Utility-based Scheduling Algorithm for Multiple Services in OFDM Cognitive Radio Networks

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***Abstract*—In this paper, the utility-based resource allocation algorithms for the secondary users (SU) supporting heterogeneous services in orthogonal frequency division multiplexing (OFDM)-based cognitive radio cellular networks (CogCells) are studied. Two kinds of users are considered: best-effort-only service users and multiple services users. According to the convex optimization theory, the Lagrangian dual method is proposed, in which the joint subcarrier assignment and power allocation are performed to achieve the optimal solution. To simplify the computation complexity, a low complexity dynamic subcarrier allocation algorithm, named Max Utility for Multiple Services on Cognitive Radio (CR-MUMS), is formulated to extend the non-linear integer optimization to a continuous convex optimization. Final simulation results illustrate that the proposed algorithm with low computational complexity provides better optimal performance than Modified Largest Weighted Delay First (M-LWDF) and Proportional Fair (PF) algorithms.**

I. Introduction

Cognitive radio (CR) has been viewed as a promising technique to solve spectrum scarcity problem of the future wireless communication system [1]. In cognitive radio cellular networks (CogCells), secondary users (SU) have access to unoccupied spectrum of primary users (PU) in an opportunistic manner to improve the licensed spectrum utilization. The SU have to meet the requirements of PU interference limits in consideration of protecting PU outage performance [2], thus resource scheduling under power constraints has become one of the main challenges in CogCells for the SU transmission.

Due to the flexibility to assign subcarriers between different SU, orthogonal frequency division multiplexing (OFDM) access method has been suggested as a candidate for CR systems [3]. The problem of resource allocation for homogeneous services in OFDM-based spectrum sharing systems has been widely studied in [4] and [5]. [4] presented optimal and suboptimal schemes to maximize the transmission rate of the single SU, which only considered best-effort-only service. In [5], the transmission power and interference threshold constraints were converted to a normalized capacity of each OFDM subchannel, an efficient algorithm was proposed to allocate bits of all subchannels to maximization the system capacity.

It is obvious that these conventional algorithms cannot meet the demand of multiple services for the SU in OFDM-based CogCells. Therefore, the scheduling algorithm should be responsible for assigning resource blocks to different users, as well as distributing the assigned resource blocks among multiple services for the same user [6]. Meanwhile, the sum power constraint and the subchannel power limits of the SU should be taken into account, which greatly increases the complexity of subcarrier assignment algorithms.

By regarding each service for a user as an independent user, traditional resource scheduling algorithms such as Modified Largest Weighted Delay First (M-LWDF) [7] and Proportional Fair (PF) [8] can be directly applied to heterogeneous services. Resource scheduling algorithms are formulated to solve subcarrier assignment problems for heterogeneous services in MIMO-OFDM systems [9], OFDM-based distributed antenna systems (DAS) [10], and OFDM-based cognitive radio multicast networks [11], respectively. However, to the best of our knowledge, there is no systematic investigation of subcarrier allocation of heterogeneous services for the SU in CogCells.

The main purpose of this paper is to propose utility-based scheduling algorithms supporting multiple services for SU in OFDM-based CogCells. In order to realize maximum total utility, the algorithm formulates joint-optimization subcarrier assignment for the SU in the condition of PU interference limits and quality of service (QoS) requirements. A low complexity optimization algorithm (CR-MUMS) is also extended to fully satisfy the convenience of implementation practice.

The reminder of this paper is organized as follows. We briefly introduce system model in Section II. The optimization of the subcarrier allocation problem for heterogeneous services of the SU is presented in Section III. In Section IV, we provide a low complexity subcarrier allocation algorithm (CR-MUMS) based on optimal relaxing solution. Our simulation and analysis results of the performance of the scheme are outlined in Section V. Finally the conclusion is drawn in Section VI.

