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A QoE-based jointly subcarrier and power allocation for multiuser multiservice networks

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Abstract Quality of experience (QoE) is widely applied to reflect user's satisfaction of the network service, which exactly conforms to the user-centric concept in 5G. In this paper, we propose a QoE-based subcarrier and power allocation algorithm for the downlink transmission of a multiuser multiservice system. For the subcarrier allocation algorithm, the rate proportional fairness factor is defined to ensure the fairness between users. Based on different QoE models of three services, i.e., file down (FD), video streaming and voice over internet protocol (VOIP), a multi-objective optimization method is exploited to allocate the power resource by minimizing the total power consumption and maximizing the mean opinion score (MOS) value of users simultaneously. Simulation results indicate that the proposed algorithm has less power consumption and higher QoE performance than the traditional proportional fairness (PF) algorithm. In addition, the proposed algorithm can achieve nearly the same fairness performance as the PF algorithm. Moreover, when the number of subcarriers becomes larger, the power assumption will be less but with little influence on both the QoE and fairness performances.

Keywords QoE, QoS, MOS, multiservice, multi-objective optimization

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1 Introduction

With the rapid development of hybrid and complicated techniques of the current mobile communication system, the demands for system performance from both operators and users become much higher and more complex, which requires more radio resource to meet these needs [1, 2]. However, the available wireless resource is not infinite, such as congested transmission space, limited spectral and power resource and so on, which results in a bottleneck to improve system performance. Hence, the proper and flexible wireless resource management design is necessary for current mobile system with rapid development [3, 4], which aims at achieving higher transmission rate, stronger wireless access ability and better user satisfaction. More importantly, the future 5G communication system, users have more expectations for variety and quality of network services, so more and more novel services are presented [5–7]. Based on this, there emerge many researches of wireless resource allocation in multiuser multiservice scenery.

Generally, in order to evaluate the system performance effectively, a conventional metric called QoS (quality of service) is always utilized. It is defined from the aspect of physical layer and includes various

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specific performance indexes, such as throughput, packet error rate, delay, jitter and so on. It is clear that all the above performance indexes only consider optimizing the system from the aspects of the physical layer. In [8], through adaptively mapping the QoS index of different services to the OFDM subcarriers, a QoS-aware wireless resource architecture is established to provide the optimal resource allocation strategy. More specific work is done in [9], it introduces three types of services, hard QoS (HQ), best effort (BE) and soft QoS (SQ) traffics respectively. Then a traffic-based resource allocation scheme is proposed to optimize the system capacity. Besides, Ref. [10] proposed an adaptive wireless allocation scheme containing the time scheduling and channel allocation to satisfy the predetermined QoS requirements. Evidently, all above researches only perform the single objective optimization. While in [11], a novel wireless allocation strategy jointly considering the link rate constraints and the proportional fairness is proposed.

However, it is clear that these works mainly concentrate on improving the QoS of system without considering the feeling of users and practical characteristics of services. To better achieve the requirement of user-centric 5G system, the concept of quality of experience (QoE) is proposed instead of QoS to measure system performance [12, 13]. QoE is defined basically as a subjective measurement of end-to-end multimedia service from the viewpoint of user, which contains both QoS parameters and service characteristics. Overall, it is a combination of subjectivity and objectivity [14, 15].

Recently, many researches are presented, which are about the QoE-based wireless resource allocation scheme for multiservice networks [16–19]. Mean opinion score (MOS) [20] is a widely used numerical measurement standard of QoE, which reflects the level of user satisfaction in a score ranging from 1 (unacceptable) to 5 (excellent). Ref. [16] formulated a general optimization objective of the QoE-based resource allocation scheme in order to maximize the average MOS value of system. However, this scheme improves the system performance at the cost of decreasing the system fairness. Besides, a QoE-based proportional fair resource allocation algorithm was also presented [17], which considered the QoE maximization as well as fairness of each user. By using the opportunistic gradient scheduling scheme, this algorithm can significantly improve the performance of cell-edge users. In addition, Ref. [18] proposed a novel QoE-driven wireless resource control architecture for providing QoE awareness to mobile operator networks, which can achieve the promotion of system transmission rate. Moreover, Ref. [19] took a QoE-based efficient power algorithm to make the transmission with energy saving. Unfortunately, most of the QoE-based resource allocation problems focus on only either maximizing average MOS value or fairness among users, which can hardly match with the practical systems for the reason that sometimes all the performance should be considered simultaneously.

In our work, we propose a QoE-based subcarrier and power allocation algorithm for the downlink transmission of a multiuser multiservice system, which aims at minimizing the total power resource consumption with guaranteeing a relatively good average MOS and fairness among users. In the subcarrier allocation stage, we take the rate proportional fairness factor which is defined as the ratio between the actual transmission rate and the maximum transmission rate of user as the optimization objective. Based on QoE models of different services, the multi-objective optimization method is exploited to get the optimal power allocation aiming at minimizing the total system power consumption and maximizing the QoE of users simultaneously. Simulation results indicate that the proposed algorithm is more effective than the proportional fairness (PF) algorithm. With the suitable tradeoff factors, the optimal solution of the proposed algorithm tends to be fixed and ensures multiple system requirements simultaneously. In addition, the proposed algorithm can achieve higher QoE performance than the PF algorithm because the PF algorithm concentrates on maintaining the fairness of the system. Moreover, compared with the PF algorithm, the proposed algorithm can obtain higher MOS values with less power consumption and ensure the acceptable fairness performance. Moreover, when the number of subcarriers becomes larger, the power assumption will be less but with little changes in both the QoE and fairness performances.

