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QoE-driven resource allocation for mobile IP services in wireless network

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Abstract In this study, quality of experience (QoE)-driven resource allocation for multi-applications in Internet Protocol (IP)-based wireless networks is studied. Considering that the mean opinion score (MOS) summation maximization problem is not fair to satisfy heterogeneous users' QoE with various mobile applications, we apply multi-objective optimization method to maximize each user's MOS utility. At the beginning of this work, the relationship between MOS utility and user transmission rate for three multimedia applications, that is, File Download, Internet Protocol Television, and Voice over Internet Protocol are discussed. However, the relations under diverse evaluation models are quite different and users in various mobile applications have different requirements, which make the optimization problem difficult to solve. To meet each user's minimum rate requirement, the idea of Nash bargaining solution is applied in the Hungarian-based subcarrier assignment problem. Then to simplify the power allocation problem, the concept of equivalent channel is introduced. Further by applying the tolerance membership function, we develop a fuzzy Max-Min decision model for generating an optimal power allocation solution. Simulation results demonstrate the satisfying characteristics of the proposed algorithm in terms of MOS utility and average data rate.

Keywords quality of experience, mean opinion score, tolerance membership function, fuzziness, multi-objective optimization

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1 Introduction

Except being used for the file download (FD) application, Internet Protocol (IP)-based wireless networks are more frequently used for various high-quality video services, for example, IP Television (IPTV) and Voice over IP (VoIP). From the perspective of a wireless network, although quality can be measured and optimized through quality of service (QoS), it is insufficient to reliably estimate users' subjective overall perception of quality by only measuring objective QoS parameters. Therefore, the concept of quality of experience (QoE) is coming up [1–3].

The most commonly used metric for QoE is the mean opinion score (MOS) [4]. Recently, several studies have been built on MOS [5–9]. In [6], a new adaptive algorithm has been proposed for the transmission

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rate adjustment of sources for VoIP applications. This algorithm obtains feedback information at each source from its corresponding receiver and aims at maximizing the voice quality perceived at the receiver. The considered voice quality is reflected by an MOS value that is estimated from statistics of the wireless network during a VoIP call. In [7], an MOS-based resource allocation has been investigated for the shared wireless downlink with limited channel state information. This algorithm provides some flexibility to the network operators to configure their policies, for example, the goal to obtain the highest possible MOS or rather the goal to serve more users. Ref. [8] constructs a QoE-driven resource allocation framework in High Speed Downlink Packet Access. The proposed scheme aims at improving the user's QoE by jointly optimizing the application layer and the lower layers of the wireless protocol stack. The common metric MOS for user-perceived quality is used in the optimization scheme. In [9], a balanced strategy for orthogonal frequency division multiple access (OFDMA) radio resource allocation based on game theory concepts is presented, which is based on application-oriented MOS and has the goal of jointly maximizing the QoE.

However, there have been few studies taking the fairness in terms of MOS utility into consideration. From the perspective of efficiency, BS usually aims at achieving the maximum system performance, which is usually measured by summing up all the users' MOS values with different mobile applications. However, it has been demonstrated that the consideration of fairness usually has a negative impact on the performance [10, 11]. The root cause of this impact is that each application has its own MOS evaluation model. Accordingly, the relationships between the MOS utility and user transmission rate for different applications are diverse. For example, it needs a higher data rate for IPTV stream than for a VoIP stream to have a "good" quality. Motivated by these, we formulate a multi-objective optimization problem in the OFDMA system in our study, which aims at achieving the best possible MOS utility for each user. But this problem is not easy to solve, because the relation between MOS utility and users' transmission rate are not always linear and heterogenous users have different minimum rate requirements. To meet all the users' minimum requirements, the idea of Nash bargaining solution (NBS) is applied in the subcarrier assignment process. Meanwhile, to overcome the problem coming from the relations between MOS utility and users' transmission rate, we introduce tolerance membership function to develop a fuzzy Max-Min decision model for the power allocation problem. Then, the solution can be easily obtained by solving a Tchebycheff problem. Simulation results demonstrate the satisfying characteristics of the proposed algorithm in terms of MOS utility and average data rate.

