A QoE-Aware Proportional Fair Resource Allocation for Multi-Cell OFDMA Networks

Yun Hee Cho, Hongseok Kim, Seung-Hwan Lee, and Hwang Soo Lee

***Abstract*—In this letter, we focus on a quality of experience (QoE) aware resource allocation that considers users' time varying channel status and heterogeneous service requirements in multicell OFDMA networks. We propose a QoE-based proportional fair (PF) scheduling considering network-wide users' QoE maximization as well as fairness among users. Our utility function is based on the mean opinion score (MOS) model reflecting the application-specific characteristics. We introduce a Bézier curve based continuously differentiable MOS model instead of using the conventional bounded logarithmic MOS model. Then, we propose a utility function, which is proven to be concave, for QoE provision to achieve the global optimality with opportunistic gradient scheduling. Our proposed technique is shown to be easily incorporated with inter-cell interference coordination (ICIC). Simulation results show that the proposed QoE-aware PF scheme significantly improves the network-wide users' average QoE as well as the edge users' performance, e.g., the 5th percentile QoE.**

***Index Terms*—OFDMA, quality of experience, Bézier curve, proportional fair scheduling, interference coordination.**

I. INTRODUCTION

MOBILE traffic is growing immensely due to the increasing number of smart devices such as smart phones and tablets that are accessing mobile networks worldwide. According to [1], mobile video traffic is estimated to be 66% of the total mobile traffic by 2017. This remarkable growth is driven by the popularity of high quality video services such as embedded video contents in the webpages, video calls, online TVs, etc. Due to the various video characteristics, the users may experience different quality of experience (QoE) even if the data rates are same, which implies that effective QoE aware resource allocation is essential to provide better user satisfaction with limited radio resources.

The QoE is generally evaluated by the mean opinion score (MOS) [2], [3], which practically ranges, e.g., from 1 to 4.5. Research in [4] and [5] proposed the bounded logarithmic relationship between a quality of service (QoS) parameter (e.g., data rate) and a QoE score for different services such as video streaming, FTP, etc. Based on the QoS to QoE mapping, QoE-oriented resource allocation researches for OFDMA system were conducted. In [6], a game theory based resource allocation was proposed to maximize the minimum MOS, which ensures users' fairness. In [4], a non-convex optimization problem was proposed to maximize the total MOS of all users, which is entirely determined by application characteristics and independently on channel conditions. However, MOS based objective functions are usually non-concave and hard to achieve optimality due to the nature of the bounded logarithmic relationship between data rate and MOS. In addition, previous works mainly focused on static channel conditions, and thus further improvement may be possible by employing the opportunistic scheduling to exploit multi-user diversity and frequency diversity.

In this paper, we propose a QoE-based proportional fair (PF) scheduling for OFDMA networks with time varying channel. In doing this, firstly, we propose a *continuously differentiable* MOS function that approximates the conventional bounded logarithmic MOS model. Specifically we adopt the second order Bezier curve [7] to avoid the zero gradient that may cause user starvation in PF scheduling. Secondly, we obtain a condition that forces the QoE-based objective function to be concave and guarantees the globally optimal solution. Our QoE-based PF scheduling is also effective when the tradeoff between aggregated QoE and user fairness is required, e.g., in the capacity limited region with a large number of users. Furthermore, the proposed QoE-based PF scheduling is easily extended to the case of multicell networks by using the adaptive fractional time reuse (FTR) scheme [8] for inter-cell interference coordination (ICIC).

