\begin{aligned}\frac{\partial\psi_t(P)}{\partial p_{k,n}} = &-t\frac{W}{N}\frac{1}{\ln 2}\frac{h_{k,n}}{1+h_{k,n}p_{k,n}} - \frac{1}{p_{k,n}}\\ &-\frac{W}{N}\frac{1}{\ln 2}\frac{1}{f_k}\frac{h_{k,n}}{1+h_{k,n}p_{k,n}} + \frac{1}{f_0} + \frac{I_{l,n}^{SP}}{g_l}.\end{aligned}$$

The Hessian of $\psi_t(P)$ is

$$\begin{aligned}\nabla^2\psi_t(P) &= \begin{bmatrix} D_1 & & & \\ & D_2 & & \\ & & \ddots & \\ & & & D_N\end{bmatrix}\\ &\quad+\frac{\nabla f_0\nabla f_0^T}{f_0^2} + \frac{\nabla^2 f_0}{f_0}\\ &\quad+\textstyle\sum_{k=1}^{K}\frac{\nabla f_k\nabla f_k^T}{f_k^2} + \sum_{k=1}^{K}\frac{\nabla^2 f_k}{f_k}\\ &\quad+\textstyle\sum_{l=1}^{L}\frac{\nabla g_l\nabla g_l^T}{g_l^2} + \sum_{l=1}^{L}\frac{\nabla^2 g_l}{g_l}\\ &= \mathbf{D} + \sum_{i=1}^{K+L+1}\mathbf{q}_i\mathbf{q}_i^T.\end{aligned} \tag{12}$$

where

$$\begin{aligned}\mathbf{D}_i &= t\tfrac{W}{N}\tfrac{1}{\ln 2}(1+\tfrac{1}{f_k})(\tfrac{h_{k^*,i}}{1+h_{k^*,i}p_{k^*,i}})^2 + \tfrac{1}{p_{k^*,i}^2},\\ \mathbf{q}_i &= \begin{cases}\frac{\nabla f_0}{f_0}, & i = 1,\\ \frac{\nabla f_k}{f_k}, & k = 1,\ldots,K, i = k+1,\\ \frac{\nabla g_l}{g_l}, & l = K+2,\ldots,K+L+1, i = K+1+l.\end{cases}\end{aligned}$$

Since the matrix $\mathbf{D}$ is positive definite and all $\mathbf{q}_i\mathbf{q}_i^T > 0$, it can be concluded that the Hessian is positive definite and also invertible. Considering the special structure of the decomposed Hessian matric (12), which can be rewritten as

$$\mathbf{\Lambda}_i = \mathbf{D} + \sum_{m=1}^{i}\mathbf{q}_m\mathbf{q}_m^T,\ i = 1, 2, \ldots, M, \tag{13}$$

where $M = K+L+1$, we can develop an $(M+1)$-step iterative algorithm to calculate the Newton step quickly. The detail of our proposed algorithm is given in Table II. Specifically, we can find that $M+1$ matrix systems $\mathbf{\Lambda}_M u_i^M = \mathbf{q}_{i-1}$ can be obtained after M step reverse while m variables $\mathbf{q}_i^{m-1},\ i = 1,\ldots,m$ in step $m-1$ can be obtained by the $m+1$ variables $\mathbf{q}_i^m,\ i = 1,\ldots,m+1$ in step m. Since $\mathbf{D}$ is a diagonal, the $M+1$ variables $u_i^M,\ i = 1, 2, \ldots, M+1$ can be obtained by solving each set of equations in step M. Thus, we can conclude that the Newton step can be indirectly figured out through an M-step reverse computation.

TABLE II
FAST CALCULATING OF NEWTON STEP

Step 1 Decompose Λ_M, $\Lambda_M = \Lambda_{M-1} + \mathbf{q}_M \mathbf{q}_M^T$.
Then we have $u^0 = u_1^1 - \frac{\mathbf{q}_M^T u_1^1}{1+\mathbf{q}_M^T u_2^1} u_2^1$,
Where $\Lambda_{M-1} u_1^1 = - \bigtriangledown \psi_t(\mathbf{P})$ and $\Lambda_{M-1} u_2^1 = \mathbf{q}_M$
After Step 1, we can figure out the $\triangle \mathbf{P}_{nt}$ by solving u_1^1 and u_2^1,
Step 2 Decompose Λ_{M-1} with $\Lambda_{M-1} = \Lambda_{M-2} + \mathbf{q}_{M-1} \mathbf{q}_{M-1}^T$
Similarly, u_1^1 and u_2^1 can be obtained by
$u_i^1 = u_i^2 - \frac{\mathbf{q}_{M-1}^T u_i^2}{1+\mathbf{q}_{M-1}^T u_i^2} u_3^2, i = 1, 2,$
where $\Lambda_{M-1} u_1^2 = - \bigtriangledown \psi_t(\mathbf{P})$, $\Lambda_{M-1} u_i^2 = \mathbf{q}_{M+2-i}, i = 2, 3.$
$\vdots$
Continue this process to Step M,
Step M
We can obtain $M + 1$ variables by solving $M + 1$ liner equation,
$\mathbf{D} u_1^M = - \bigtriangledown \psi_t(\mathbf{x})$
$\mathbf{D} u_i^M = \mathbf{q}_{M+2-i}, i = 2, 3, \ldots, M + 1.$