The paper is organized as follows. In Section 2, the relationship between MOS utility and user transmission rate for three multimedia services, that is, FD, IPTV, and VoIP are investigated first, and then the multi-objective optimization problem is formulated, which aims at achieving the best possible MOS utility for each user. In Section 3, an efficient subcarrier allocation scheme is proposed in the beginning, and then a concept of equivalent channel is introduced to make the power allocation problem simplified. The optimal power allocation problem is solved in the last subsection. Some of the simulations are reported in Section 4. Section 5 concludes the paper.

2 System model and problem formulation

Consider a downlink OFDMA system with a base station (BS) communicating with K users over N subcarriers, in which K_1 users enjoy FD service, K_2 users enjoy IPTV application, and K_3 users are served by the VoIP application. For diverse multimedia with different evaluation models, the MOS utility functions are different. Fortunately, the MOS evaluation models are always viewed as subjective evaluation on user transmission rate. With the relationships between MOS utility and user transmission rate for the three mobile applications, our study is formulated and then discussed. Different from other existing MOS maximization problems, a multi-objective optimization problem, which aims at maximizing each user's MOS utility, is considered. To better solve the problem, a joint subcarrier and power allocation scheme is proposed in the study.

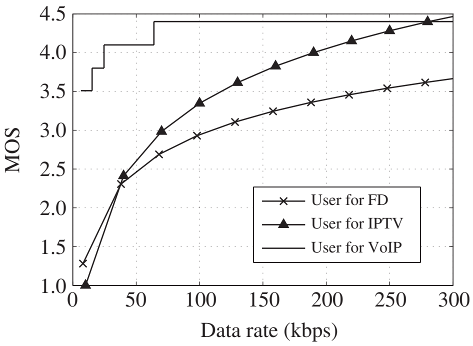

Figure 1 Relation between user transmission rate and MOS for three multimedia applications.

2.1 Relation between MOS utility and user transmission rate

For FD application, the logarithmic MOS-throughput model proposed in [12] is used which assumes that MOS utility is a strictly increasing concave and continuously differentiable function of throughput. The relationship model of FD service between MOS and user transmission rate R is described as follows

$$\mathrm{MOS}_{\mathrm{FD}} = \begin{cases} 1.0, & R < 10 \text{ kbps}, \\ \alpha \lg(\beta R), & 10 \text{ kbps} \leqslant R < 300 \text{ kbps}, \\ 4.5, & R \geqslant 300 \text{ kbps}, \end{cases} \tag{1}$$

where α and β can be calculated from the upper bound and lower bound of the MOS utility, and they are 2.3473 and 0.2667, respectively.

For IPTV application, the video quality in terms of MOS is estimated by a combination of network and application parameters, specifically, send bit rate (SBR), frame rate (FR), and packet error rate (PER) [4]. The relationship can be given by

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

where $a_1 - a_5$ are coefficients set based on different classified video applications, which includes typical video call (gentle walking, GW), video conference application (slight movement, SM), and video streaming (rapid movement, RM). Here, they are set to be -0.0228, -0.0065, 0.6582, 10.0437, and 0.6865, which are a specialized set of parameters for the RM video. We assume that the variables of FR and PER are fixed to establish the relation between SBR and MOS. Assuming that there are no network losses, PER is set to be 0 and the FR is fixed at 10 fps. Then, for the RM content the SBR against MOS utility function can be formulated as

$$\mathrm{MOS}_{\mathrm{IPTV}} = -0.0878 + 0.6582 \ln(\mathrm{SBR}). \tag{3}$$

For VoIP application, assessment by performing subjective tests are not reasonable for online system optimization. Alternatively, objective measurements given by the user can be used, such as the ITU-T perceptual evaluation of speech quality (PESQ) [13]. Considering the retransmission at the MAC-layer, we define MOS as a function of the transmission rate R for simplicity [14]. The graphical representation is the polylines in Figure 1, which shows the MOS measured from a set of speech samples under different codecs and different contents with error-free transmission. The four discrete points indicate four codecs operating at fixed bit rates of 6.4 kbps, 15.2 kbps, 24.6 kbps, and 64 kbps, respectively.