The rest of this paper is organized as follows. Section 2 gives the basic assess functions of QoE. Section 3 describes the system model with QoE models of various services and formulates the optimization problem. In Section 4, the first part proposes the subcarrier allocation scheme which can ensure the fairness of system, while the second part presents the power resource allocation scheme aiming at minimizing the total power consumption and maximizing MOS value of users simultaneously. Section 5 provides the simulation results of the proposed algorithm compared with the PF algorithm. Finally, conclusion is given in Section 6.

2 Fundamental definition of QoE

In order to get users' subjective experience, we denote QoE as the end-to-end quality perceived by users from the whole system's point of view. Based on the research, we find that there are two common methods to evaluate QoE. One is based on the utility function, while the other utilizes the specific MOS model for different applications. In the following subsections, the two evaluation methods are described in detail.

2.1 Utility-based quality of experience

As we all know, the utility theory is often utilized in economics to obtain the maximum profit. However, there are already plenty of researches considering the resource allocation problem with the utility function optimization, which can significantly reduce the complexity of allocating various resource [21,22]. Further, the utility function can also be designed to be associated with two or more performance indexes. Thus, the good tradeoff among multiple performance indexes can be achieved. The frequently used utility function model for wireless resource allocation is described in [19], in which the three types services corresponding to different parameter settings are taken into account, such as, QoS service, voice service and best effort service. Mathematically, it can be formulated as

$$U_i(r) = \frac{1}{A_i + B_i \mathrm{e}^{-C_i(R_i - R_i^0)}} + D_i, \quad i = \text{QoS, voice, BE}, \tag{1}$$

where A_i, B_i, C_i and D_i are i-th service related parameters. C_i denotes the slope of the curve. A_i, B_i, D_i mainly determine the value range of the utility function. By adjusting these parameters properly according to different service characteristics, the utility values of various services have the definite comparability, thus the wireless resource allocation can be achieved effectively.

2.2 MOS-based quality of experience

Besides the unified utility function for various services, there are also various MOS-based functions for different services. Compared with the unified utility function, the MOS-based function is more widely accepted as the QoE evaluation model in most researches. In addition, Figure 1 [23] illustrates the relationship between MOS value and data rate for these three services. Thus, according to the MOS requirements from users, it is easy to find its minimum data rate.

2.2.1 *File down service*

The logarithmic MOS-throughput model is utilized in [24] for the FD service which is generally considered to be a non-real-time service. The relationship between MOS and user transmission rate R is described as follows:

$$\mathrm{MOS_{FD}} = \begin{cases} 1.0, & R < 10 \text{ kbps}, \\ \alpha \lg(\beta R), & 10 \text{ kbps} \leqslant R < 300 \text{ kbps}, \\ 4.5, & R \geqslant 300 \text{ kbps}, \end{cases} \tag{2}$$

where α and β can be obtained from the upper and lower bound of the users' MOS value for FD service, respectively.

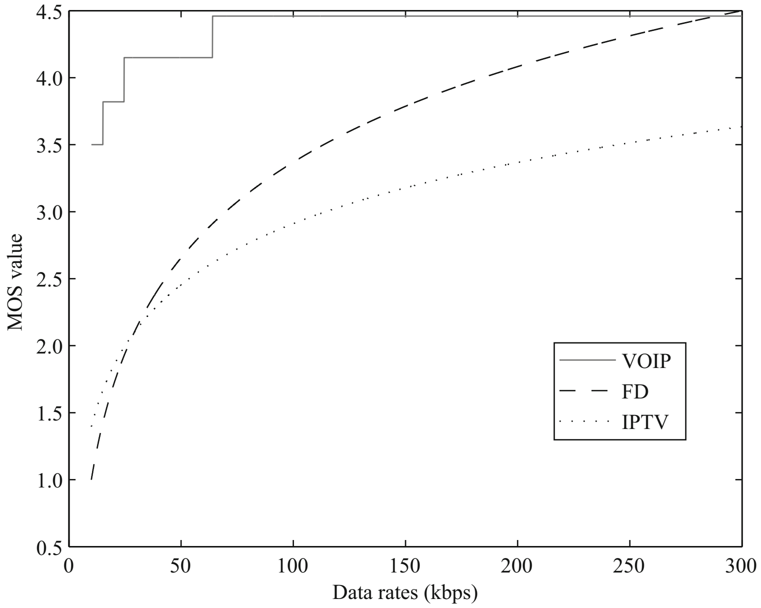

Figure 1 The QoE models of file download service, IPTV service and VoIP service [24].

