A Bandwidth Allocation Method to Improve User QoS Satisfaction Without Decreasing System Throughput in Wireless Access Networks

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Kenta Suzuki†, Hiroki Nishiyama†, Nei Kato†, Hirotaka Ujikawa§, Ken-Ichi Suzuki§, and Naoto Yoshimoto§
†Graduate School of Information Sciences, Tohoku University, Sendai, Japan
§NTT Access Service System Laboratories, NTT Corporation, Yokosuka, Japan
E-mail: †{suzuki, bigtree, kato}@it.ecei.tohoku.ac.jp
§{ujikawa.hirotaka, suzuki.kenichi, yoshimoto.naoto}@lab.ntt.co.jp

***Abstract*—In this paper, we focus on the bandwidth allocation issue in wireless access networks, which are made up of Ethernet Passive Optical Network (EPON) and Worldwide Interoperability for Microwave Access (WiMAX) networks, i.e., Fiber-Wire (FiWi) networks. Since the bandwidth allocation scheme largely determines the performance of the entire wireless access network, in the past decades, researchers have dedicated much effort to design bandwidth allocation algorithms based on different criteria in order to satisfy various performance requirements. Various types of bandwidth allocation scheme based on Max-Min Fairness (MMF) or Proportional Fairness (PF) criteria have been developed to increase not only system throughput but also user fairness. However, in general, there is a tradeoff relationship between maximizing system throughput and increasing the fairness among users in throughput, and the users satisfaction in their Quality of Service (QoS) cannot always be maximized by adopting fair bandwidth allocation methods. To cope with this issue, we propose a bandwidth allocation method which improves the QoS satisfaction of all users while maintaining the system throughput similar to standard schemes, such as MMF and PF. In our method, users satisfaction is quantified by using utility functions which can be different among users according to their applications and services. By transferring portions of bandwidth from fully filled users to others so as not to decrease the system throughput, the proposed scheme is able to eventually converge to a compromised point. The results of performance evaluation through computer simulations have demonstrated that our proposed scheme can successfully enhance the performance of wireless access networks.**

I. Introduction

Due to the wide development of wireless communication networks, we can easily access the Internet from everywhere, and can use a lot of different types of network applications, e.g., web browsing, video streaming, and Voice over IP (VoIP). As the number of mobile users increase and multimedia services become more popular, the amount of traffic passing through each Base Station (BS) also dramatically increases. In such environments, the bandwidth allocation techniques equipped in each BS significantly affect the system performance and the users' Quality of Service (QoS) satisfaction.

As studied in many works, Signal-to-Noise Ratio (SNR)-based bandwidth allocation techniques lead to significantly unfair bandwidth sharing among users because the link rate of each user can be largely affected by its radio environment (fading, interference, and phasing), i.e., only a few number of users with higher link rates consume the whole network capacity. In other words, SNR-based bandwidth allocation schemes can maximize the system throughput, i.e., total throughput over all users, but never keep the balance in throughput among users.

As a solution for the above mentioned issue, we know of two major bandwidth allocation criteria, i.e., Max-Min Fairness (MMF) and Proportional Fairness (PF). However, these schemes are not effective under the situation in which different users experience different satisfaction levels even if the same bandwidth is allocated. Actually, many researchers have pointed out that Real-Time (RT) and Non-Real-Time (NRT) users have different functions of satisfaction, referred to as utility functions [1]. Utility functions quantifying users QoS experience are suitable not only to evaluate the fairness among users according to their satisfaction levels but also to define system utility which implies how much the system resource are efficiently utilized to maximize users' satisfaction [1].