II. SYSTEM MODEL

We consider the general downlink multi-cell OFDMA networks [9]. Let $\mathcal{N} = \{1, \cdots, N\}$ and $\mathcal{K} = \{1, \cdots, K\}$ be sets of BSs and users, respectively. Each user is assumed to be connected to one BS. Denote by $\mathcal{K}_n$ a set of users associated with the BS n. Let $\mathcal{S} = \{1, \cdots, S\}$ be a set of sub-channels, and the transmit power for sub-channel $s \in S$ be denoted by p_s^n. The SINR for user k from BS n on sub-channel s at time-slot t can be written as $SINR_{k,s}^n(t) = \frac{p_s^n G_{k,s}^n(t)}{\sigma_{k,s}^n + \sum_{j \in \mathcal{N}, j \neq n} p_s^j G_{k,s}^j(t)}$, where $G_{k,s}^n(t)$ is a channel gain between BS n and user k at time-slot t, and $\sigma_{k,s}^n$ is a noise power. Following Shannon's formula, the achievable data rate for user k from BS n on sub-channel s is given by $r_{k,s}^n(t) = \frac{B}{S} \log_2(1 + \gamma SINR_{k,s}^n(t))$, where B is a system bandwidth, and γ is a SINR gap to capacity, which is typically a function of a target bit error rate [9]. We assume that each BS n knows the instantaneous achievable data rates on all sub-channels for all its associated users through channel state information feedback. Denote by $\mathbf{I}(t) = [I_{k,s}^n(t) : n \in \mathcal{N}, k \in \mathcal{K}_n, s \in \mathcal{S}]$ a user scheduling indicator vector, i.e., $I_{k,s}^n(t) = 1$ when BS n schedules its associated user k on sub-channel s at time-slot t, and otherwise, 0. Since at most one user can be scheduled in sub-channel s of each BS n every time-slot, we have $\sum_{k \in \mathcal{K}_n} I_{k,s}^n(t) \leq 1, \forall n \in \mathcal{N}, \forall s \in \mathcal{S}$. The actual data rate of user k at time-slot t can then be written

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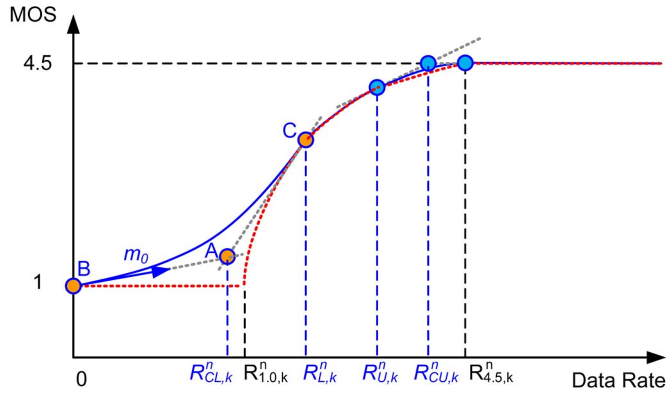

Fig. 1. Original MOS model (red curve) vs. CD-MOS model based on Bezier curves (blue curve).

as $R_k^n(t) = \sum_{s\in\mathcal{S}} I_{k,s}^n(t) r_{k,s}^n(t)$. Then, the average throughput up to time-slot t with a window size W is given by $\bar{R}_k^n(t) = \frac{1}{W}\sum_{\tau=t-W+1}^{t} R_k^n(\tau)$.

Typically, the objective of user scheduling for OFDMA networks is to maximize the network-wide utility which is generally the sum of individual utilities U_k^n,

$$\begin{aligned}\max_{\mathbf{I}(t)} \quad & U(t) = \sum_{n\in\mathcal{N}}\sum_{k\in\mathcal{K}_n} U_k^n(t)\\ \text{subject to} \quad & \sum_{k\in\mathcal{K}_n} I_{k,s}^n(t) \le 1,\ \forall n\in\mathcal{N},\ \forall s\in\mathcal{S}.\end{aligned} \tag{1}$$

For the conventional generalized PF scheduling with QoS provision, the α-fair utility can be described as follows [8]:

$$U_k^n(t) = \begin{cases} \log \bar{R}_k^n, & \alpha = 1\\ (1-\alpha)^{-1}\left(\bar{R}_k^n\right)^{1-\alpha}, & \alpha \ge 0 \text{ and } \alpha \ne 1\end{cases} \tag{2}$$

where α is a fairness factor between users. When $\alpha = 1$ and $\alpha \to \infty$, proportional fairness and max-min fairness are achieved, respectively. Unfortunately, the QoS parameter, $\bar{R}_k^n$, in (2) does not reflect the quality of experience perceived by users. Therefore, we propose a PF scheduling with QoE provision after deriving a novel MOS model.

