QoE-driven Bandwidth Allocation Method Based on User Characteristics

Huong Pham-Thi, Hiep Hoang-Van, Takumi Miyoshi
Graduate School of Engineering and Science
Shibaura Institute of Technology
Saitama, Japan
nb13510@shibaura-it.ac.jp

Tatsuya Yamazaki
Graduate School of Science and Technology
Niigata University
Niigata, Japan

***Abstract*— Network providers are nowadays facing with a big question in allocating network resources due to the constantly increasing of Internet services. While the network resource is not unlimited, users always desire the best quality of experience (QoE) with the huge information exchange. Therefore, finding a justice of network resource allocation based on the user experience is mandatory. In previous studies, network resources were allocated to all users by using a specific utility function without considering the user characteristics. In fact, the network resource consumptions are very different among individual users and directly depend on users' behavior. For instance, the network demands of relax users are usually lower than those of busy users. Thus, allocating the same amount of resources to all users might not meet their expectations. In this paper, we propose two bandwidth allocation methods by classifying users into different groups based on their characteristics such as relax, short-time busy, and long-time busy users. To allocate the bandwidth in each group, specific utility functions are applied. By using these methods, the obtained results show that users get the different allocated bandwidth while they still experience the same level of QoE. On the other hand, the allocation considers users' behavior to allocate suitable bandwidth based on the real resource consumption of users. As a result from these analyses, our proposal tends toward a fair allocation as well as an efficient management of the network resources.**

Keywords—QoE; Bandwidth Allocation; Utility Function

I. INTRODUCTION

In the past few years, quality of service (QoS) is used to express the quality measurement based on the totality of technical characteristics of a service [1]. From the viewpoint of QoS, when the QoS parameters achieve the thresholds, the service quality shall be deemed to meet customers' expectation. However, the QoS metrics cannot exactly reflect the perceived quality of end users. In addition, the success of services depends on the satisfied level of the end users. In other words, users, who directly experience services, are the ones who decide the success of the services. Therefore, the service quality should nowadays be considered from not only QoS viewpoint but also users' viewpoint, which is also known as the quality of experience (QoE).

In general, QoE is defined as the overall acceptability of an application or a service, as subjectively perceived by end users [2]. QoE is naturally subjective and depends on many factors such as applications, contexts, and past experiences. For web applications, users' expectation is finally related to the tolerable waiting time for web page download [3], [4]. Based on previous studies concerning web-users' waiting time, the study in [3] shows that the users' tolerance tends to be shorter in recent years. As a rule, the user demands for network resource have been continuously increasing along with the decreasing of user tolerance. The network resource allocation more than ever is now one of the most important challenges for network providers: how to allocate the resource effectively and satisfy the users' expectation.

To deal with this issue, previous studies first classified users in their characteristics or their degree of relaxation. Then, they proposed to use the utility function to map the relationship between QoE and waiting time for each user group [5], [6], [7]. In [8], the authors furthermore expand to the mapping function between QoE and the allocated bandwidth. The solution of network resource allocation will give the allocated bandwidth for each user group by considering a correlation among users' satisfaction degrees. In these studies, busy users always require broader bandwidth than relax users to get the same QoE. As a result, most of bandwidth will be held by busy users. In fact, however, the resource demand of users who are in a busy mode during a brief period will be completely different from that of users who are continuously busy.

To address this problem, this paper categorizes users into three groups. Beside busy and relax groups, we propose to classify the busy group into 2 subgroups: short-time and long-time busy users. This categorization method is suitable for real applications when users have different busy time and different resource demands. With the new categories, it is expected that this approach can distribute suitable QoE for all users with the limited network resources.

In this paper, we also propose two network resource allocation strategies for web applications based on the above user classification. The strategies are based on the correlation of QoE among three user groups. By adjusting the correlation, the network resource allocated for each user group can be changed. In particular, we use two utility functions to specify the mapping between QoE and the allocated bandwidth for users. Some specific case studies are analyzed with the proposed methods. The obtained results show not only the allocated bandwidth but also the satisfaction level of users in each group.

The rest of this paper is structured as follows. The next section introduces the utility function as well as shows the proposed network resource allocation in detail. Section III presents the obtained results in some case studies with our proposal. Finally, the last section presents the conclusion and future works.