Also, the "triangle" line in Figure 1 denotes the MOS utility relation for the FD application, and the line with "cross" indicates the relation for the IPTV application. As can be seen, the ranges of the MOS value for different mobile applications are diverse. When we set the user transmission rate from 10 kbps to 300 kbps, the range of MOS value for the FD users is 1.0–4.5, for IPTV users is 1.4–3.7, and for VoIP users is 3.5–4.4. As the upper and the lower bounds of these MOS utilities differ, it is not fair to maximize the MOS summation when the users are in different mobile applications. Because the VoIP users are easily fulfilled, they would give a relatively high MOS with a very low data rate; for example, the MOS value is 3.5 when the user data rate is 5 kbps. However, for the FD and IPTV users, the same MOS value 3.5 is achieved when their transmission rate reaches at least 120 and 250 kbps, respectively. Therefore, it can be inferred that all VoIP users' MOS requirements would meet first if our goal is to maximize the system MOS value, FD users are the second to be considered, and IPTV users are usually the least thought out. To guarantee all the users' MOS at a relatively high level, we propose a multi-objective optimization problem in Subsection 2.2 [15, 16], which aims at maximizing each user's MOS utility.

2.2 Optimization problem formulation

Based on the MOS utility functions obtained in the previous section, we propose a multi-objective optimization problem that aims at maximizing each heterogeneous user's MOS utility. This problem is formulated as

$$\begin{aligned}
\max_{\boldsymbol{p}}\ & F(\boldsymbol{p}) = \big(f_1(\boldsymbol{p}),\dots,f_{K_1}(\boldsymbol{p}),\\
&\qquad f_{K_1+1}(\boldsymbol{p}),\dots,f_{K_1+K_2}(\boldsymbol{p}),\\
&\qquad f_{K_1+K_2+1}(\boldsymbol{p}),\dots,f_{K_1+K_2+K_3}(\boldsymbol{p})\big)\\
\text{s.t.}\quad & \boldsymbol{p}\in\mathcal{G}=\Bigg\{\boldsymbol{p}\ \Bigg|\ \sum_{n=1}^{N} p_n \leqslant P_{\max},\\
&\qquad R_k(\boldsymbol{p}) \geqslant 32,\quad \forall k=1,\dots,K_1,\\
&\qquad R_k(\boldsymbol{p}) \geqslant 128,\quad \forall k=K_1+1,\dots,K_1+K_2,\\
&\qquad R_k(\boldsymbol{p}) \geqslant 5.9,\quad \forall k=K_1+K_2+1,\dots,K_1+K_2+K_3\Bigg\},
\end{aligned} \tag{4}$$

where $\boldsymbol{p}=\{p_1,\dots,p_N\}$ is the power allocation vector with p_n the transmit power on subcarrier n. $\mathcal{G}$ is the set of feasible choices for $\boldsymbol{p}$. $R_k(\boldsymbol{p})$ denotes the transmission rate of the kth user when the power allocation vector $\boldsymbol{p}$ is applied. As $R_k(\boldsymbol{p})$ is a function of $\boldsymbol{p}$ according to the Shannon formula and the MOS utility is a one to one mapping to $R_k(\boldsymbol{p})$, it can be easily deduced that the MOS utility is a function of $\boldsymbol{p}$. Therefore, we denote the MOS utility by $f_k(\boldsymbol{p})$ to present the functional relationships between MOS utility and $\boldsymbol{p}$. The user indexes from 1 to K_1 denote K_1 FD users, whose minimum data rate requirements are 32 kbps; indexes from K_1+1 to K_1+K_2 denote K_2 IPTV users, whose minimum data rate requirements are 128 kbps; and indexes from K_1+K_2+1 to $K_1+K_2+K_3$ denote K_3 VoIP users, whose minimum data rate requirements are 5.9 kbps [17].