2.2.2 *Video streaming service*

The quality of video service which is represented by MOS is influenced by both network parameters and service parameters [25], such as send bit rate (SBR), packet error rate (PER) and frame rate (FR). The MOS function can be formulated as

$$\mathrm{MOS} = \frac{a_1 + a_2\mathrm{FR} + a_3 \ln(\mathrm{SBR})}{1 + a_4\mathrm{PER} + a_5(\mathrm{PER})^2}. \tag{3}$$

For a known kind of video service, these parameters are fixed. Taking the IPTV service as an example, a_1, a_2, a_3, a_4 and a_5 are set to be -0.0228, -0.0065, 0.6582, 10.0437 and 0.6865 [25], respectively. Additionally, we can focus on the relationship between transmission rate R and MOS value by fixing FR at 15 fps and PER at 0, which indicates that there are hardly any network losses. Thus, the MOS utility function can be formulated as

$$\mathrm{MOS}_{\mathrm{IPTV}} = -0.0878 + 0.6582 \ln(\mathrm{SBR}). \tag{4}$$

2.2.3 *VoIP service*

For VOIP service, the MOS function is measured from a set of different speech samples under different codecs, which can be clearly found in Figure 1 [24]. The 4 discrete points represent 4 codecs operated at bit rates of 6.4 kbps, 15.2 kbps, 24.6 kbps and 64 kbps, respectively. In the actual simulation, we often perform a smooth curve which is exactly fitting this fold line.

3 System model and problem formulation

In our work, we focus on the downlink transmission of a multi-user multi-service cellular communication system with one base station and K users. As shown in Figure 2, these served users may experience different services, some of which are real-time services while others are non real-time services. For real-time services, higher transmission rate and lower latency are acquired. In our work, we assume that there are K_1 users with non real-time service, i.e., FD service, and $(K - K_1)$ users with real-time service, K_2 of which are users with IPTV service while K_3 of which are users with VoIP service.

Different from traditional researches on QoS, we concentrate on QoE-based wireless resource allocation design. In addition, similar to most researches, the MOS function is exploited to assess QoE instead

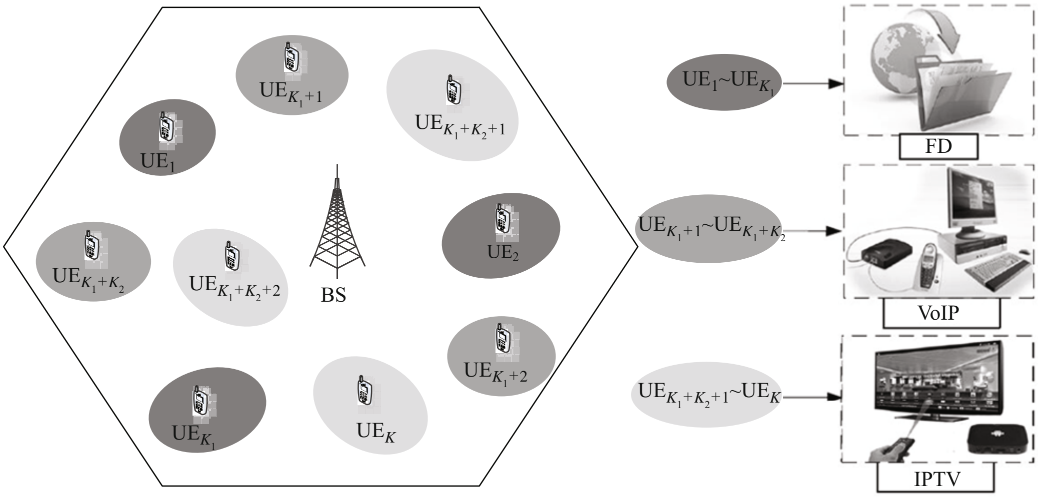

Figure 2 The QoE models of file download service, IPTV service and VoIP service.

of utility function in our paper. From Section 2, it is easy to find that the MOS function is generally associated with the user transmission rate R, so the relationship between them is necessary to be presented out. Based on this relationship, the QoE-based wireless resource allocation problem is formulated and the corresponding algorithm is proposed, including both subcarrier allocation and power allocation.

In our work, we stand by the side of users, so the experience of users is taken as one of the most important performance. Figure 1 tells us that the experiences are related to data rate, which has a close relationship with transmit power. In other words, the higher user experience is acquired, the larger transmit power is needed. However, too large transmit power can bring interference to the users or base stations nearby. In addition, the energy resource is very valuable especially in the remote areas, where the batteries of base stations can not be replaced too often. Thus, with an acceptable system performance or user experience, the transmit power of base station should be minimized. Moreover, based on different MOS functions, users between different services can not get the same MOS value with the same data rate and each user has its own maximum data rate limitation, which leads to the unfairness among users. Considering all the above factors, we formulate the optimization problem as follows:

$$
\begin{aligned}
\min \quad & \{P_{\mathrm{total}}, -\mathrm{MOS}_k, k=1,\ldots,K\} \\
\text{s.t.} \quad & \mathrm{C1}: \quad P_{\mathrm{total}} = \sum_{k=1}^{K}\sum_{n=1}^{N} \pi_{k,n} P_{k,n} \leqslant P_{\max}, \\
& \qquad\quad \sum_{n=1}^{N} \pi_{k,n} P_{k,n} > P_{k,\min}, \\
& \qquad\quad \forall k,n, \quad k=1,\ldots,K, \quad n=1,\ldots,N, \\
& \mathrm{C2}: \quad \mathrm{MOS}_k = U_k\left(R_k\right) \geqslant \mathrm{MOS}_{k,\min}, \\
& \mathrm{C3}: \quad \sum_{k=1}^{K} \pi_{k,n} = 1,\ \pi_{k,n} = [0,1],\ \forall k,n, \\
& \mathrm{C4}: \quad R_1 : R_2 : \cdots : R_K = R_{1,\max} : R_{2,\max} : \cdots : R_{K,\max},
\end{aligned}
\tag{5}
$$

where K is the total number of users and N is the number of subcarriers. P_{total} denotes the actual system power consumption which should not be larger than the system total available power $P_{\max}$, and $P_{k,n}$ represents the amount of power resource allocated to the subcarrier n of user k. It is obvious that the transmit power of each user can not be larger than $P_{k,\min}$. Define U_k as the MOS utility function, which is determined by the transmission rate of user k and the category of its service. In order to guarantee the experience requirement, U_k cannot be larger than the minimum MOS requirement of corresponding

Algorithm 1 Subcarrier allocation for the j-th iteration

```
Require:
 1: SNR matrix $\boldsymbol{\Gamma} \in \mathbb{R}^{K\times N}$
 2: user minization rate vector $\boldsymbol{R}_{\min} \in \mathbb{R}^{1\times K}$
Ensure:
 3: Initialize: SNR matrix for the first stage $\boldsymbol{\Gamma}_1 = \boldsymbol{\Gamma}$
 4: repeat
 5:     Choose the best subcarrier for each user
        $[k', n'] = \max(\boldsymbol{\Gamma}_1(k, n))$
 6:     Calculate the actual rate vector of each user:
        $\boldsymbol{R}_{\mathrm{act},k'} = \boldsymbol{R}_{\mathrm{act},k'} + B\log(1 + \boldsymbol{\Gamma}_1(k', n'))$
 7:     Set: $\boldsymbol{Q}(k', n')$, $\boldsymbol{\Gamma}_1(k', n') = 0$;
 8:     if $\boldsymbol{R}_{\mathrm{act},k'} \geqslant \boldsymbol{R}_{\min,k'}$ then
 9:         $\boldsymbol{\Gamma}_1(k', n) = 0, \forall n = 1, 2, \ldots, N$
10:     end if
11: until $\boldsymbol{\Gamma}_1 == \mathbf{0}$
12: Initialize: $\boldsymbol{\Gamma}_2 = \boldsymbol{\Gamma} \cdot (\boldsymbol{I} - \boldsymbol{Q})$
                proportional fairness vector $\boldsymbol{f} \in \mathbb{R}^{1\times K}$ with
                $f_k = \frac{R_{\mathrm{act},k}}{R_{\min,k}}, \forall k = 1, 2, \ldots, K$
13: repeat
14:     Choose the minimum proportional fairness user:
        $k^* = \min(\boldsymbol{f})$
15:     Find the best subcarrier for user $k^*$
        $n^* = \max(\boldsymbol{\Gamma}_2(k^*, n)), \forall n = 1, 2, \ldots, N$
16:     Calculate:
        $\boldsymbol{R}_{\mathrm{act},k^*} = \boldsymbol{R}_{\mathrm{act},k^*} + B\log(1 + \boldsymbol{\Gamma}_2(k^*, n^*))$
17:     Set:
        $\boldsymbol{Q}(k^*, n^*) = 1$,  $\boldsymbol{\Gamma}_2(k^*, n^*) = 0$
18: until $\boldsymbol{\Gamma}_2 == \mathbf{0}$
19: return subcarrier allocation matrix $\boldsymbol{Q} \in \mathbb{R}^{K\times N}$
```

service $\mathrm{MOS}_{k,\min}$, which is presented as C2. In addition, $\pi_{k,n}$ is denoted as the subcarrier allocation index with a value of 0 or 1 (0 is unallocated, while 1 is allocated). The condition C3 guarantees that one subcarrier can only be allocated to one user. Finally, the condition C4 indicates that the acquired data rate of each user should be proportional, which ensures the fairness of users.

4 Wireless resource allocation

In this section, we mainly propose the wireless resource allocation algorithm to minimize the total system power with guaranteing the system fairness and maximizing each user's MOS at the same time. Considering both frequency and power resource, an iterative allocation algorithm is proposed to achieve the optimal solution, which can be divided into two parts. The first one is subcarrier allocation, most of which aim at maximizing the system total transmission rate under the constrained power resource condition without considering the fairness of each user. However, fairness is one of the most significant factors to evaluate the system performance. Thus, by considering this shortage, our algorithm give a good trade-off between fairness and throughput. The second one is power allocation, which is based on the allocated subcarrier in the first part. The overall algorithm is described in the following.