Here, we are aware that there are two potential goals in a bandwidth allocation optimization problem, i.e., maximizing system throughput or maximizing system utility. The maximization of total throughput is the most important issue from the view point of network system operators who aim to efficiently utilize the limited bandwidth to carry much more traffic. As a result, users whose wireless link state are not so good tend to be allocated less bandwidth because they cannot achieve high throughput even if more bandwidth is allocated. On the other hand, from the view point of users, the system throughput is not important rather than the system utility. A user's interest is in its QoS satisfaction and no longer in the absolute value of achievable throughput by using the allocated bandwidth. If the achievable throughput is equal to the user's request, the user's satisfaction can be maximized while it never contributes to increasing the system throughput. As clear from the above discussion, there is unfortunately a tradeoff relationship between the maximizations of system throughput and system utility. Therefore, we need a balance between both of them.

In this paper, we focus on Fiber-Wireless (FiWi) access networks, which integrates optical networks and wireless net-

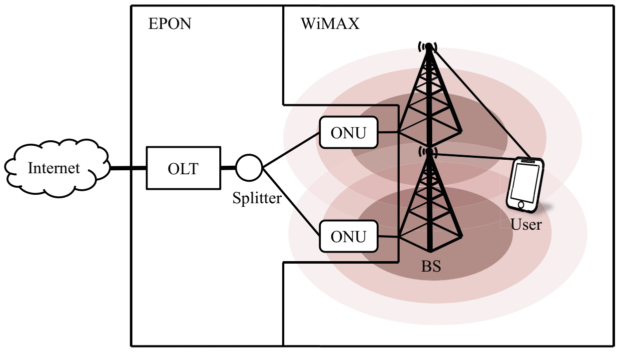


Fig. 1. A topology of a FiWi access network.

works. EPON is used for optical network part. In addition, for wireless network part, any wireless networks are available, such as Wireless Fidelity (WiFi) [2] or Ad-hoc [3], [4] networks. In this paper, we assume Worldwide Interoperability Microwave Access (WiMAX) networks for wireless network system shown in Fig.1. FiWi network provides huge network capacity, a wide coverage area, and QoS management mechanisms. In FiWi access networks, the traffic control scheme of the WiMAX BS largely dictates the system performance because users interact closely with the WiMAX BS. Therefore, a smart resource management scheme for WiMAX is essential.

The rest of this paper is organized as follows. Section II discusses resource allocation issues for wireless broadband. Section III presents objective and algorithms for the proposed resource allocation method. Section IV evaluates the proposed method via simulations in several scenarios, and analyzes the simulation results. Section V concludes this paper.

II. Related work

In this section, we introduce studies about resource management schemes for enhancing system throughput, user QoS satisfaction, or fairness in FiWi access networks, especially in the WiMAX side. In general, resource management schemes are divided into traffic control and bandwidth allocation schemes. Traffic control schemes mainly manage the link association between a BS and a user. Bandwidth allocation schemes manage the ratio of communication opportunity between the users. These two factors significantly affect the system performance.

A. Traffic control

In existing traffic control methods for wireless access networks, the link association between a BS and a user is determined by channel condition in order to achieve higher data rates. Channel condition changes due to factors in the wireless environment such as multi path fading or the distance between the BS and users. In the over lapping coverage area shown in Fig.1, a user can select both BSs. Naturally, the user would select the BS that has better channel conditions. In this situation, if there are a lot of users in this common area and most of them select a specific BS, the amount of resources of the BS are dramatically decreased while the unutilized BS has plenty of unutilized resources, which causes the degradation of system throughput and unfairness of bandwidth allocation.

In order to improve system throughput and bandwidth allocation fairness, load balancing was proposed by Yigal *et al*. [5] and Li *et al*. [6]. They have investigated multiple access point network, similar to the WiMAX part of Fig.1, and have optimized the link association in wireless access networks. In [5], Yigal proposed a Min-Max load balance scheme, which is based on the MMF criterion. The simulation results show that the overall network throughput is increased by balancing the load on the access points. In [6], Li proposed the cvapPF algorithm in order to maximize system throughput and fairly allocate the bandwidth among users by using the PF criterion. The simulation results show that cvapPF algorithm can obtain a system throughput higher when compared with the MMF-based method of [5].