3 The solution concept

In general, resource allocation includes subcarrier allocation and power allocation. Often, the two problems are discussed separately for the discrete nature of the subcarrier assignment. Similarly, they are separately studied in this study. With regard to the MOS utilities for these mobile applications all grow with the increase of user transmission rate, we consider only the user transmission rate optimization rather than MOS optimization in (4) for the subcarrier allocation to simplify the assigning process.

3.1 Subcarrier allocation

Most of the previous subcarrier assignment algorithms aim at efficiently maximizing the total transmission rate under some constraints. But these approaches always benefit the users closer to the BS and do not take fairness issue into consideration. However, fairness is one of the most important factors to QoE. Under this consideration, the concept of NBS is applied in the subcarrier allocation problem, which is

Table 1 Efficient subcarrier allocation algorithm

1	Let n denote the subcarrier index and k the user index. Then, construct the subcarrier list as $\mathcal{N} = \{1, \dots, N\}$, the user list as $\mathcal{K} = \{1, \dots, K\}$.
2	The average transmit power allocated to each subcarrier is set to be equal. Then, BS transmits reference signals over all the subcarriers at the same time.
3	Each user measures his SINRs over all the subcarriers, that is, $\mathrm{SINR}(k, n), \forall k, n$ and feeds all the information back to BS.
	Repeat
4	Find $(\hat{k}, \hat{n}) = \arg\max\limits_{k,n} \mathrm{SINR}(k, n)$.
5	Allocate the $\hat{n}$th subcarrier to the $\hat{k}$th user, and delete the $\hat{n}$th subcarrier from the subcarrier list $\mathcal{N}$.
	• If the minimum transmission rate requirement of the $\hat{k}$th user is satisfied, then stop allocating subcarriers to this user.
	Until all the users' minimum rate requirements are satisfied.
6	Construct the $Z \times Z$ assignment matrix $\boldsymbol{B}_{\mathrm{ex}}$ for the remaining M subcarriers. The formation of the matrix is shown in Figure 2.
7	Based on $\boldsymbol{B}_{\mathrm{ex}}$, allocate the remaining M subcarriers to the users by the Hungarian algorithm in Table 2.

a compromising solution to the fairness of resource allocation and system efficiency [18]. The intuitive idea of NBS is that after the minimal requirements are satisfied for all users, the rest of the resources are allocated proportionally to users according to their conditions. This can be formulated as

$$\mathrm{NBS} = \arg\max_{\boldsymbol{p}\in\mathcal{G}} \prod_{i=1}^{K} \left(R_i(\boldsymbol{p}) - R_i^{\min}\right), \tag{5}$$

where $R_i(\boldsymbol{p})$ is the transmission rate of user i when the power allocation vector $\boldsymbol{p}$ is applied. $R_i^{\min}$ is the minimal rate requirement user i expects and it is called the initial agreement point.

Based on the idea of NBS, an efficient subcarrier allocation algorithm is proposed in Table 1. Taken as a whole, the algorithm consists of two parts mainly:

1) According to each user's channel gains over different subcarriers, assign the users with minimum amount of subcarriers to satisfy their minimal rate requirements. This process is done by looping through steps 4 and 5.

2) Fairly assign the remaining M subcarriers to the users by the Hungarian method. The fairness defined here is that almost the same number of subcarriers is allocated to all the users.