III. PROPOSED QOE-BASED PF UTILITY FUNCTION

Our key idea is to define a concave QoE-based PF utility function reflecting application-specific characteristics. In this section we describe the proposed MOS model based on Bezier curve, which is to be combined with PF scheduling to balance the network-wide users' QoE maximization and fairness guarantee. Then, we verify the concavity of the proposed QoE-based PF utility function that ensures the global optimality.

A. Basic MOS Model

For real-time video streaming or FTP service, the relationship between average data rate and MOS is typically modeled by the *bounded* logarithmic function[1] [4], [5], as shown by a red dot line in Fig. 1 and given by

$$MOS_k^n\left(\bar{R}_k^n\right) = \begin{cases} 1, & \text{if } \bar{R}_k^n \le R_{1.0,k}^n,\\ \frac{1}{a_k^n}\log\frac{\bar{R}_k^n}{b_k^n}, & \text{if } R_{1.0,k}^n < \bar{R}_k^n < R_{4.5,k}^n,\\ 4.5, & \text{otherwise,}\end{cases} \tag{3}$$

with $0 \le R_{1.0,k}^n < R_{4.5,k}^n, \forall n \in \mathcal{N}, \forall k \in \mathcal{K}_n$. The positive parameters a_k^n and b_k^n are derived according to $R_{1.0,k}^n$ and $R_{4.5,k}^n$ which are the threshold data rates to achieve MOS equal to 1 and 4.5, respectively [4]. Unfortunately, the MOS function in (3) is neither concave nor continuously differentiable, which hinders the systematic approach in achieving the optimal solution of (1); the MOS model (3) is not differentiable at $R_{1.0,k}^n$ and $R_{4.5,k}^n$, and the gradients in $[0, R_{1.0,k}^n]$ and $[R_{4.5,k}^n, \infty]$ are zero. Note that zero gradient on $[R_{4.5,k}^n, \infty]$ is not a problem because the MOS is already saturated and thus additional resource is not required to increase the MOS for user k. However, zero gradient on $[0, R_{1.0,k}^n]$ can be critical unless carefully handled because the marginal utility in this regime is zero. This implies that once $\bar{R}_k^n$ becomes less than $R_{1.0,k}^n$, the user may be stuck in the *dead-lock* state under PF scheduling scheme; no resources will be given to the user because its marginal utility is zero, and it further keeps the user in the starvation regime.

B. Continuously Differentiable MOS Model

To avoid this unfavorable starvation in solving (1), we derive a new MOS function. Specifically, we remodel (3) using Bezier curves [7] to make the MOS function continuously differentiable and strictly increasing for a data rate range of interest, $[0, R_{4.5,k}^n]$, as shown in Fig. 1 with some exaggeration for illustration. We will see that the deviation from the original MOS is negligible in the next section.

As can be seen in Fig. 1, the MOS curve has two new (blue line) curve segment on $[0, R_{L,k}^n]$ and $[R_{U,k}^n, R_{4.5,k}^n]$, which are modified from the original bounded log function (red dot). The brief procedure of making the Bézier curve is as follows [7].

To construct Bézier curve on $[0, R_{L,k}^n]$, we need to specify one intermediate point, say point A, which is the intersection of two lines. The first line passes through (0,1), say point B, and has some slope, denoted by m_0 that determines the Bézier characteristic. The second line is tangential to the original MOS curve at $(R_{L,k}^n, MOS_k^n(R_{L,k}^n))$, say point C. Then, the Bézier curve is characterized by a *single* variable $p \in [0,1]$ such that each point on Bézier curve is $p{:}1-p$ dividing point between two points, each of which is again $p{:}1-p$ dividing point between point B and point A, and point A and point C, respectively. The procedure of constructing another Bézier curve on $[R_{U,k}^n, R_{4.5,k}^n]$ is similar. Then, the abscissa of point A is given by