B. Bandwidth allocation

In a WiMAX system, resource allocation is conducted by the scheduler in the MAC layer of the BS. The scheduler distributes slots, which are the smallest logical unit for bandwidth allocation, to the users. For designing a scheduler in WiMAX, QoS, throughput, and fairness are important factors. According to [7], existing schedulers can be classified to channel-unaware or channel-aware schedulers.

Channel-unaware schedulers ensure the QoS requirements of users, which are mainly delay and throughput constrains. First-In-First-Out and Round-Robin are the very fast and simple scheduling algorithms. These algorithms do not consider the QoS requirements, which vary with each user. Weighted Round-Robin algorithm was proposed [8] to assure the differing QoS requirements of users. Channel-aware schedulers can be designed according to different objectives such as fairness, system throughput maximization, or QoS guarantee. MMF [9] was proposed to provide absolute throughput fairness among users. In MMF, users get the same throughput and system throughput extremely decreases because of the lower link rates of users who occupy more resources than higher link rate users. PF is proposed to improve the deficits of MMF and achieve better system throughput than that of MMF, with fairness guarantee in the long-term [10]. PF ensures the fairness of the best effort traffic but does not provide any QoS guarantees. However, channel-aware schedulers suffer from high computational complexity. Therefor, rendering high computational costs when making resource allocation decisions for a large number of users that cannot be computed in the allowable system time.

Shenker [1] proposed a QoS-aware bandwidth allocation method based on a utility function. Utility functions can express QoS requirements which differ by application type and can evaluate user QoS satisfaction due to the allocated bandwidth. While Shenker [1] only proposed a few utility functions, the research in [11] proposed various utility functions to model many differing network applications, in addition to proposing a solution to the trade-off between resource efficiency and user fairness. The research in [12] applied the utility function based QoS-aware bandwidth allocation method of [1] to wireless networks, in addition to proposing a system utility maximization method for elastic and QoS traffic.

III. Utility based resource allocation

In this section, we propose a resource allocation method based on utility functions. The proposed method is implemented into each BS, and independently controls the bandwidth allocated to users connected to each BS. Bandwidth allocation is periodically updated based on the changes in the number of users, channel quality of each user, users' requested bandwidth, application, and so on. In this paper, we discuss the bandwidth allocation algorithm which is invoked upon every update timer expiration. How to dynamically adjust the update interval is beyond our scope. In the following, the considered wireless access network system is presented at first, and then the utility functions, which indicate users' satisfaction for different allocated bandwidth, are introduced followed by the description of the proposed algorithm of bandwidth allocation in each BS. Our method decides the proportion of user resource to the whole resources that the BS has.

A. Considered wireless access network system

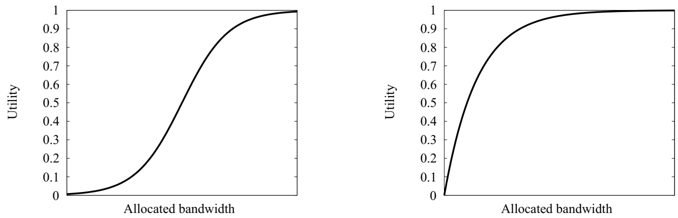
In general, the maximum throughput of each user is limited by its link rate, which is determined by the modulation technology employed at the physical layer based on the radio environment between the user and its BS. Users located near to the BS tend to get higher link rates and vice versa as shown in Fig. 1. For example, 18Mbps, 11Mbps, and 7Mbps are available in Media Access Control (MAC) layer in the case of WiMAX. As for the bandwidth allocation technique, we assume a time-slot based scheme as in WiWAX. When slots s_i are assigned to user i with the link rate equal to r_i, the maximum throughput becomes s_i times r_i. In other words, more slots contribute to achieve larger throughput while the transmittable data size per slot depends on its link rate. In our method, slot allocations are controlled so that users' satisfaction are improved while maintaining the system throughput. In addition, our method is not only for FiWi access networks, but also can be applied to any wireless access networks with time-slot based bandwidth allocation.