4.1 Subcarrier allocation algorithm

The first part of resource allocation is the subcarrier algorithm, which is operated in two main procedures. One aims at reaching each user's minimum rate requirement. Specifically, we find the minimum SNR value in the $\boldsymbol{\Gamma}$ matrix and allocate the corresponding subcarrier to the corresponding user until all users achieve the minimum rate requirement, which is presented as Steps 3–11 of Algorithm 1. Note that the SNR matrix $\boldsymbol{\Gamma}$ could be obtained from the Rayleigh distribution wireless channel. The other process intends to achieve the proportional fairness among users. Based on the subcarrier allocation results in the first phase, we allocate the remaining subcarriers according to the rate proportional fairness factor.

It is also said that the remaining subcarriers are allocated according to the proportional fairness factor f_k of user k, which is defined as

$$f_k = \frac{R_k}{R_{k,\max}},\ k = 1, \ldots, K, \tag{6}$$

where R_k represents the transmission rate of user k from the first stage and $R_{k,\max}$ is the maximum required transmission rate of user k. Specifically, the user with the smallset f_k is chosen and allocated the best one of the unallocated subcarriers. This stage is illustrated as Steps 12–19 of Algorithm 1. After the two stages, the subcarrier allocation process is completed and fairness of users improves dramatically. It is easy to find that the algorithm with fairness achieves the goal of increasing the system total transmission rate as much as possible. Moreover, the power allocation algorithm with minimizing the total system power consumption guarantees a certain system QoE performance.

4.2 Power allocation algorithm

In this subsection, a power allocation algorithm is proposed based on the fixed subcarrier allocation. From the definition of MOS utility function, it is obvious that MOS is a two-level logarithmic function of power. Thus, if the power resource consumption is directly chosen as the optimization objective, the amount of calculation is huge and the problem will be difficult to be solved. In order to avoid this, based on the subcarrier allocation results, the total power minimization problem can be transformed to a data rate minimization problem. Thus, the optimization problem (4) can be reformulated as

$$\begin{aligned} \min\ & \{R_k, -\mathrm{MOS}_k, k = 1, \ldots, K\} \\ \text{s.t.}\ & \mathrm{C1}':\ \ R_k = \sum_{n=1}^{N} \pi_{k,n} R_{k,n} \geqslant R_{k,\min}, \\ & \mathrm{C2}':\ \ R_{\text{total}} = \sum_{k=1}^{K} R_k \leqslant R_{\max}, \\ & \mathrm{C3}':\ \ \mathrm{MOS}_k = U_k\left(R_k\right) \geqslant \mathrm{MOS}_{k,\min}, \end{aligned} \tag{7}$$

where $R_{\max}$ corresponds to maximal power constraint in C1. It can be seen clearly that date rate minimization and MOS value maximization cannot achieve its own optimal solution at the same time, so there is a tradeoff between them. In order to solve this problem, the idea of multi-objective optimization is exploited. Simultaneously, taking fairness into consideration, the weighted metrics method with the least square is used to derive the straightforward solution.

First of all, let us define the error function $e_i(t)$ for each user i by using weighted metrics method:

$$\begin{aligned} e_i(t) = {} & \lambda_{i,1}|R_i(t) - R_{i\min}| + \lambda_{i,2}|U_i(t) - U_{i,\max}| \\ & + \lambda_{i,3}|U_i(t) - U_{i,\min}|, \end{aligned} \tag{8}$$

where t denotes the time window and $\lambda_{i,1}, \lambda_{i,2}, \lambda_{i,3}$ are tradeoff factors with limitation.

$$\sum_{k=1}^{3} \lambda_{i,k} = 1. \tag{9}$$

The $U_i(t)$ function denotes the exponential form of MOS value of user i, which can simplify the computation greatly,

$$U_i\left(t\right) = f_i(\mathrm{MOS}_i\left(t\right)) = k_{i,2}\mathrm{e}^{\frac{\mathrm{MOS}_i(t)+c_i}{k_{i,1}}} = k_{i,3}R_i(t), \tag{10}$$

where $k_{i,1}$, $k_{i,2}$ (both are positive constants) and c_i all are determined by the service type. It is clearly seen that $U_i(t)$ is defined to obtain the $R_i(t)$ related function via MOS function of user i. The first term of the error function $e_i(t)$ aims at minimizing the data rate of users, which will make the power consumption approach to the minimum power as close as possible. In addition, the second term is formulated to reach the maximum MOS value. Moreover, the third term means that the transmission power should make the MOS value of the user close to the minimum required MOS value, which can reduce the unfairness in transmission. Based on the error function, our goal is to find the optimal power vector, which can minimize the following cost function:

$$\min\ J = \sum_{i=1}^{K}\sum_{t=1}^{T} e_i^2(t), \tag{11}$$

where T is the total number of time windows and in our paper, it is set to be 1.