After all the users' minimum rate requirements are satisfied, each user i's transmission rate over the remaining M subcarriers can be viewed as an increase in the transmission rate relative to the minimal requirements $R_i^{\min}$. To maximize the whole system's rate increase, the assignment problem for the remaining M subcarriers can be formulated as follows

$$\begin{aligned} &\max_{\boldsymbol{X}} \sum_{i=1}^{K}\sum_{j=1}^{M} X_{ij} r_{ij} \\ &\text{s.t.} \begin{cases} \sum_{i=1}^{Z} X_{ij} = 1, & \forall j = 1, \dots, M, \\ \sum_{j=1}^{Z} X_{ij} = 1, & \forall i = 1, \dots, K, \\ X_{ij} \in \{0, 1\}, & \forall i, j, \end{cases} \end{aligned} \tag{6}$$

where r_{ij} is the transmission rate of the user i over subcarrier j and X_{ij} represents whether or not the subcarrier j is assigned to the user i.

$$X_{ij} = \begin{cases} 1, & \text{if subcarrier } j \text{ is assigned to user } i, \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

Substitute r_{ij} into a $K \times M$ matrix $\boldsymbol{R}$, then the Hungarian algorithm can be applied to select the best pairs between users and remaining subcarriers. However, the solution of (6) can only maximize the

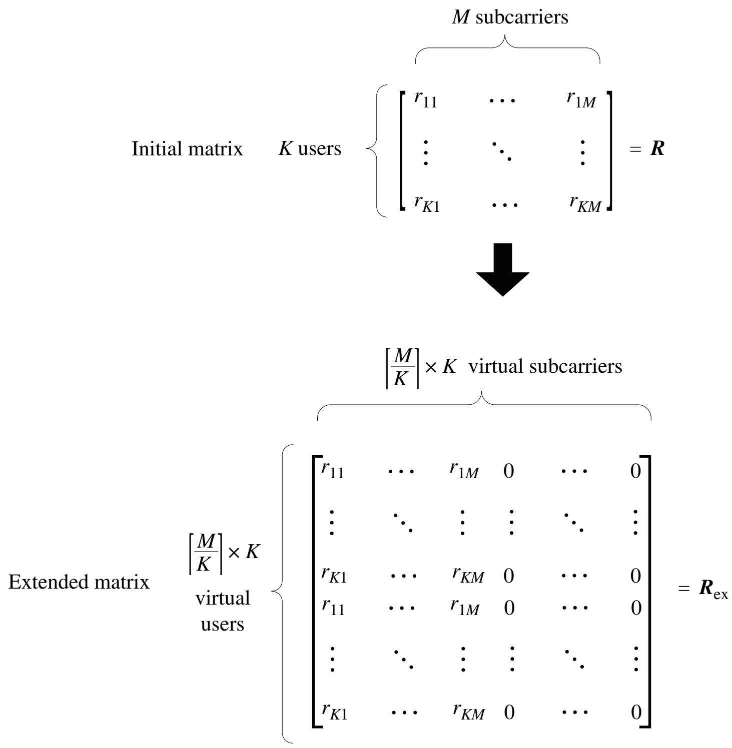

Figure 2 Formation of the assignment matrix $\boldsymbol{R}_{\mathrm{ex}}$.

Table 2 Hungarian method

1	From each row of $\boldsymbol{B}$, find the row minimum and subtract it from all entries on that row.
2	From each column, find the column minimum and subtract it from all entries on that column.
3	Draw lines across rows and columns in such a way that all zeros are covered and that the minimun number of lines have been used.
4	A test for optimality:
	If the number of lines just drawn is Z, we are done.
	else (the number of lines $< Z$), go to step 5.
5	Find the smallest entry which is not covered by the lines, subtract it from each entry not covered by the lines, and also add it to each entry which is covered by a vertical and a horizontal line. Then, go back to step 3.

overall system rate increase but cannot guarantee each user's rate increase. To synthesize each kind of increase, we extend the $K \times M$ matrix $\boldsymbol{R}$ into a $Z \times Z$ matrix $\boldsymbol{R}_{\mathrm{ex}}$, where $Z = \lceil \frac{M}{K} \rceil \times K$ is an integral multiple of K with $\lceil \cdot \rceil$ the roundup function. The formation of the extended matrix $\boldsymbol{R}_{\mathrm{ex}}$ is shown in Figure 2.