B. Utility function

In general, utility functions are classified into RT and NRT applications. VoIP and video streaming are examples of RT applications, and e-mail and web browsing are classified into belonging to the NRT application. In our method, utility functions studied in [1] are used for RT and NRT users. The utility function of RT users is defined as a sigmoid function as follows,

$$U_r = \frac{1}{1 + \alpha \cdot \exp\left(-\beta \cdot \frac{b^{allo}}{b^{req}}\right)}, \quad (1)$$

where b^{allo} and b^{req} show the bandwidth allocated to and requested from a user, respectively. α and β dominate the curve



(a) For RT applications. (b) For NRT applications.

Fig. 2. Utility functions.

of the sigmoid function. Their values depend on the kind of applications, i.e., delay-adaptive or rate-adaptive applications. On the other hand, the utility function of NRT users has been designed based on the law of diminishing marginal utility, which can be expressed by using an exponential function as follows,

$$U_n = 1 - \exp\left(-k \cdot \frac{b^{allo}}{b^{req}}\right), \quad (2)$$

where k is an adaptive parameter. In the study by Nasser et al. [13], k is equal to $\ln(1 - u_i^{max})$ where u_i^{max} is set equal to $u_i(b^{req})$. Since NRT users can be regarded as greedy users, b^{req} is similar to the maximum throughput, i.e., user's link rate. We can see that utility functions for RT and NRT users are monotonically increasing functions. Also, all functions are normalized by the value of their requested bandwidth, so the peak of the utility value is not more than 1, shown in Fig. 2. Although only the allocated bandwidth is utilized as a QoS parameter in the above utility functions, additional metrics, such as delay, jitter, and packet loss, can also be introduced, which is beyond the scope of this paper.

The biggest difference between RT and NRT applications is that RT applications have a minimum bandwidth requirement to allow sufficient performance of applications. According to the minimum bandwidth, utility value of RT applications increase dramatically when the function gets a allocated bandwidth similar to the minimum bandwidth, shown in Fig. 2(a). On the other hand, as shown in Fig. 2(b), NRT applications do not have such behaviours because such applications can function even if the allocated bandwidth is very small. In other words, non-real time applications are delay tolerant.

C. Bandwidth allocation algorithm

In the proposed method, the bandwidth decision process consists of two stages. The first stage is to decide the user assignment among BSs which have the same users in an overlapping service area. In this stage, a tentative slot allocation is determined such that the total system throughput over all BSs is increased similar to traditional schemes based on MMF or PF criteria described in section II-A. The second stage is our original process, which is independently conducted in each BS in order to increase the system utility by exchanging slots among users within the same BS. Here, it should be noted that the increase of the system throughput and the improvement of the system utility have a trade-off relationship. In other

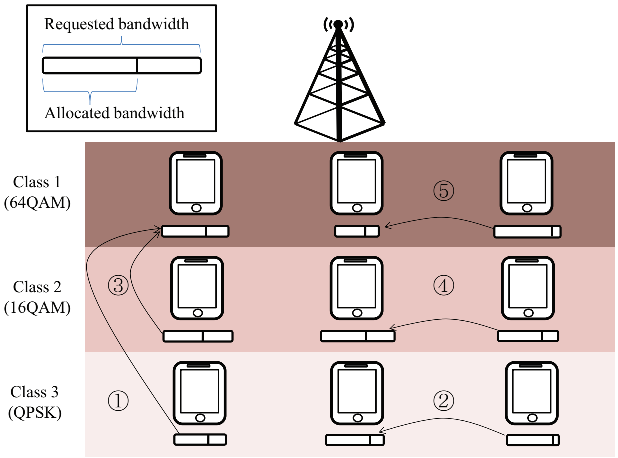


Fig. 3. Algorithm illustration (Number of classes, K, set to 3).