To solve the problem, we first use the simple linear autoregressive model $R_i(t) = w_i R_i(t-1)$. Then the optimal solution is achieved when the first order function (11) equals to 0,

$$\frac{\mathrm{d}J}{\mathrm{d}\omega_i} = 2e_i(t)\frac{\mathrm{d}e_i(t)}{\mathrm{d}\omega_i} = 0 \tag{12}$$

To get the property of e_i, the characteristic of $\frac{\partial e_i(t)}{\partial \omega_i}$ should be discussed first, which is easy to be obtained,

$$\frac{\partial e_i(t)}{\partial \omega_i} = (\lambda_{i,1} + k_{i,3}(\lambda_{i,2}+\lambda_{i,3}))\,R_i(t-1) > 0. \tag{13}$$

Therefore, in order to satisfy the formulation (14), the following must be satisfied:

$$\begin{aligned} e_i(t) = 0 &\Rightarrow \omega_i(\lambda_{i,1} + k_{i,3}(\lambda_{i,2}+\lambda_{i,3}))\,R_i(t-1) - (\lambda_{i,1}R_{\min,i} + \lambda_{i,2}U_{\min,i} + \lambda_{i,3}U_{\max,i}) = 0 \\ &\Rightarrow \omega_i = \frac{(\lambda_{i,1}R_{\min,i} + \lambda_{i,2}U_{\min,i} + \lambda_{i,3}U_{\max,i})}{(\lambda_{i,1} + k_{i,3}(\lambda_{i,2}+\lambda_{i,3}))\,R_i(t-1)} \\ &\Rightarrow \omega_i = \frac{(\lambda_{i,1}R_{\min,i} + \lambda_{i,2}U_{\min,i} + \lambda_{i,3}U_{\max,i})}{\lambda_{i,1}R_i(t-1) + (\lambda_{i,2}+\lambda_{i,3})U_i(t-1)}. \end{aligned} \tag{14}$$

Finally, we can derive the optimal achievable rate of user i,

$$R_i(t) = \frac{\lambda_{i,1}R_{i,\min} + \lambda_{i,2}U_{i,\min} + \lambda_{i,3}U_{i,\max}}{\lambda_{i,1}R_i(t-1) + (\lambda_{i,2}+\lambda_{i,3})U_i(t-1)}R_i(t-1). \tag{15}$$

Based on this optimal rate value, we obtain the optimal power resource allocated to user i as

$$P_i(t) = G^{-1}(R_i(t)), \tag{16}$$

where the function G is defined according to the Shannon formula below:

$$R_i(t) = N_i B_i \log_2\left(1 + \frac{P_i(t)|H_i(t)|^2}{N_i N_0 B_i}\right) = G(P_i(t)), \tag{17}$$

where N_i denotes the number of subcarriers allocated to user i. Here, we assume that the obtained optimal power $P_i(t)$ is equally allocated over each subcarrier of user i. Besides, $H_i(t)$ denotes the equivalent channel gain when power is equally allocated, which can be calculated from [**?**].

Therefore, the detailed power allocation algorithm is described as Algorithm 2. We set the maximum possible MOS value $[\mathrm{MOS}_{1,\max}, \ldots, \mathrm{MOS}_{K,\max}]$ and the minimum MOS value $[\mathrm{MOS}_{1,\min}, \ldots, \mathrm{MOS}_{K,\min}]$ for all users. In addition, the minimum data rate vector $[R_{1,\min}, \ldots, R_{K,\min}]$ could be obtained from user's minimum required power $[P_{1,\min}, \ldots, P_{K,\min}]$.

Note that the correlated channel is assumed more than one time slot delay between the MOS measurement and the power update of each user. The proposed algorithm given by (15) and (16) has certain flexibility. By changing the value of tradeoff factors, i.e., $\lambda_{i,1}$, $\lambda_{i,2}$ and $\lambda_{i,3}$, different solutions can be obtained by focusing on different system performances. It should be highlighted that a proper tradeoff between these objectives should be proposed to obtain the best system performance, which focuses on the decreasing the total transmission power consumption as much as possible under the condition of ensuring system fairness and satisfying the MOS value of users. Actually the selection of the tradeoff factors is

Algorithm 2 Power allocation algorithm of the j-th iteration

```
Require:
  subcarrier matrix $\boldsymbol{Q}$
  weighted factor of $i$-th user $[\lambda_{i,1}, \lambda_{i,2}, \lambda_{i,3}]$
  user minimization rate vector $[R_{1,\min}, \ldots, R_{K,\min}]$
  the maximum MOS vector $[\mathrm{MOS}_{1,\max}, \ldots, \mathrm{MOS}_{K,\max}]$
  the minimum MOS vector $[\mathrm{MOS}_{1,\min}, \ldots, \mathrm{MOS}_{K,\min}]$
Ensure:
  Initialize: user initial rate $\boldsymbol{R}(0) = \boldsymbol{R}_{\min}$
              power iterative threshold $\varepsilon$
              user index $i = 1$
  while $i \leqslant K$ do
      repeat
          Calculate the next iteration rate of $ith$ user
          $R_i(t) = \frac{(\lambda_{i,1}R_{\min,i}+\lambda_{i,2}U_{\min,i}+\lambda_{i,3}U_{\max,i})}{\lambda_{i,1}R_i(t-1)+(\lambda_{i,2}+\lambda_{i,3})U_i(t-1)} R_i(t-1)$
      until $|R_i(t) - R_i(t-1)| \leqslant \varepsilon$
      Obtain the optimal data rate $R_{i,\mathrm{opt}}$
      Use the optimal rate to achieve the optimal power $P_{i,\mathrm{opt}} = G^{-1}(R_{i,\mathrm{opt}}(t))$
      $i = i + 1$
  end while
  return optimal power allocation vector $\boldsymbol{P}_{\mathrm{opt}} \in R^{1\times K}$ and for each subcarrier of any user $i$, the allocated power is
      $p_{n,i} = \frac{P_i}{N_i}$, $n = 1, 2, \ldots, N_i$
```

based on channel information and the service requirements of users, so it should be time-varying. However, in our simulation we only utilize one heuristic method to select the value of tradeoff factors. In future research it will be an attractive topic that how to form the dynamic mechanism to decide the tradeoff factors. Overall, based on the iterative subcarrier and power resource algorithm as described above, we can ultimately get the system's optimal performance, which can be proved by the simulation results in the next section.