II. System Model

A typical OFDM-based CR system is depicted in Fig. 1. We consider a scenario where the spectrum accessible by the SU is divided into M subchannels, each of which is an unused frequency band occupied originally by the PU. Δf and m_j are assumed to be subcarrier interval and index of the first subcarrier in the *j*th subchannel, respectively. Each

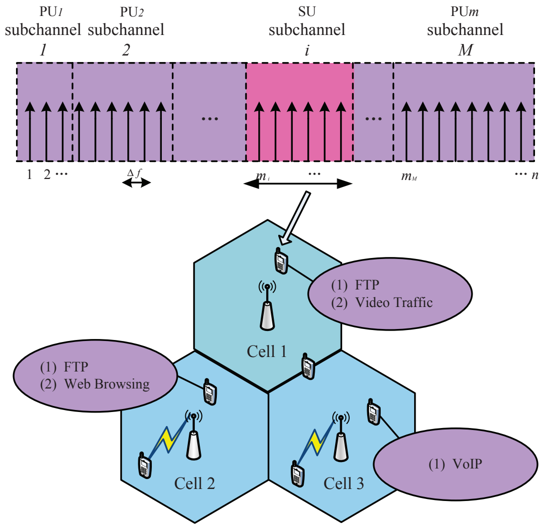

Fig. 1. Heterogeneous services for the SU in OFDM-based CogCells

subcarrier is supposed to experience flat fading in virtue of cyclic prefix.The SU may appeal for multiple services simultaneously, such as best-effort service and delay sensitive service. According to [12], when continuous rate adaptation is adopted, the achievable throughput of user k on subcarrier n is

$$R_{n,k} = B\log_2(1+\beta\gamma_{n,k}), \quad (1)$$

where B is the bandwidth of one subcarrier, $\gamma_{n,k}$ is the current SNR for user k on subcarrier n and β is a constant related to the target BER by

$$\beta = \frac{-1.5}{\ln(5\times \mathrm{BER})}. \quad (2)$$

III. Problem Formulation for Heterogeneous Services

In this section, an optimal resource allocation problem for heterogeneous services of the SU is proposed restricted to the maximum transmit power constraint and the subchannel transmit power constraint correlating with the PU interference limits simultaneously.

A. Power Constraints to the SU in CR System

In the OFDM-based CogCells, in order to avoid disturbing the PU transmission and to decide the transmit power limit on a certain subchannel, the CR base station estimates the channel state information (CSI) at the beginning of each scheduling slot. By observing all data buffers of SU, the queue state information (QSI) can be collected through uplink dedicated pilots from all SU. The idle subcarriers are detected through sensing technologies which are widely studied in [13].

Let's assume G_j as the transmit power constraint on the *j*th subchannel, which can be defined as follows:

$$G_j \triangleq \begin{cases} \delta_j & ,\mathrm{PU}_j \text{ is detected;} \\ \eta_j(\ell_j-\xi_j)^{\sigma_j} & ,\mathrm{PU}_j \text{ is not detected,} \end{cases} \quad (3)$$

where δ_j is the transmit power threshold for the *j*th subchannel, which can be set to infinitely small or even zero. η_j is the interference power constraint of PU_j; ℓ_j is the distance between the SU and the nearest active PU; ξ_j is the radius of protection region of PU_j and σ_j is the path loss factor.

Besides the influence of power assigned to the subcarriers inside the subchannel, the SU transmit power limit is also affected by the sidelobes power of the subcarriers in adjacent subchannels. Assume $J_{i,j}$ as the transmit power of the *i*th subcarrier in the *j*th subchannel with unit power. The subcarrier interval is denoted as Δf. Then we have

$$J_{i,j} = \frac{1}{\Delta f}\int_{\Delta f(m_j)}^{\Delta f(m_{j+1}-1)} \left[\frac{\sin\left(\frac{\pi}{\Delta f}(f-i\Delta f)\right)}{\frac{\pi}{\Delta f}(f-i\Delta f)}\right] df. \quad (4)$$

It is assumed that P_i is the power assigned to the *i*th subcarrier, and the transmit power on the *j*th subchannel can be denoted as $\sum_{i=1}^{N} J_{i,j}P_i$. Combining with (3), the subchannel transmission power constraint correlated with the PU interference limits can be expressed in the form of inequality.