II. BANDWIDTH ALLOCATION METHODS

A. Utility Functions

In order to estimate the QoE from the measureable QoS parameters, a utility function is applied to map the application and network performance parameters (QoS) into user experience (QoE). QoE is typically expressed in terms of mean opinion score (MOS) [9]. MOS is a subjective assessment, which is obtained directly in real experiments to reflect user satisfaction with the perceived quality [10]. In [8], the authors performed some experiments with 31 users who were 18 to 23 years old. The obtained utility functions show the relationship between users' waiting time tolerance and average MOS. The result obtains a realistic relationship between QoE and waiting time because it is carried out on the real statistical data. For this reason, our proposal implements the allocation methods based on these functions, which are expressed as follows:

$$U_R(B_R) = C_R e^{-Q_R \frac{S}{B_R}}, \tag{1}$$

$$U_B(B_B) = C_B e^{-Q_B \frac{S}{B_B}}, \tag{2}$$

where S [bits] is the size of data file. It is assumed that all users download the same data file S in a shared network link of bandwidth B_{ALL}. U_B, U_R, B_B, and B_R are the utility functions and the allocated bandwidth for busy users and relax users, respectively. C_B, Q_B, C_R, and Q_R are constants of the utility functions. Based on the experimental results in previous study [8], these constant values are as follows: C_B = 74.218, Q_B = 0.174, C_R = 81.045, and Q_R = 0.076.

B. User Classification

As mentioned above, this study classifies users into three groups including relax (R), short-time busy (ST), and long-time busy (LT) users. Therein, the relax users use the utility function shown in (1) while ST and LT users use the utility function shown in (2).

$$U_{ST}(B_{ST}) = C_B e^{-Q_B \frac{S}{B_{ST}}}, \tag{3}$$

$$U_{LT}(B_{LT}) = C_B e^{-Q_B \frac{S}{B_{LT}}}, \tag{4}$$

where U_{ST}, U_{LT}, B_{ST} and B_{LT} are introduced to specify the utility functions and the allocated bandwidth to each user in the ST busy and LT busy user groups, respectively.

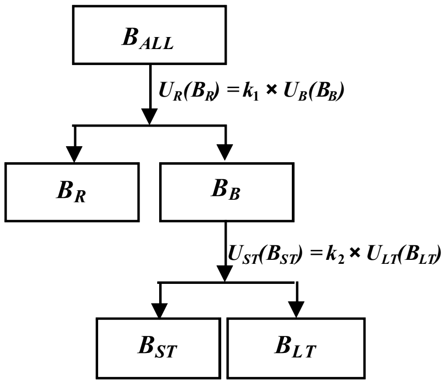

Fig. 1. Method 1 for bandwidth allocation.

Given that N_{ALL} is the number of all users. N_B, N_R, N_{ST}, and N_{LT} are the numbers of busy users, relax users, ST busy users, and ST busy users, respectively. The relationships are expressed as follows:

$$B_{ALL} = B_B N_B + B_R N_R, \tag{5}$$

$$B_B N_B = B_{ST} N_{ST} + B_{LT} N_{LT}, \tag{6}$$

$$N_{ALL} = N_B + N_R, \tag{7}$$

$$N_B = N_{ST} + N_{LT}. \tag{8}$$

C. Proposed Allocation Methods

(1) Method 1

Figure 1 shows the diagram process of method 1. Method 1 introduces a two-stage algorithm to decide the capacity allocation for three groups. The method is based on the following relationships,

$$U_R(B_R) = k_1 \times U_B(B_B), \tag{9}$$

$$U_{ST}(B_{ST}) = k_2 \times U_{LT}(B_{LT}), \tag{10}$$

where k_1 and k_2 are parameters to control the correlation of the utility function values of three user groups.

In this method, all users are first divided into relax and busy users. The allocated bandwidth for each user in both groups can be calculated based on the relationship in (9). Then, busy users will be categorized into ST and LT busy users. Therefore, based on the relationship in (10), the allocated bandwidth for ST and LT busy users will be derived. The transformation in the method is similar to that in [8].

From (1), (2), and (9), the following equation is obtained,

$$\frac{Q_B}{B_B} - \frac{Q_R}{B_R} = \frac{1}{S}\ln\left(k_1 \frac{C_B}{C_R}\right). \tag{11}$$