$$R_{CL,k}^n = \frac{-m_L R_{L,k}^n + MOS_k^n\left(R_{L,k}^n\right) - 1}{m_0 - m_L} \tag{4}$$

and the abscissa of the other intermediate point in making the Bezier curve on $(R_{CU,k}^n, 4.5)$ is given by

$$R_{CU,k}^n = \frac{4.5 - MOS_k^n\left(R_{U,k}^n\right)}{m_U} + R_{U,k}^n \tag{5}$$

where $m_L = \frac{1}{a_k^n R_{L,k}^n}$ and $m_U = \frac{1}{a_k^n R_{U,k}^n}$ are the slopes of the basic MOS curve (3) at data rates $R_{L,k}^n$ and $R_{U,k}^n$, respectively. Then, the continuously differentiable (CD) MOS, $\widetilde{MOS}_k^n$, is given by (6), as shown at the bottom of the next page, as a function of $p \in [0,1]$ instead of $\bar{R}_k^n$.

The virtue of Bézier curve is that the curve is completely characterized by a single variable p, as can be seen in (6), because p and $\bar{R}_k^n$ have one to one correspondence for given application-specific characteristics, e.g., $R_{CL,k}^n$ and $R_{L,k}^n$; we

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[1] We do not claim that one MOS model may be best for all traffic types.

compute p from $\bar{R}_k^n$ by solving the quadratic equation in (6b) or (6e) to compute $\widetilde{MOS}_k^n$. In addition, for strictly increasing Bézier curves, we have the following constraints on $R_{CL,k}^n$ and $R_{CU,k}^n$;

$$0 \leq R_{CL,k}^n \leq R_{L,k}^n \tag{7}$$

$$R_{U,k}^n \leq R_{CU,k}^n \leq R_{4.5,k}^n. \tag{8}$$

C. Our PF Utility Function With Forcing Concavity

Using the MOS derived so far, our generalized PF utility function in terms of MOS becomes

$$U_k^n = \begin{cases} \log\left(\widetilde{MOS}_k^n\left(\bar{R}_k^n\right) - 1\right), & \alpha = 1 \\ (1-\alpha)^{-1}\left(\left(\widetilde{MOS}_k^n\left(\bar{R}_k^n\right) - 1\right)\right)^{1-\alpha}, & \alpha > 1. \end{cases} \tag{9}$$

Note that we subtract one because the minimum of $\widetilde{MOS}_k^n(\bar{R}_k^n)$ is one. In solving (1) with U_k^n in (9), if the utility function is concave, the optimal solution can be obtained in a systematic manner. Because the sum of concave functions is concave, we just need to check whether the individual utility function is concave. Let m_0 be zero without loss of generality for simple proof.

Proposition 1: The proposed individual utility function in (9) is concave when the lower Bézier bound $R_{L,k}^n$ satisfies

$$b_k^n e^{a_k^n + \frac{1}{2\alpha+1}} \leq R_{L,k}^n \leq b_k^n e^{a_k^n + 1}. \tag{10}$$

Proof: It is sufficient to check the second derivative of U_k^n in (9) with respect to $\bar{R}_k^n \in [0, R_{L,k}^n]$,

$$\frac{\partial^2 U_k^n}{\partial {\bar{R}_k^n}^2} = -\frac{Y\left(2p\alpha\left(R_{L,k}^n - 2R_{CL,k}^n\right) + (2\alpha-1)R_{CL,k}^n\right)}{2p^{2\alpha}\left(p\left(R_{L,k}^n - 2R_{CL,k}^n\right) + R_{CL,k}^n\right)^3} \tag{11}$$

where $Y = ((MOS_k^n(R_{L,k}^n) - 1))^{1-\alpha}$, is negative or zero for all $p \in [0, 1]$. This leads to the following condition:

$$-\frac{2\alpha R_{L,k}^n - (2\alpha+1)R_{CL,k}^n}{2(R_{L,k}^n - R_{CL,k}^n)^3} \leq 0. \tag{12}$$