5 Simulation results

In the simulation, we consider a multi-user multi-service OFDMA-based network with $N = 512$ and $N = 1024$ subcarriers, each of which has a 15 kHz subcarrier spacing. Besides, $K = 10$ users are uniformly distributed in one cell. The first $K_1 = 3$ users apply FD service, whose minimum transmission rate requirement are $R_{i,\min} = 30$ kbps with $i = 1, 2, 3$. The next $K_2 = 3$ users apply video streaming service whose minimum data rate requirement are $R_{i,\min} = 130$ kbps with $i = 4, 5, 6$. The last $K_3 = 4$ users use VoIP service with the $R_{i,\min} = 6$ kbps minimum transmission rate, where $i = 7, 8, 9, 10$. The Rayleigh fading channel is assumed with unit variance and the coverage range radius of a cell is 500 m. Moreover, the large-scale path loss is set to be $L = 128.1 + 37.6 \lg d$ (dB) [26] where d is the distance between the base station and the user. As for the system total power resource, the maximum total transmission power is assumed to be $P_{\max} = 46$ dBm. These specific parameters are listed in Table 1.

To better analysis, the PF algorithm is chosen as a comparison. The conventional PF algorithm only considers the rate proportional fairness among users applying the different applications. Hence, we utilize this algorithm as a comparison to demonstrate that our proposed algorithm can achieve the power minimization, MOS maximization and users fairness simultaneously. Figure 3 depicts power actual consumption of two algorithms respectively with different number of subcarriers. By continuously changing the amount of total power in a reasonable range, it is easy to find that the actual power resource consumed by the proposed algorithm is always less than the PF algorithm. In other words, the proposed algorithm is more effective with the higher total transmit power. Once the suitable tradeoff factors set, the optimal solution of the proposed algorithm tends to be fixed, which can ensure multiple requirements of the system simultaneously. However, if the amount of available power is not enough, the proposed algorithm will consume all available power and the performance of system may decrease. In addition, the proposed algorithm with $N = 1024$ has less power assumption than that with $N = 512$, so it is obvious

Table 1 Simulation parameters

Parameters	Value
Subcarrier bandwidth	15 kHz
Number of subcarriers	512 or 1024
Number of BS	1
Cell coverage radius	500 m
Number of users	10
FD service users	1,2,3
Video service users	4,5,6
VoIP service users	7,8,9,10
Noise density	−174 dBm/Hz
Maximum transmit power of BS	46 dBm
Path loss model between BS and users	$L = 128.1 + 37.6 \cdot \text{lg}R \quad (R \text{ in km})$

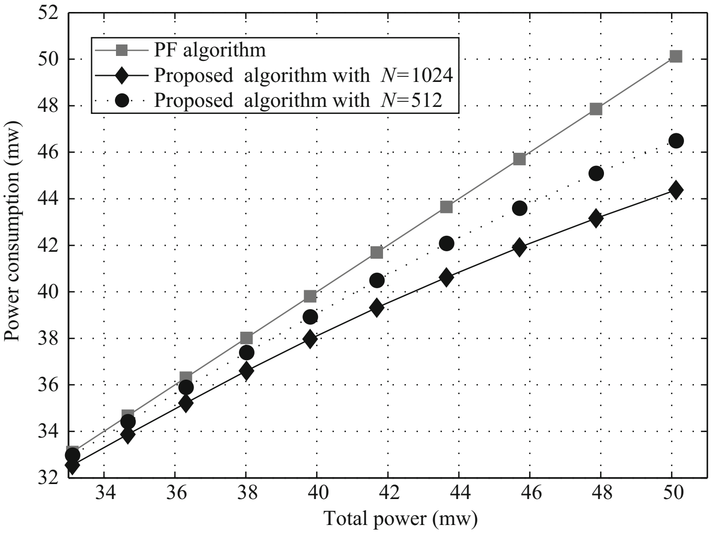

Figure 3 Power consumption of an OFDMA system for the proposed algorithm compared with PF algorithm in the case of $N = 512$ and $N = 1024$.

that when the number of subcarriers becomes larger, the advantages of the proposed algorithm will be more obvious.

In Figure 4 the MOS value of users for two algorithms is presented with different number of subcarriers. By choosing a suitable system total power value (46 dBm) which satisfies all user's minimum power requirements, the average MOS value of each user is obtained after a very large number of simulations. Compared with the PF algorithm, our proposed algorithm can promote the MOS value of real-time services with higher level, such as VOIP service and IPTV service, by reducing the MOS value of the non-real time FD service with lower level. Moreover, the proposed algorithm can achieve higher QoE performance than the PF algorithm because the PF algorithm concentrates on maintaining the fairness of the system, which leads to a decrease of system throughput. However, the number of subcarriers has little influence on the QoE performance.