The right side of (11) can be replaced as a constant value C_1,

$$C_1 = \frac{1}{S}\ln\left(k_1 \frac{C_B}{C_R}\right). \tag{12}$$

Then, the formulae in (1) and (2) are transformed into the general quadric equations as follows:

$$C_1 N_B B_B^2 - ((Q_B - Q_R)N_B + Q_R N_{ALL} + C_1 B_{ALL})B_B + Q_B B_{ALL} = 0, \quad (13)$$

$$C_1 N_R B_R^2 + ((Q_R - Q_B)N_R + Q_B N_{ALL} - C_1 B_{ALL})B_R - Q_R B_{ALL} = 0. \quad (14)$$

The solution of the above quadric equations are derived for B_B and B_R which are of the form:

$$B_B = \frac{-b_B \pm \sqrt{b_B^2 - 4Q_B C_1 N_B B_{ALL}}}{2C_1 N_B} \quad (N_B \neq 0), \quad (15)$$

$$B_R = \frac{-b_R \pm \sqrt{b_R^2 + 4Q_R C_1 N_R B_{ALL}}}{2C_1 N_R} \quad (N_R \neq 0), \quad (16)$$

where

$$b_B = -((Q_B - Q_R)N_B + Q_R N_{ALL} + C_1 B_{ALL}), \quad (17)$$

$$b_R = (Q_R - Q_B)N_R + Q_B N_{ALL} - C_1 B_{ALL}. \quad (18)$$

Thus the allocated bandwidth for busy and relax user groups are obtained. In the same way, based on (10) B_{ST} and B_{LT} are derived for ST and LT busy users as follows:

$$B_{ST} = \frac{(C_2 N_B B_B - N_B) \pm \sqrt{(C_2 N_B B_B - N_B)^2 + 4C_2 N_{ST} N_B B_B}}{2C_2 N_{ST}} \quad (N_{ST} \neq 0), \quad (19)$$

$$B_{LT} = \frac{(C_2 N_B B_B + N_B) \pm \sqrt{(C_2 N_B B_B + N_B)^2 - 4C_2 N_{LT} N_B B_B}}{2C_2 N_{LT}} \quad (N_{LT} \neq 0), \quad (20)$$

where

$$C_2 = \frac{1}{SQ_B} \ln k_2. \quad (21)$$

The allocated bandwidth of relax, ST and LT busy users are given by (16), (19), and (20), respectively. There are two values can be assigned for B_R, B_{ST}, and B_{LT} based on these equations. In fact, however, only one value is suitable to choose for real applications. In this case, the negative values should be omitted.

(2) Method 2

Method 2 introduces a one-stage algorithm to decide the capacity allocation for three groups at a stroke. The approach is based on the following relationships for the QoE of users,

$$U_R(B_R) = l_1 \times U_{ST}(B_{ST}) = l_2 \times U_{LT}(B_{LT}), \quad (22)$$

where l_1 and l_2 are controlling parameters.

Figure 2 presents the relationship of the utilities among three user types. Based on the relationship in (22), then (1), (3), and (4) are transformed as follows:

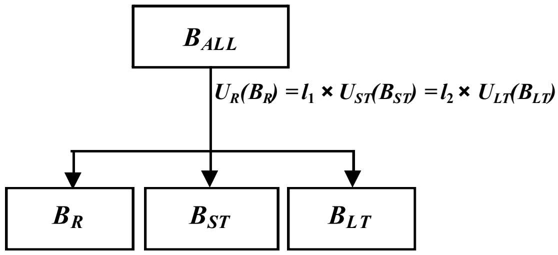

Fig. 2. Method 2 for bandwidth allocation.

$$\frac{Q_B}{B_{ST}} - \frac{Q_R}{B_R} = \frac{1}{S} \ln\left(l_1 \frac{C_B}{C_R}\right), \quad (23)$$

$$\frac{Q_B}{B_{LT}} - \frac{Q_R}{B_R} = \frac{1}{S} \ln\left(l_2 \frac{C_B}{C_R}\right), \quad (24)$$

$$\frac{1}{B_{ST}} - \frac{1}{B_{LT}} = \frac{1}{SQ_B} \ln \frac{l_1}{l_2}. \quad (25)$$

The right side of (23), (24), and (25) can be regarded as constant values,

$$h_1 = \frac{1}{S} \ln\left(l_1 \frac{C_B}{C_R}\right), \quad (26)$$

$$h_2 = \frac{1}{S} \ln\left(l_2 \frac{C_B}{C_R}\right), \quad (27)$$

$$h_3 = \frac{1}{SQ_B} \ln \frac{l_1}{l_2}. \quad (28)$$

After the transformation, the formulae for B_R, B_{ST}, and B_{LT} have the form of the general cubic equations as follows:

$$ax^3 + bx^2 + cx + d = 0 \quad (a \neq 0), \quad (29)$$

where

$$a(B_R) = h_1 h_2 N_R, \quad (30)$$

$$b(B_R) = Q_B h_2 N_{ST} + Q_B h_1 N_{LT} + Q_R N_R (h_1 + h_2) - h_1 h_2 B_{ALL}, \quad (31)$$