Because $R_{CL,k}^n$ is less than $R_{L,k}^n$ as shown in Fig. 1, (12) leads to the inequality

$$R_{L,k}^n \geq \frac{2\alpha+1}{2\alpha} R_{CL,k}^n. \tag{13}$$

This can be further simplified by using (4):

$$R_{L,k}^n \geq b_k^n e^{a_k^n + \frac{1}{2\alpha+1}}. \tag{14}$$

Then, combining (7) and (4) results in

$$b_k^n e^{a_k^n} \leq R_{L,k}^n \leq b_k^n e^{a_k^n + 1}. \tag{15}$$

Therefore, the constraints (14) and (15) provide (10). For $\bar{R}_k^n \in \{[R_{L,k}^n, R_{U,k}^n], [R_{U,k}^n, R_{4.5,k}^n], [R_{4.5,k}^n, \infty]\}$, the similar procedure results in no additional constraints, which completes the proof.

Our Bézier curve based MOS model can successfully avoid unfavorable starvation and provide the convexity in PF scheduling with enough small deviation, e.g., for ‘Foreman‘ video stream, the maximum deviations for fairness factor $\alpha = 1$ and 10 are 0.1652 and 0.0388 at $R_{1.0,k}^n$, respectively.

IV. QOE-BASED PROPORTIONAL FAIR SCHEDULING

Using the concave utility function derived in Section III-C with the constraint of $R_{L,k}^n$ expressed in (10), we reformulate the optimization problem (1) to maximize the sum of logarithmic users' QoE for $\alpha = 1$, as follows:

$$\begin{aligned} \max_{\mathbf{I}(t)} \quad & U(t) = \sum_{n \in \mathcal{N}} \sum_{k \in \mathcal{K}_n} \log\left(\widetilde{MOS}_k^n\left(\bar{R}_k^n\right) - 1\right) \\ \text{subject to} \quad & \sum_{k \in \mathcal{K}_n} I_{k,s}^n(t) \leq 1, \ \forall n \in \mathcal{N}, \ \forall s \in \mathcal{S}. \end{aligned} \tag{16}$$

Note that thanks to Proposition 1, we can apply the gradient scheduling [9] in solving the problem of (16), which greatly simplifies the original problem into user scheduling subproblems for each BS n and sub-channel s:

$$\begin{aligned} \max_{\mathbf{I}(t)} \quad & \sum_{k \in \mathcal{K}_n} \frac{\nabla \widetilde{MOS}_k^n\left(\bar{R}_k^n\right)}{\widetilde{MOS}_k^n\left(\bar{R}_k^n\right) - 1} I_{k,s}^n(t) r_{k,s}^n(t) \\ \text{subject to} \quad & \sum_{k \in \mathcal{K}_n} I_{k,s}^n(t) \leq 1. \end{aligned} \tag{17}$$

Finally, the QoE-based PF user scheduling for each BS n and sub-channel s can be determined as follows:

$$I_{k,s}^n(t) = \begin{cases} 1, & \text{if } k = \arg\max_{k \in \mathcal{K}_n} \frac{\nabla \widetilde{MOS}_k^n\left(\bar{R}_k^n\right)}{\widetilde{MOS}_k^n\left(\bar{R}_k^n\right) - 1} r_{k,s}^n(t), \\ 0, & \text{otherwise.} \end{cases} \tag{18}$$

Furthermore, the proposed technique can be easily extended to the case of multi-cells. Note that the QoE-based PF utility in (9) is a concave function with a constraint (10), which enables us to apply the adaptive FTR [8] for ICIC. In the adaptive FTR, time resource is partitioned so that adjacent cells transmit high power in different partitions. The resource partitioning ratio $\mathbf{\Phi} = (\phi_0, \cdots, \phi_L)$, where $\sum_{l=0}^{L} \phi_l = 1$, is adaptively determined every T time-slot to maximize the network-wide objective function under dynamic network condition. To do this, we first solve the QoE-based intra-cell user scheduling $I_{k,s,l}^n$ for each time-slot which belongs to partition $l \in \mathcal{L} = \{0, \cdots, L\}$ as in (18), and then we compute the average user scheduling $\bar{I}_{k,l}^n$ and data rate $\bar{R}_{k,l}^n$ per partition l. Obviously the data rate $\bar{R}_k^n$ is a function of the partitioning ratio such as $\bar{R}_k^n(\mathbf{\Phi})$, and the inter-cell resource partitioning problem can be described as [8]:

$$\begin{aligned} \max_{\mathbf{\Phi}} \quad & \sum_{n \in \mathcal{N}} \sum_{k \in \mathcal{K}_n} \log\left(\widetilde{MOS}_k^n\left(\bar{R}_k^n(\mathbf{\Phi})\right) - 1\right) \\ \text{subject to} \quad & \sum_{l \in \mathcal{L}} \phi_l = 1. \end{aligned} \tag{19}$$

$$\widetilde{MOS}_k^n\left(\bar{R}_k^n\right) = \begin{cases} \begin{matrix} (1-p)^2 + 2p(1-p)\left(m_0 R_{CL,k}^n + 1\right) + p^2 MOS_k^n\left(R_{L,k}^n\right) & \text{(6a)} \\ \text{where } \bar{R}_k^n = 2p(1-p)R_{CL,k}^n + p^2 R_{L,k}^n & \text{(6b)} \end{matrix}, & \text{if } \bar{R}_k^n \leq R_{L,k}^n, \\ \frac{1}{a_k^n} \log \frac{\bar{R}_k^n}{b_k^n} \qquad \text{(6c)}, & \text{if } R_{L,k}^n < \bar{R}_k^n < R_{U,k}^n, \\ \begin{matrix} (1-p)^2 MOS_k^n\left(R_{U,k}^n\right) + 2p(1-p)4.5 + p^2 4.5 & \text{(6d)} \\ \text{where } \bar{R}_k^n = (1-p)^2 R_{U,k}^n + 2p(1-p)R_{CU,k}^n + p^2 R_{4.5,k}^n & \text{(6e)} \end{matrix}, & \text{if } R_{U,k}^n \leq \bar{R}_k^n \leq R_{4.5,k}^n, \\ 4.5, & \text{otherwise} \end{cases} \tag{6}$$

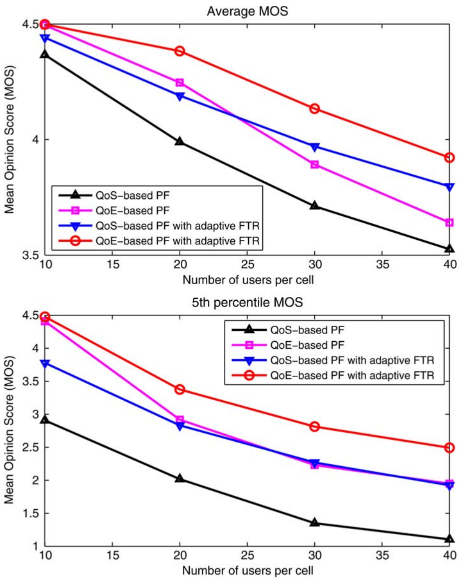

Fig. 2. Average MOS and 5th percentile MOS comparision in the number of users per cell.

The optimal resource partitioning ratio ϕ_l^* for the next T time-slots can be obtained under the previous partitioning ratio $\mathbf{\Phi}$ as follows:

$$\phi_l^* = \frac{\sum_{n\in\mathcal{N}} D_l^n}{\sum_{l\in\mathcal{L}}\sum_{n\in\mathcal{N}} D_l^n} \tag{20}$$

where

$$D_l^n = \sum_{k\in\mathcal{K}_n} \frac{\nabla \widetilde{MOS}_k^n\left(\bar{R}_k^n\right)}{\widetilde{MOS}_k^n\left(\bar{R}_k^n\right) - 1}\bar{I}_{k,l}^n \bar{R}_{k,l}^n. \tag{21}$$

Note that QoE-based inter-cell resource partitioning ratio $\mathbf{\Phi}$ is determined by the marginal utility in terms of MOS rather than the data rate to improve cell edge users' QoE.