Note that the Hungarian method has the minimization optimization goal, so we change the maximization problem into a minimization problem by defining $b_{ij} = -r_{ij} + \max(r_{ij})$. Then, the $Z \times Z$ matrix $\boldsymbol{B}$ is constructed. The Hungarian algorithm is briefly explained in Table 2.

3.2 The concept of equivalent channel

The nonlinear characteristic of the relationship between MOS and user transmission rate makes the optimization complex. To make the optimization simplified further, the concept of equivalent channel is proposed, which is based on the bit error rate (BER) constraint.

Assume that the adaptive quadrature amplitude modulation (QAM) is adopted for each subchannel. Denoting L as the modulation level, which takes from the set $L = \{0, 2^2, \ldots, 2^b, \ldots, 2^B\} =$

$\{0, 4, \ldots, L_b, \ldots, L_B\}$, where b is the number of total bits per symbol in the QAM and

$$L_b = \begin{cases} 0, & b = 0, \\ 2^b, & b \text{ is even and } 0 < b \leqslant B. \end{cases} \tag{8}$$

For simple analysis, the average transmit power assigned to each subcarrier is set to be equal to P_s for all users. If the nth subcarrier is allocated to the kth user, the instantaneous signal noise ratio (SNR) of the kth user on the nth subcarrier is given by

$$\mathrm{SNR}_k^{[n]} = \frac{P_s \cdot T_s \cdot (g_k^{[n]})^2}{N_0}, \tag{9}$$

where T_s is the symbol duration, $g_k^{[n]}$ represents the channel condition from the BS to the kth user on the nth subcarrier, and N_0 denotes the noise variance. With $l_k^{[n]}$-ary QAM in additive white Gaussion noise (AWGN) channel, the instantaneous BER can be approximated as [19]

$$\beta_k^{[n]} \simeq 0.2 \exp\left(-\frac{1.6\ \mathrm{SNR}_k^{[n]}}{l_k^{[n]} - 1}\right) = 0.2 \exp\left(-\frac{1.6 P_s \cdot T_s \cdot (g_k^{[n]})^2}{N_0(l_k^{[n]} - 1)}\right). \tag{10}$$

We further assume that the modulation levels for all the subcarriers allocated to one user are the same, that is, $l_k^{[n_1]} = \cdots = l_k^{[n_{N_k}]} = \tilde{l}_k$, where n_i denotes the ith subcarrier allocated to the kth user which is also the n_ith subcarrier in the subcarrier list and N_k is the total number of subcarriers allocated to the kth user. Then, we get the equivalent instantaneous BER on all the subcarriers allocated to the kth user,

$$\tilde{\beta}_k \simeq 0.2 \exp\left(-\frac{1.6 T_s \cdot P_s \cdot (\tilde{g}_k)^2}{N_0(\tilde{l}_k - 1)}\right) = \frac{1}{N_k} \sum_{n=n_1}^{n_{N_k}} \beta_k^{[n]} = \frac{1}{N_k} \sum_{n=n_1}^{n_{N_k}} 0.2 \exp\left(-\frac{1.6 T_s \cdot P_s \cdot (g_k^{[n]})^2}{N_0(\tilde{l}_k - 1)}\right). \tag{11}$$

To remove other influence factors in (11), define $\eta = \frac{N_0(\tilde{l}_k - 1)}{1.6 T_s \cdot P_s}$. Thus, the equivalent channel gain on all the subcarrier allocated to the kth user is achieved as

$$(\tilde{g}_k)^2 = -\eta \ln\left[\frac{1}{N_k} \sum_{n=n_1}^{n_{N_k}} \exp\left(-\frac{(g_k^{[n]})^2}{\eta}\right)\right]. \tag{12}$$

Therefore, the data rate of the kth user R_k can be expressed as follows

$$R_k = N_k \triangle f \log_2\left(1 + \frac{P_k \cdot T_s \cdot (\tilde{g}_k)^2}{N_0}\right), \tag{13}$$

where P_k is the transmission power on each subcarrier assigned to the kth user, and $\triangle f$ denotes the subcarrier spacing.