$$c(B_R) = Q_B Q_R N_B + Q_R Q_R N_R - Q_R h_1 B_{ALL} - Q_R h_2 B_{ALL}, \quad (32)$$

$$d(B_R) = -(Q_R)^2 B_{ALL}, \quad (33)$$

$$a(B_{ST}) = -h_1 h_3 N_{ST}, \quad (34)$$

$$b(B_{ST}) = h_1 N_B + Q_B h_3 N_{ST} + Q_R N_R h_3 + h_1 h_3 B_{ALL}, \quad (35)$$

$$c(B_{ST}) = -(Q_B N_B + Q_R N_R + Q_B h_3 B_{ALL} + h_1 B_{ALL}), \quad (36)$$

$$d(B_{ST}) = Q_B B_{ALL}, \quad (37)$$

$$a(B_{LT}) = h_2 h_3 N_{LT}, \quad (38)$$

$$b(B_{LT}) = -(Q_B h_3 N_{LT} - h_2 N_B + Q_R h_3 N_R + h_2 h_3 B_{ALL}), \quad (39)$$

$$c(B_{LT}) = Q_B h_3 B_{ALL} - Q_R N_R - Q_R N_R - h_2 B_{ALL}, \quad (40)$$

$$d(B_R) = Q_B B_{ALL}. \quad (41)$$

To solve the formulae represented by (29), there are some solutions such as Cardano method, Vieta method, Lagrange method, and trigonometric method [11], [12]. These methods are different in the transformation process. However, the general roots of (29) can be expressed as the geometric interpretation as follows:

$$x_1 = \frac{2\sqrt{\Delta}\cos\left(\dfrac{\cos^{-1}\mu}{3}\right) - b}{3a}, \tag{42}$$

$$x_2 = \frac{2\sqrt{\Delta}\cos\left(\dfrac{\cos^{-1}\mu}{3} - \dfrac{2\pi}{3}\right) - b}{3a}, \tag{43}$$

$$x_3 = \frac{2\sqrt{\Delta}\cos\left(\dfrac{\cos^{-1}\mu}{3} + \dfrac{2\pi}{3}\right) - b}{3a}, \tag{44}$$

where

$$\Delta = b^2 - 3ac, \tag{45}$$

$$\mu = \frac{9abc - 2b^3 - 27a^2 d}{2\sqrt{|\Delta|^3}} \quad (\Delta \neq 0), \tag{46}$$

with conditions: $\Delta > 0$ and $|\mu| \leq 1$.

Equations (42), (43), and (44) show the general form of allocated bandwidth for users. By changing parameters a, b, c, and d from (30) to (41), the bandwidth for relax, ST busy, and LT busy users will be obtained, respectively. Each equation can give three root values. However, only one suitable value is chosen as the allocated bandwidth for each user group. Too large or negative values should be omitted.

III. NUMERICAL RESULTS

This section shows the numerical results obtained by two allocation methods in the previous section. It is assumed that the total number of users N_{ALL} is 20 and they download the same content whose size is 6.44 Mbits. The total bandwidth B_{ALL} is 100 Mbps, and the number of busy users, N_B, is 18.

A. Method 1

Figures 3, 4, and 5 present the obtained results with the different values of k_1 and k_2 by using method 1. The relationship among users' QoE is set by k_1 and k_2 in (9) and (10). In this case, the allocated bandwidth and the utilities are calculated for all users when the rates of ST and LT busy users change. Therein, the horizontal axis denotes the number of the ST busy users. The utility values are shown on the primary vertical axis (left side). On the other hand, the secondary vertical axis indicates the allocated bandwidth in Mbits (right side).

In this method, the utilities and the allocated bandwidth for relax users are independent of the number of ST busy users. Figure 3 shows the results in the first scenario, in which k_1 = 1.0 and k_2 = 1.2. It means that the average QoE of all busy users is the same as that of the relax users. In addition, the ST busy users experience 20% better QoE than LT users. The utility that is assigned to ST busy users is more than others, and the allocated bandwidth for ST busy users also becomes higher.

Figure 4 shows the results of scenario 2, in which both k_1= k_2 = 1.2. The utility for relax users is 20% higher than the average utility of ST and LT busy users. In addition, the utility for LT busy users becomes 20% less than ST busy users. In both case studies shown in Figs. 3 and 4, the bandwidth allocated to the ST and LT busy users decreases as the number of the ST busy users increases. In this case, the relax users receive the highest utility while their allocated bandwidth is not the largest.