Theorem 1. *The equation (11) can be solved with the complexity of* $O(M^2N)$.

Proof: The complexity of the proposed method can be calculated as follows. First, we need M decompositions to solve (12), while each decomposition yields an additional matrix equation. Thus, solving the matrix systems in step M has the computation complexity of $O(MN)$. Secondly, a reverse substitution with M steps is required to work out u^0 after we obtain $M + 1$ variables. Thus, we can conclude the computational complexity of our proposed algorithm for solving the formulated problem (11) is $O(M^2N)$.

IV. SIMULATION RESULTS AND DISCUSSIONS

We consider an OFDM-based multiuser CR system, where all SUs share a licensed bandwidth with PUs. Each user randomly locate in a 3×3 km area, while the receiver of the user uniformly distributes around the transmitter within 0.5 km. The channel suffers from frequency selective fading. The amplitude of multipath fading is Rayleigh. The variance of logarithmic normal shadow fading is 10 dB and the path loss exponent is 4. The noise power is 10^{-13} W while the interference thresholds of all PUs are 5×10^{-13} W. The parameters of the barrier method are the typical values discussed in [15].

First, we study the spectrum utilization efficiency performance achieved by the proposed aggregation-aware spectrum assignment (AASA) and the contiguous spectrum assignment algorithm. The spectrum utilization efficiency is defined as B_a/B_v, where B_a indicates the allocated spectrum bandwidth while B_v indicates the vacant spectrum bandwidth. It can be observed from Fig. 3 that the performance of AASA significantly outperforms traditional contiguous spectrum assignment algorithm. With the increase of number of spectrum fragments, AASA always achieves a better performance, especially as the number of spectrum holes is larger than 20, the spectrum utilization efficiency of the contiguous spectrum assignment algorithm decreases sharply even close to zero.

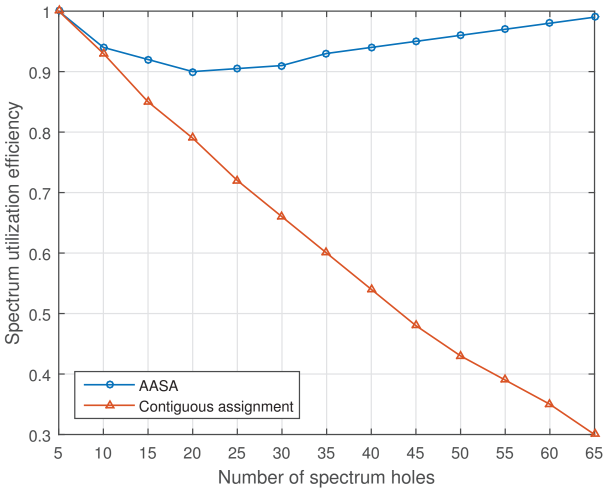


Fig. 3. Spectrum utilization efficiency as a function of the number of spectrum holes.

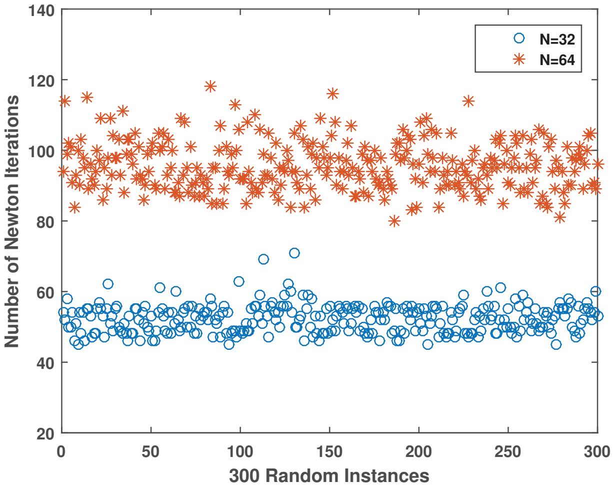


Fig. 4. Number of Newton iterations of the algorithm with $K = 4, L = 2$ and $P_T = 1$ W.