3.3 Optimal power allocation

In this section, we use the concepts of tolerance membership function and multi-objective optimization to develop a fuzzy Max-Min decision model for generating satisfactory solution to problem (4) [20].

To build membership functions, goals, and tolerances should be determined first. The individual best solutions (f_k^*) and individual worst solutions (f_k^-) for each objective of (4) should be found first, where

$$f_k^* = \max_{\boldsymbol{p} \in \mathcal{G}} f_k(\boldsymbol{p}), \quad f_k^- = \min_{\boldsymbol{p} \in \mathcal{G}} f_k(\boldsymbol{p}), \quad k = 1, \ldots, K. \tag{14}$$

It can be inferred that f_k^- is achieved when the kth user's minimal requirement just meets, and f_k^* is achieved when other users' minimal requirements just meet such that more power can be allocated to the kth user.

Goals and tolerances can then be reasonably set for individual solution and the differences of the best and worst solutions, respectively. It can then be formulated as the following membership functions:

$$\mu_{f_k}[f_k(\boldsymbol{p})] = \begin{cases} 1, & \text{if } f_k(\boldsymbol{p}) > f_k^*, \\ \frac{f_k(\boldsymbol{p}) - f_k^-}{f_k^* - f_k^-}, & \text{if } f_k^- < f_k(\boldsymbol{p}) \leqslant f_k^*, \\ 0, & \text{if} f_k^- \geqslant f_k(\boldsymbol{p}). \end{cases} \tag{15}$$

Actually, $\mu_{f_k}[f_k(\boldsymbol{p})]$ is a relative value of MOS utility $f_k(\boldsymbol{p})$. Using the relative MOS value $\mu_{f_k}[f_k(\mathbf{p})]$ rather than the absolute value $f_k(\boldsymbol{p})$ can not only avoid the impact introduced by the diverse evaluation models, but also better describe users' subjective perception of quality to some degree. Because for different evaluation models, the MOS value is usually unequal when the same transmission rate is achieved. Also, $\mu_{f_k}[f_k(\boldsymbol{p})]$ offers us a way to compare the MOS utilities for the users with different mobile applications.

Then, we can get solution of (4) by solving the following Tchebycheff problem

$$\begin{aligned} \max_{\boldsymbol{p}} \quad & \lambda \\ \text{s.t.} \quad & \boldsymbol{p} \in \mathcal{G}, \\ & \mu_{f_k}[f_k(\boldsymbol{p})] \geqslant \lambda, \\ & \lambda \in [0, 1], \end{aligned} \tag{16}$$

where λ is the overall satisfaction. Procedures in [21] can be referred. Thus, by finding the maximum λ in (16), the optimal MOS utilities $f_k(\boldsymbol{p}),\ k = 1, \ldots, K$, can be found

$$f_k(\boldsymbol{p}^*) = f_k^- + \lambda(f_k^* - f_k^-). \tag{17}$$

Correspondingly, the optimal power solution $\boldsymbol{p}^*$ can be achieved at the same time.

4 Simulation results

In the simulations, we consider an OFDMA-based network with 10 users normally distributed in this area. The first three users are served by FD service, whose minimum transmission rate requirement is set to 32 kbps. The next three users whose index ranges from 4 to 6 are IPTV users, each with a minimum rate requirement of 128 kbps. The last four are VoIP users, whose minimum transmission rate requirement is set to 5.9 kbps [17]. Rayleigh fading frequency-selective channel is considered in the simulations. The large-scale path loss is given by $L = 128.1 + 37.6 \lg d$ (in dB) [22], where d (in kilometers) is the distance between BS and the user. The transmit power of the BS is assumed to be 46 dBm, and the coverage radius of the cell is 500 m. Forty subcarriers available for the 10 users, and the subcarrier spacing is 15 kHz.