$$\sum_{i=1}^{N} J_{i,j}P_i \le G_j, j=1,2,\cdots,M. \quad (5)$$

B. Resource Allocation Algorithm for Heterogeneous CogCells

There are K users in each cell and the frequency band consists of N subcarriers. We consider the set of users as $\mathcal{K}=\{1,2,\cdots,k\}$ and the set of subcarriers as $\mathcal{N}=\{1,2,\cdots,n\}$. Let A_k represent the best-effort services set of user k and s_k is the cardinality of the set. According to utility theory, the utility function for best-effort service is signified as algorithm form with respect to average data rate. Define U_k to be the sum function utility of user k , which can be expressed in the following form:

$$U_k = \sum_{j=1}^{s_k} \alpha_{k,j}[a+b\times\ln(r_{k,j}^{(t)}-c)] \ (c<r_{k,j}^{(t)}), \quad (6)$$

where $\alpha_{k,j}$ is the utility weight of service j, which depends on the priority level of service, and $\sum_{j\in A_k}\alpha_{k,j}=1$. In case of best-effort services, $\alpha_{k,j}=\frac{1}{s_k}$. $r_{k,j}^{(t)}$ denotes average data rate of service j of user k at the *t*th time slot and a, b, c are constants.

We define $g_{n,k}$ as a subcarrier allocation indicator variable. $g_{n,k}=1$ means subcarrier n is allocated to user k for packet transmission, or else $g_{n,k}=0$. It is clear that to any subcarrier n, $\sum_{k=1}^{K} g_{n,k}=1$. For the sake of refraining from co-channel interference, each subcarrier is assumed to be just allocated at most one user.

$b_{k,j}$ is assumed to be the assigned transmission bits for service j of user k and $b_{k,j}\ge 0$. Considering that the available throughput of user k on all allocated subcarriers is generally equal to the assigned transmission bits for all services of user k, we have $\sum_{n=1}^{N} g_{n,k}R_{n,k} = \sum_{j=1}^{s_k} b_{k,j}$.Then, $r_{k,j}^{(t)}$ can be updated as follows:

$$r_{k,j}^{(t)} = \frac{t-1}{t} r_{k,j}^{(t-1)} + \frac{b_{k,j}}{t \times T}, \tag{7}$$

where T is the time slot duration.

Compared with best-effort service, user experience mainly depends on delay restriction, which is in connection with deadline. Owing to the provision of buffer for each service, scheduling scheme for delay sensitive service should transmit packets before deadline, rather than as soon as possible. In terms of head-of-line (HOL) packet delay depicted in Fig. 2, the delay sensitive service is divided into three parts: Absolute Priority Services (APS), Relative Priority Services (RPS) and Common Priority Services (CPS). d_j is the transmit deadline of the HOL packet of delay sensitive service j,while d_1 and d_2 $(0 \leq d_1 \leq d_2)$ are two parameters.

The available subcarriers for the SU are firstly assigned to APS until the HOL packet delay is out of $[d_j - d_1, d_j]$. The remaining subcarriers are allocated among best-effort services, RPS, and CPS, which all are reckoned as best-effort services. The solution of optimal resource allocation problem is proposed as follows:

$$\begin{aligned}
S1 &: \max_{g_{n,k}, b_{k,j}} \sum_{k=1}^{K} \sum_{j \in A_k'} U_k \\
s.t. C_1 &: \sum_{n=1}^{N} g_{n,k} R_{n,k} = \sum_{j=1}^{s_k} b_{k,j}, \forall k \in K \\
C_2 &: \sum_{k=1}^{K} g_{n,k} = 1, g_{n,k} \in \{0,1\}, \forall n \in N \\
C_3 &: P_i \geq 0 \\
C_4 &: \sum_{i=1}^{N} P_i \leq P_t \\
C_5 &: \sum_{i=1}^{N} J_{i,j} P_i \leq G_j, j = 1, 2, \cdots, M
\end{aligned} \tag{8}$$

where $A_k^{'}$ denotes the service set of user k subtract APS sensitive service, and P_t is the maximum transmit power of the SU transmitter.

The optimization solution is a non-linear integer solution with $N \times K$ optimal variables; as a result the computation complexity is pretty high. For the practice implementation, a low complexity continuous convex optimization solution is formulated in the next section.