Then we investigate the convergence of our proposed algorithms in Fig. 4 and Fig. 5. It can be concluded in Section IV that Newton step contributes most of the computational load for barrier method. Fig. 4 and Fig. 5 show the number of Newton iterations for convergence in 300 random instances and the Cumulative Distribution Function (CDF) of the number of Newton iterations of our proposed algorithm with different settings of N, respectively. As can be seen in both Fig. 4 and Fig. 5, the number of Newton iterations is not large when the number of subchannels is given. Furthermore, the variation range of our proposed algorithm is small, indicating our proposed algorithm is efficient.

We also compare our proposed algorithm with the Max-Min method proposed in [16] for comparison. Fig. 6 (a) and (b)

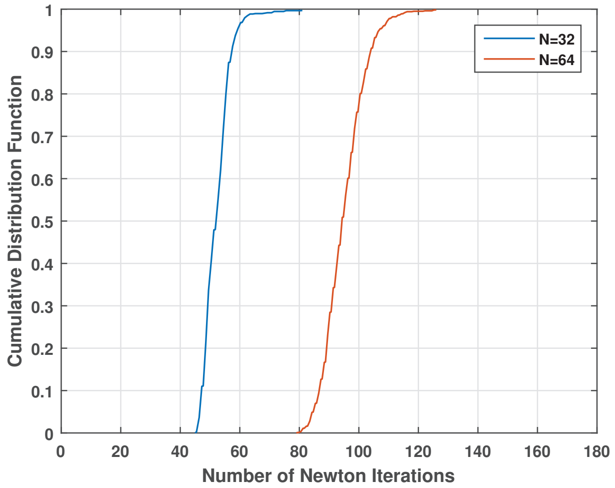
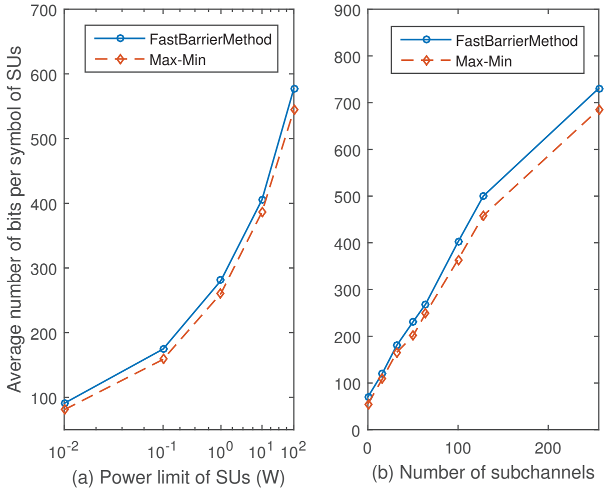


Fig. 5. CDF of number of Newton iterations over 1000 instances of the algorithm with $K = 4, L = 2$ and $P_T = 1$ W.



(a) Power limit of SUs (W)

(b) Number of subchannels

Fig. 6. (a) Average number of bits per OFDM symbol of SUs as a function of the transmission power, R_{min} = 20bits/symbol, $N = 64, K = 4, L = 2$; (b) Average number of bits per OFDM symbol of SUs as a function of the number of subchannels, R_{min} = 20bits/symbol, $P_T = 1W, K = 4, L = 2$.

show the average system throughput of the SUs as a function of the transmission power limit and the number of subchannels, respectively. The minimal rate (QoS) requirements of SUs are uniformly set to 20 bits/symbol. The number of PUs and SUs are 2 and 4, respectively. In Fig.6 (a), there are 64 subchannels in the OFDM-based CR system and we can observe that the sum capacity of the SUs increases as the transmission power limit increases since the growth of the transmission power limit makes the system able to afford higher achievable transmission rate of SUs. In Fig.6 (b), the transmission power limit is set to 1W and it can be seen that as the increase of the number of subchannels, the sum rate of the SUs increases. The reason is that the SUs can benefit from channel diversity in wireless environment. Both of the simulations in Fig.6 (a) and (b) show that our proposed algorithm outperforms the Max-Min.

V. CONCLUSIONS

In this paper, we presented an aggregation-based radio resource allocation algorithm for the downlink of multiuser OFDM-based cognitive radio networks, in which our target is to maximize the sum capacity of all SUs. We first aggregate small spectrum fragments that cannot be utilized by contiguous spectrum assignment algorithms into one channel to improve the spectrum utilization efficiency. Secondly, we introduce a heuristic subchannel assignment to remove the intractable integer constraints and develop a fast barrier method with a low complexity of $O(M^2N)$ by exploiting its special structure to quickly calculate Newton step. Numerical results show that our proposal can always achieve high system capacity, while converging quickly and stably.

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