TABLE I
PRIORITY ORDER IN SLOT TRANSFERS

Priority order	Inter or Intra	Slot provider	Slot receiver
1	Inter-class	Class K	Class 1 to K-1
2	Intra-class	Class K	Class K
3	Inter-class	Class K-1	Class 1 to K-2
4	Intra-class	Class K-1	Class K-1
⋮	⋮	⋮	⋮
$2K-1$	Intra-class	Class 1	Class 1

Algorithm I Slot transfer

```
for k in 1 to 2K − 1 do
  loop
    for all user i ∈ U_k^p do
      calculate Δu_i^−
    end for
    for all user j ∈ U_k^r do
      calculate Δu_j^+
    end for
    if max_i Δu_i^+ > min_j Δu_j^− then
      transfer a slot j to i
    else
      break loop
    end if
  end loop
end for
```

TABLE II
VARIABLES FOR ALGORITHM

Variable	Definition
k	Priority order in Table I
U_k^p	Slot provider set according to k
U_k^r	Slot receiver set according to k
i	A user $\in U_k^p$
j	A user $\in U_k^r$
Δu_i^-	Utility value of i according to Eq. (6)
Δu_j^+	Utility value of j according to Eq. (7)

words, slot trading in the second stage can decrease the system throughput which has been optimized from the global point of view in the first stage. To avoid this issue, the proposed method employed in each BS aims to maximize its system utility, which is defined as a summation of utilities of its users, under the condition that its system throughput is maintained. Our goal can be formulated as follows;

$$\max \sum_{i=0}^{N} u_i(b_i^{new}), \tag{3}$$

$$s.t., \sum_{i=0}^{N} b_i^{new} \geq \sum_{i=0}^{N} b_i^{pre}, \tag{4}$$

$$\sum_{i=0}^{N} s_i \leq \mathrm{S_{BS}}. \tag{5}$$

N is the number of users assigned to the BS. b_i^{pre} and b_i^{new} are the allocated bandwidth to i^{th} user before and after the slot trading, respectively. The utility function of i^{th} user, u_i, is U_r or U_n. It should be recalled that the bandwidth of i^{th} user is equal to the product of its link rate r_i and its assigned slots s_i. It is evident that the summation of slots assigned to users is less than or equal to the number of slots available in the BS, S_{BS}. Although the above optimization problem can be solved by using a nonlinear programing solution, it becomes almost impossible with a large number of users (variables) to frequently solve the problem as quickly as it can follow the time changes in the network condition in practice. Therefore, we propose an alternative solution as described in the remainder of this section.

In our proposed bandwidth allocation algorithm, users are classified based on their link rates. The slot transfer is allowed within the same class or to the class with a higher link rate as shown in Fig. 3. By doing so, the system throughout is restricted to be higher than or equal to the first stage. In the calculation process, the inter-class slot transfer is prior to the intra-class slot transfer, and the slot transfer is preceded from the class having a smaller link rate Table I shows an example of the calculation order of slot transfers in the case that Class 1, 2, and K exist, such that Class 1 has the maximum link rate and Class K has the minimum link rate.

As summarized in Algorithm I and Table II, the calculation methods for inter-class and intra-class slot transfer are same, which is an iteration of transferring a slot from a user serving a slot and another user receiving it. In inter-class slot transfer, the server and the receiver need to be selected from the class with a lower link rate and the class with a higher link rate, respectively, in order to preserve the system throughput. An appropriate pair of server and receiver is determined such that the system utility can be maximally increased by the transfer of a slot between them. When the i^{th} user having a slot equal to s_i with link rate r_i, the expected decrement utility value due to the lost of a slot is formulated as follows,

$$\Delta u_i^- = u_i(s_i \cdot r_i) - u_i((s_i - 1) \cdot r_i). \tag{6}$$

In a similar way, the expected incremental utility value if the user gets an additional slot can be expressed as follows,

$$\Delta u_i^+ = u_i((s_i + 1) \cdot r_i) - u_i(s_i \cdot r_i). \qquad (7)$$

It is evident that users having the smallest value of Δu_i^- and the biggest value of Δu_i^+ should be chosen as the server and the receiver, respectively, in order to maximize the effect of the slot transfer in the system utility improvement. When Δu_i^+ becomes less than Δu_i^-, the iteration process of the slot transfer is terminated because the system utility cannot be further improved by exchanging slots in the inter-class or intra-class slot transfer calculation. By conducting the same calculation process for all combinations of classes, our method approximately maximizes the system utility while maintaining the system throughput.