IV. Low Complexity Algorithm for Heterogeneous Services in CR System

In this section, a low complexity combinational dynamic subcarrier assignment algorithm for multiple services, named Max Utility for Multiple Services on CR (CR-MUMS), is formulated. The non-linear integer optimization algorithm mentioned above can be further extended to a continuous convex optimization, by substituting $\rho_{n,k}$ for $g_{n,k}$, where $0 \leq \rho_{n,k} \leq 1$ for $\forall k \in K$, $\forall n \in N$.According to the solution mentioned in section III for heterogeneous services in CR system, the low complexity algorithm consists of four parts:

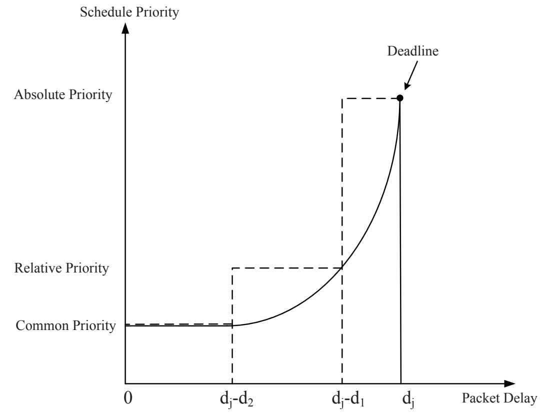

Fig. 2. Priority of Delay Sensitive Service

Step 1: The CR base station estimates the channel state information (CSI) through uplink dedicated pilots from all SU and collects the queue state information (QSI) by observing all data buffers of the SU. According to Eq. 3, we can obtain the transmit power constraint G_j on the *j*th subchannel.

Step 2: Since the APS of SU is prior to other services, the available subcarriers are allocated to the service at first until the HOL packet is out of $[d_j - d_1, d_j]$, adopting the greedy subcarrier allocation algorithm.

Step 3: The remaining subcarriers are allocated among best-effort services, RPS, and CPS. Because of the total power's uniform distribution to all subcarriers, the sum power constraint of each cell can always be satisfied. Then the optimal subcarrier allocation problem can be extended to continuous convex solution with low complexity. We have

$$\begin{aligned}
S2 &: \max_{g_{n,k}, b_{k,j}} \sum_{k=1}^{K} \sum_{j \in A_k'} U_k \\
s.t. C_1 &: \sum_{n=1}^{N} \rho_{n,k} R_{n,k} = \sum_{j=1}^{s_k} b_{k,j}, \forall k \in K \\
C_2 &: \sum_{k=1}^{K} \rho_{n,k} = 1, 0 \leq \rho_{n,k} \leq 1, \forall n \in N \\
C_3 &: \sum_{i=1}^{N} J_{i,j} P_i \leq G_j, j = 1, 2, \cdots, M
\end{aligned} \tag{9}$$

According to convex theory, the utility function is the concave function with respect to $\rho_{n,k}$. For S2, the objective function is the sum of K utility functions of best effort service, thus the algorithm S2 is converted into a linear concave optimization problem, which can be figured out by many software packages.

Consequently, for the SU with best effort services, the remaining subcarriers are assigned to user with the value of $\rho_{n,k} > 0$.If there is only one corresponding user with

$\rho_{n,k} > 0$, allocate the subcarrier to this SU; or else distribute the subcarrier to the SU with the maximal value of $\rho_{n,k}$.

Theorem1: Define k^* as the user that subcarrier n is allocated to, the optimal SU with best effort services to maximize the utility function is

$$k^* = \arg\max_{k \in K} u_k(\sum_{n=1}^{N} \rho^* R_{n,k}) R_{n,k}, \tag{10}$$

where $u_k(\sum_{n=1}^{N} \rho^* R_{n,k}) = \frac{d(U_k(\sum_{n=1}^{N} \rho^* R_{n,k}))}{d(\rho^* R_{n,k})}$, and $\rho_{n,k^*} = 1$, $\rho_{n,k} = 0$, while $k \in K$, $k \neq k^*$. ρ^* is the optimal solution of algorithm P2. Then CR-MUMS resource allocation algorithm is presented as follows:

CR-MUMS Resource Allocation Algorithm

1) subcarrier set:$N = \{1, 2, \cdots, n\}$, user set:$K = \{1, 2, \cdots, k\}$. CSI check and get G_j
2) allocate subcarriers $N^{'}$ to users $K^{'}$ with APS according to the greedy subcarrier allocation algorithm
3) remaining subcarrier set:$N^{'} = N - N^{'}$, remaining user set:$K^{'} = K - K^{'}$
4) while $(N^{'} \neq \emptyset \; and \; K^{'} \neq \emptyset)$ do
5) a) randomly select a subcarrier $n^* \in N^{'}$, and identify an optimal user $k^* \in K^{'}$ such that $k^* = \arg\max_{k \in K^{'}} u_k(\sum_{n=1}^{N} \rho^* R_{n,k}) R_{n,k}$
   b) assign subcarrier n^* to user k^*
   c) $N^{'} = N - n^*$
6) end while

Step 4: If user k has RPS sensitive service, the available throughput is assigned to RPS at first until the HOL packet delay is out of $[d_j - d_2, d_j - d_1]$. The remaining transmission bits are shared within multiple services.

V. Numerical Results and Discussion

A. Simulation Design

system-level simulations are conducted to confirm the performance of the proposed algorithms for the SU. For comparison, the low complexity optimal scheme CR-MUMS is contrasted with another two traditional scheduling algorithms, M-LWDF and PF algorithm. Two kinds of SU are set in the system. Kind A represents best-effort-only service user in need of a FTP service while Kind B represents heterogeneous service user in need of a video streaming service and a FTP service. The channel fading distribution on each subcarrier is I.I.D.Rayleigh with a factor of 1. Set the utility weight α_j for video streaming and FTP service to be 0.7 and 0.3 respectively. For ease of consideration, the subchannel power constraints in CR-MUMS are approximated by ignoring the subcarrier sidelobes, and $J_{i,j}$ is defined as Eq. 11. The simulation parameters are listed in TABLE I.

$$\begin{cases} J_{i,j} = 1 & , i \in [m_j, m_j - 1]; \\ J_{i,j} = 0 & , else. \end{cases} \tag{11}$$

TABLE I
SIMULATION PARAMETERS

Parameters	Values
Bandwidth	2.5MHz
Subcarriers Available	160
User Number per Cell	25
User Moving Speed	3km/h
Cell Radius	1000m
Average Data Rate	128kbps
FTP Utility Function	$U(\bar{r}) = 0.16 + 0.18 \ln(\bar{r} - 0.3)$
Path Loss Model	$128.1 + 37.6 \log_{10}(D)$
Channel Model	$SCM\ 1 \times 1$

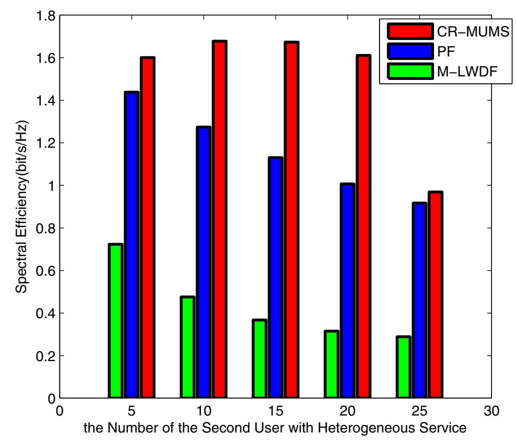

Fig. 3. Spectral efficiency of the CR system

B. Simulation Results

Fig. 3 shows the system spectral efficiency with the CR-MUMS, M-LWDF and PF algorithms respectively. In CR-MUMS algorithm, joint subcarrier scheduling is implemented and we fully take advantage of the deadline of video streaming service. simulation results indicate that CR-MUMS is superior to two other algorithms on the condition of protecting the PU's output performance. As video traffic is prior to FTP service and is firstly allocated subcarriers, the system spectral efficiency of CR-MUMS performs a slight increase when the number of Kind B users is below 10; whereas that of M-LWDF and PF presents a decrease all the time.