Figure 5 illustrates the fairness among users for these two algorithms. If all proportional fairness factors f_k defined in Eq. (5) have the same values, it means that the perfect fairness is achieved. Thus, the smaller difference between the factors is, the better fairness performance becomes. From Figure 4 it is obvious that the PF algorithm takes the fairly good fairness with a range of $f_k \in [0.37, 0.39]$, while the proposed algorithm has nearly the same fairness with a range of $f_k \in [0.41, 0.47]$. In other words, compared with the PF algorithm, the proposed algorithm can obtain higher MOS values with less power consumption and ensure the acceptable fairness performance. However, the number of subcarriers has little influence on the fairness performance.

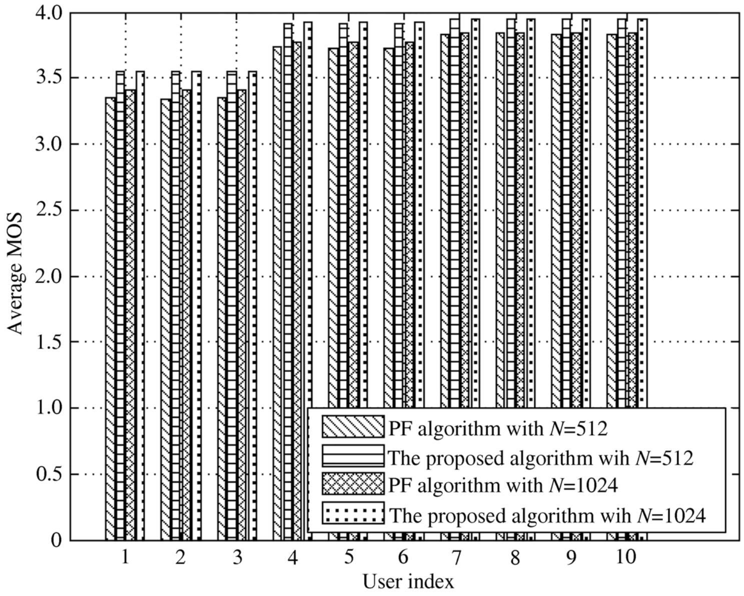

Figure 4 Average MOS value of each user for the proposed algorithm compared with PF algorithm in the case of $N = 512$ and $N = 1024$.

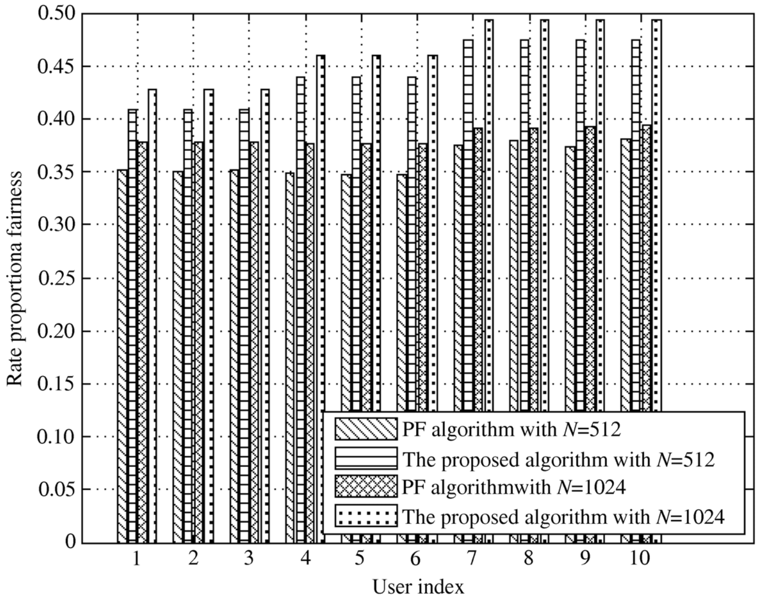

Figure 5 Proportional fairness factor of each user for the proposed algorithm compared with PF algorithm in the case of $N = 512$ and $N = 1024$.

6 Conclusion

In this paper, a QoE-based subcarrier and power allocation algorithm is proposed for the downlink transmission of a multiuser multiservice system, which aims at minimizing the total power consumption with guaranteeing a relatively good average MOS and fairness among users. In the subcarrier allocation stage, we define the rate proportional fairness factor which takes the ratio of maximum requirement transmission rate as the objective. Based on the QoE models of different services, the multi-objective optimization method is exploited to get the optimal power allocation aiming at minimizing the total system power consumption and maximizing the MOS value of users simultaneously. Simulation results indicate that the proposed algorithm has less power consumption and higher QoE performance than the

PF algorithm. In addition, the proposed algorithm can achieve nearly the same fairness performance as the PF algorithm. Moreover, when the number of subcarriers becomes larger, the power assumption will be less but with little influence on both the QoE and fairness performances.

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Conflict of interest The authors declare that they have no conflict of interest.

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