IV. Simulation

In this section, we evaluate the performance of our algorithm through extensive computer simulation programed in Ruby [14]. The simulation parameters are summarized in Table III. We suppose that the wireless access network system is like a WiMAX, and three classes, i.e., 64QAM, 16QAM, and QPSK modulation schemes are available as depicted in Fig. 3. In our simulations, 64QAM, 16QAM, and QPSK modulations correspond to 18Mbps, 11Mbps, and 7Mbps in link rate, respectively. The channel capacity of a BS is shared among users using RT or NRT applications and their utility functions are defined by using Eq. (1) or Eq. (2), respectively. The number of users is fixed at a certain value within the rage from 4 to 100 in each simulation. The ratio of RT users to NRT users is also a simulation parameter ranging from 0 to 1. Requested bandwidth of RT users is randomly selected within the range [128Kbps, 512Kbps]. To purely evaluate the impact of slot allocation among users on the users' satisfaction, we assume that the request bandwidth of each user is equal to or less than its link rate.

In our simulations, the proposed bandwidth allocation algorithm is applied to MMF or PF. In other words, after the decision of the initial bandwidth allocation by MMF or PF, slots are reallocated by the proposed scheme. Therefore, the original MMF and PF are utilized for comparison. The values depicted in each graph show the simulation results, which are the averaged value over three hundred trials with the same parameter configuration. The performance comparison is conducted in terms of system throughput, system utility, and utility fairness. The system throughput is calculated by summing up the allocated bandwidth to users, and the system utility is defined as the summation of utility values over all users divided by the total number of users. To quantify the fairness in bandwidth allocation, the following Fairness Index (FI) is used,

TABLE III
Simulation parameters

Number of users		4 ∼ 100
Request bandwidth	RT	128 ∼ 512 [Kbps]
	NRT	512 [Kbps]
Ratio of NRT to RT		0.0 ∼ 1.0
Maximum speed	Class 1	18 [Mbps]
	Class 2	11 [Mbps]
	Class 3	7 [Mbps]

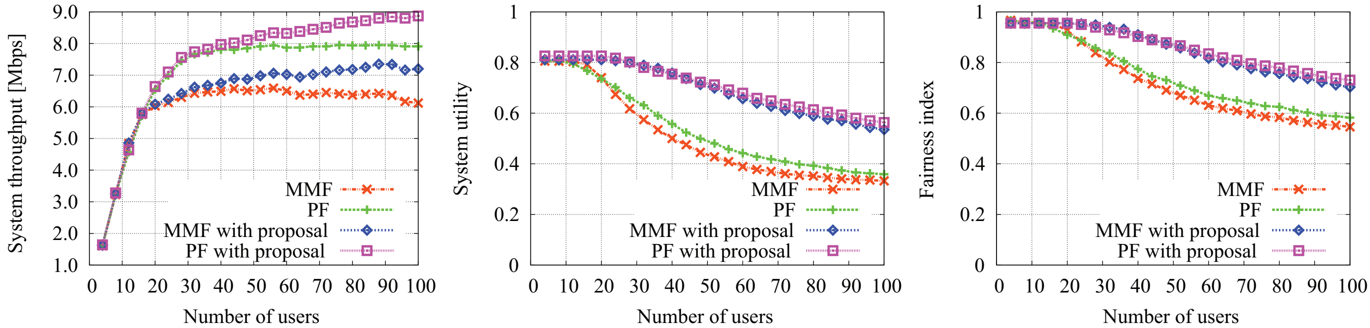
$$FI = \frac{\left(\sum_{j=1}^{N} U_j\right)^2}{N \cdot \sum_{j=1}^{N} {U_j}^2}, \qquad (8)$$

where U_j and N are the utility value of j^{th} user and the total number of users, respectively.