The effect of increasing of Kind B users on the FTP traffic throughput is depicted in Fig.4. When the SU with heterogeneous service are ranging from 5 to 20, the results of PF algorithm are varying from 10.21Mbps to 5.45Mbps, while our CR-MUMS gives 11.34Mbps and 9.44Mbps correspondingly. We can conclude that PF algorithm declines much faster than our CR-MUMS algorithm. From Fig. 4, it is obvious that M-LWDF algorithm is not practical.

Fig. 5 and Fig. 6 show the performance of video streaming service. It can be seen from Fig. 5 that the video traffic throughput of these three algorithms all rise with the increasing of Kind B users. The throughput of CR-MUMS algorithm increases fastest and obviously higher than that of two other

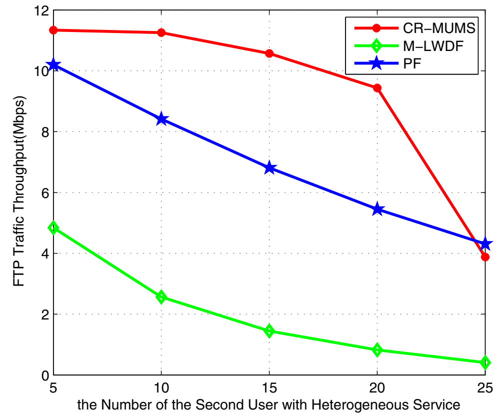

Fig. 4. The FTP traffic throughput of the second user

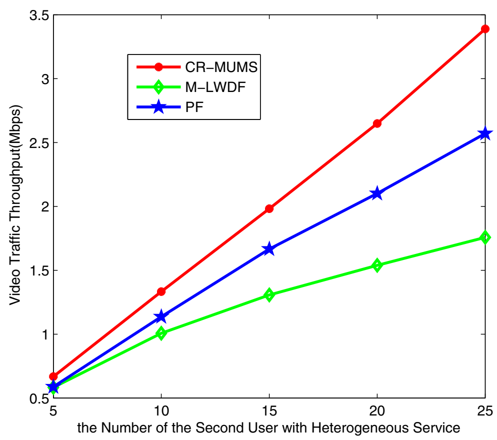

Fig. 5. Video traffic throughput of the second user

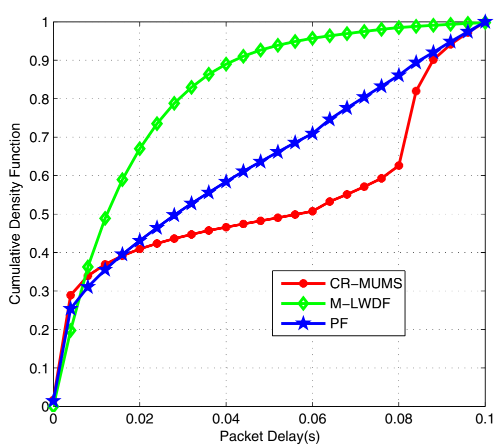

Fig. 6. The CDF of packet delay of video streaming service

algorithms. Fig.6 compares the cumulative density function (CDF) of packet delay of video streaming service in condition of 25 Kind B users. It is observed that about 70% packet delay of M-LWDF algorithm is 0.023s, while that of CR-MUMS and PF is 0.056s and 0.082s respectively. Owing to the provision of buffer for each service, scheduling scheme for delay sensitive service should transmit packets before deadline, rather than as soon as possible. CR-MUMS algorithm makes full use of this property and allocates resource blocks (RB) to better adaptive users, which can exactly explain Fig. 6. The excellent performance of spectral efficiency and system throughput are shown in Fig. 3, Fig. 4 and Fig. 5.

VI. Conclusion

The utility-based resource allocation algorithms for the SU supporting heterogeneous services in OFDM-based CogCells are presented in this paper. The Lagrangian dual method is proposed to get the optimal solution for the optimization problem, a low complexity algorithm is designed with good performance to reduce the computation complexity. Finally, simulation results illustrate that the proposed algorithm with low computational complexity provides better optimal performance than M-LWDF and PF algorithms on aspects of system capacity, spectral efficiency and service throughput.

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