In the simulations, equal power allocation scheme and the method in [9] are chosen as comparisons. In the legend, "max-min MOS" denotes the method in [9], "EPA" is short for equal power allocation. Satisfying all the users' transmission rate requirements, we can find the boundaries of each user's real MOS in Figure 3, that is, "Maximum MOS a user may achieve" and "Minimum MOS a user requires". It can be concluded that any feasible MOS should be within this boundary. For the EPA method, the obtained MOS varies greatly. While the proposed algorithm and the max- min MOS method make it stable. Compared with EPA method, the proposed one guarantees the MOS fairness within each service. The advantage of the proposed algorithm compared with max min-MOS method is that it takes the fairness among different mobile applications into consideration. Since users in different mobile applications have different maximum MOS and minimum MOS values, it is not fair to make all heterogenous users' MOS be the same. In other words, the proposed algorithm considers the requirement differences among these applications. In addition, the overall performance in terms of MOS may be decreased.

Figure 4 shows the average/minimum MOS achieved by the BS-user distance. As can be seen, the proposed algorithm is a compromise between "EPA" and "max-min MOS" either in terms of average MOS or minimum MOS. Figure 5 shows the achieved sum-rate versus the BS-user distance.

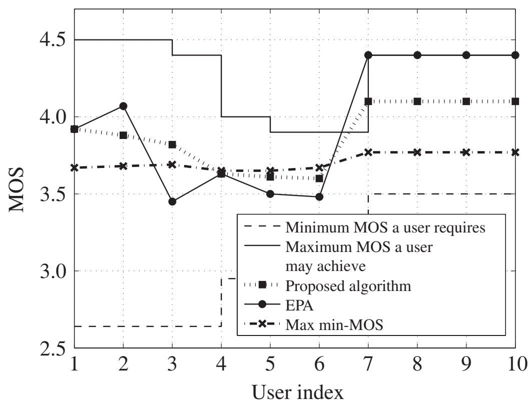

Figure 3 MOS values for all users in different mobile applications.

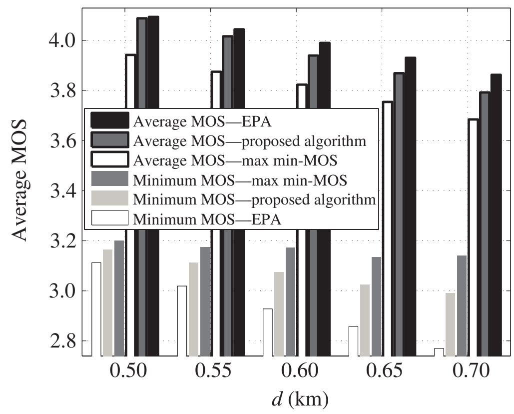

Figure 4 The average/minimum MOS achieved by the BS-user distance.

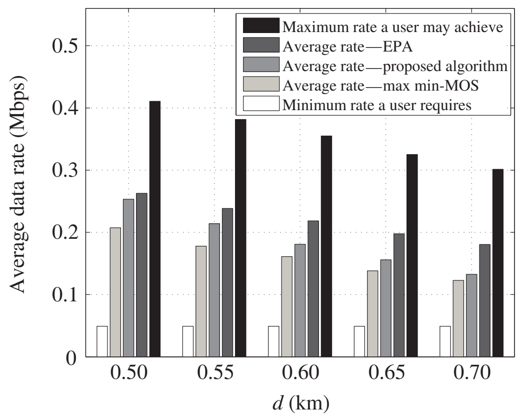

Figure 5 Achieved sum-rate versus BS-user distance.

5 Conclusion

This study considers the resource allocation problem for the QoE-driven IP-based wireless networks with different mobile applications. To solve the multi-objective optimization problem that aims at achieving the best possible MOS utility for each user in different services, an efficient subcarrier allocation scheme is proposed based on the idea of Nash bargaining solution, and then an optimal power allocation algorithm is proposed based on the tolerance membership function. Simulation results demonstrated the satisfying characteristics of the proposed algorithm in terms of MOS utility and average data rate.

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