A. Result

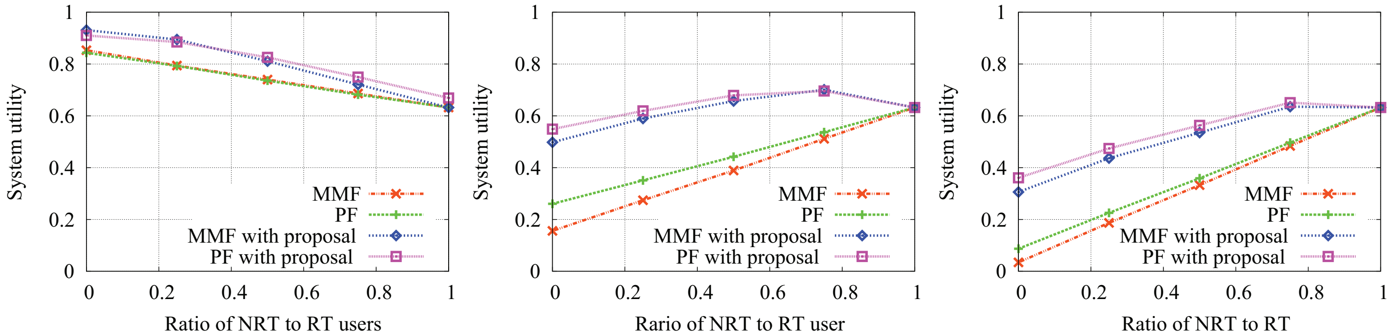
First, we set the ratio between RT to NRT users to 1:1, and plotted the system performance as shown in Figs. 4. Fig. 4(a) shows that MMF with proposal and PF with proposal maintain their system throughput higher than existing methods. Thus, the proposed method effectively improves the system utility and the system throughput. In Fig. 4(b), shows the system utility is near to its maximum value when the number of users is under 12 because the BS has sufficient resources for meeting users' requested bandwidth. Naturally, the resource allocated by the BS to each user decreases with the increase of number of users, which causes the decrease of system utility. In spite of this situation, when the number of users is over 16, MMF with proposal and PF with proposal enhance the system utility by 66% and 55% on average, respectively. Moreover, in Fig. 4(c), utility fairness is also improved, which shows that our proposed resource allocation scheme can modify the excess or starved allocated slots of each users in terms of utility.

Secondly, we varied the ratio of NRT to RT users, while keeping their total number equal to evaluate our proposed method under different user ratios. Also, the number of users was set to 20, 60, and 100. Figs. 5 show the results of our simulation. The results show the our proposed method can successfully improve system utility while RT users are in simulation environment. When there are no RT users in the environment, which equals to the ratio of NRT to RT users is 1, system utility is not improved because the behavior of the NRT utility function prevents the slot transferring function of our proposed method. In other words, the absence of RT users in the network renders conditions equal to traditional best-effort access networks, and such networks do not guarantee QoS requirements. The simulation results also show that it does not make any sense to consider the QoS requirements in the best-effort networks. Therefore, our method will produce the best possible utility. In conclusion our proposal is a promising



(a) System throughput. (b) System utility. (c) Utility fairness index.

Fig. 4. The performance change with different number of users.



(a) With 20 users. (b) With 60 users. (c) With 100 users.

Fig. 5. System utility value for different ratio of NRT to RT users.

method to enhance the system performance in wireless access network.

V. Conclusion

Existing resource allocation methods do not consider QoS even though there are many kinds of applications in wireless access networks, which cause the degradation of system utility. However, simple utility maximization causes dramatic decease of system throughput because of trade-off relationship between them. Therefore, we proposed a utility-based resource allocation scheme. Our extensive simulation results show that our proposed method improves system throughput in compared with other existing methods. Also, our proposal shows distinctive results when system bandwidth is scarce, where our proposal can significantly improve system utility compared with existing methods. Thus, our proposal is an effective allocation method in QoS adaptive wireless access network.

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