V. SIMULATION RESULTS AND ANALYSIS

To evaluate the performance of the proposed QoE-based PF scheduling algorithm, we consider two-tier multi-cell OFDMA networks composed of 19 hexagonal cells. Pathloss models and other setup parameters are based on [8]. Users are uniformly distributed in each cell. We consider mixed user groups with heterogeneous services (30% "Foreman" and 40% "News" real-time video streamers in CIF resolution, and 30% FTP users, which have $R_{4.5,k}^n = \{2156, 638, 300\}$ kbps, respectively [4], [5]. We use $R_{L,k}^n$ in (10) to approximate the original MOS function. The performance metrics are the average MOS, 5th percentile MOS (the average of the lowest 5% MOS of users) and fairness index [10], $\frac{(\sum_{n\in\mathcal{N}}\sum_{k\in\mathcal{K}_n} MOS_k^n)^2}{K\sum_{n\in\mathcal{N}}\sum_{k\in\mathcal{K}_n}(MOS_k^n)^2}$. We compare the proposed techniques with QoS-based PF scheduling as in (2) and QoS-based PF scheduling with adaptive FTR [8].

Fig. 2 shows the average MOS and 5th percentile MOS in the number of users per cell. The proposed QoE-based PF scheduling outperforms the QoS-based PF scheduling in terms of average MOS. Furthermore, the improvement of 5th percentile MOS achieved by the proposed one is even more significant; with a small number of users per cell, the 5th percentile MOS is sufficiently high, and then, as the number of users per cell increases, i.e., in the capacity limited region, the 5th percentile MOS somehow decreases but still exhibits significant performance gain (51–77%). This implies that the application-agnostic data rate itself is difficult to satisfy users' QoE. Similarly, our QoE-based PF scheduling with adaptive FTR achieves the better average MOS and 5th percentile MOS than those of the QoS-based PF scheduling with adaptive FTR. This is because the QoE-based PF scheduling with adaptive FTR appropriately adjusts the resource partitioning ratio to improve users QoE, particularly for cell edge users. Therefore, as can be seen in Fig. 2, the QoE-based scheme can serve more users (e.g., up to 40) than QoS-based PF scheme (e.g., at most 15) while maintaining the same 5th percentile MOS. Next, we compare our QoE-based scheme with QoS-based scheme under various fairness factor α, when the number of users is 20. As α increases, the fairness and 5th percentile MOS are improved at the cost of reduced average MOS, while our scheme maintains the best performance as shown in Table I.

TABLE I
PERFORMANCE COMPARISION UNDER VARIOUS FAIRNESS FACTORS

	α	1	5	10	20
Average MOS	QoS-based PF	3.9916	4.0616	4.0435	4.0303
	QoE-based PF	4.2488	4.2003	4.1233	4.0418
5th percentile MOS	QoS-based PF	1.849	2.599	2.6213	2.6141
	QoE-based PF	2.7971	3.1467	3.2478	3.2802
Fairness Index	QoS-based PF	0.9617	0.9757	0.9747	0.9740
	QoE-based PF	0.9874	0.9902	0.9912	0.9912

VI. CONCLUSION

In this paper, we presented a continuously differentiable MOS model using Bézier curves to overcome the limitation of the bounded logarithmic MOS model. Then, we forced it to be a concave PF utility function for QoE provision to achieve the global optimality with opportunistic gradient scheduling. Our proposed QoE-based PF scheduling was further incorporated with the adaptive FTR for ICIC with ease. Consequently, the proposed QoE-based PF scheme, which can be applied in opportunistic gradient scheduling, guarantees significant benefits in terms of network-wide users' QoE maximization as well as fairness among users. Throughout extensive simulations, we verified that the proposed scheme achieves the good performance in terms of the network-wide users, average QoE, the 5th percentile users' QoE and fairness among users.

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