The important point is shown in both Figs. 3 and 4: When the number of users belonging to ST busy user group is small, much bandwidth is allocated to the users in this group.

Figure 5 presents the results when k_1 and k_2 are changed to 1 and 0.8, respectively. As the rule, the more ST busy users are, the less LT busy users are. In the case, much more bandwidth is allocated to LT busy users. Moreover, the utilities of ST and LT busy users increase as the number of ST busy users increases.

In general, the allocated bandwidth and utility of relax users are stable when the number of ST busy users changes in this method. Choosing the controlling parameter values

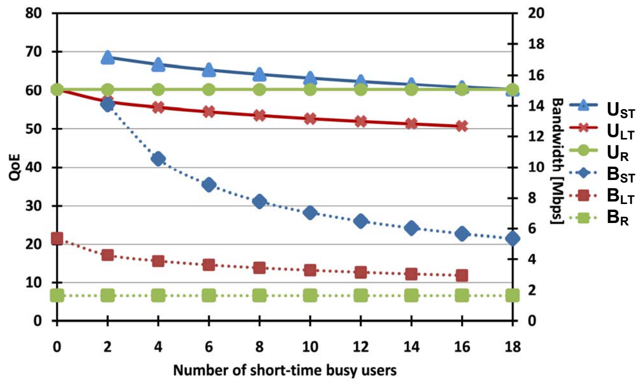

Fig. 3. Computation results with method 1, k_1=1, k_2=1.2.

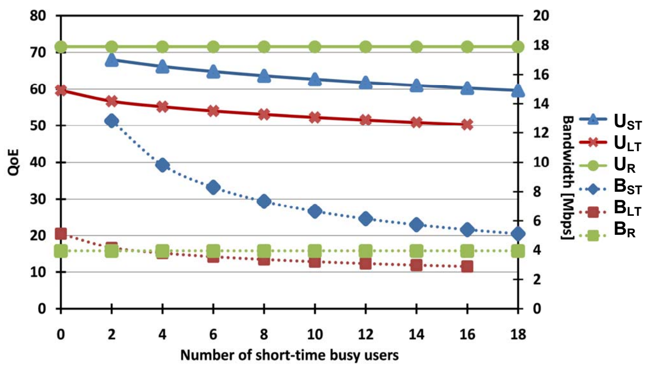

Fig. 4. Computation results with method 1, k_1=k_2=1.2.

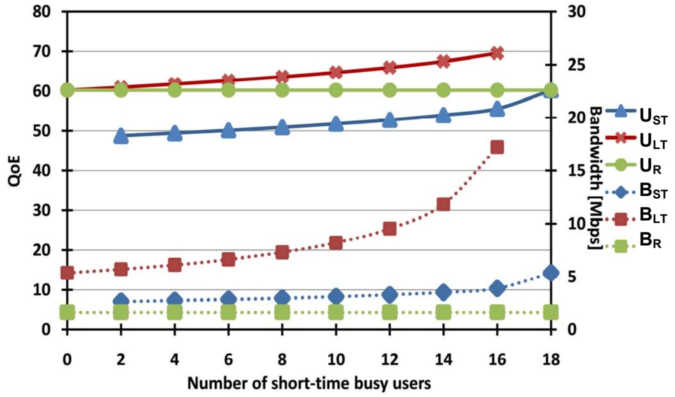

Fig. 5. Computation results with method 1, k_1=1, k_2=0.8.

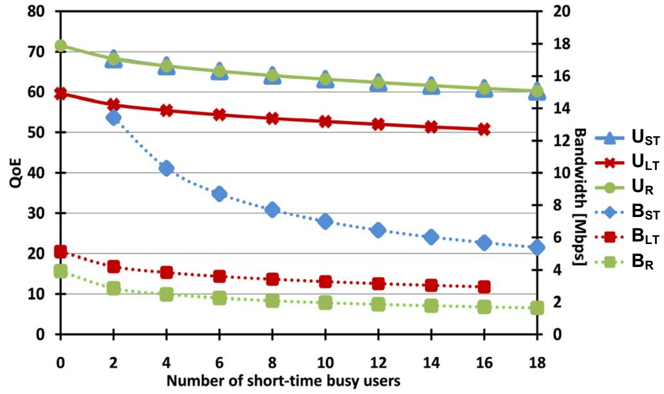

Fig. 6. Computation results with method 2, l_1=1, l_2=1.2.

depends on the specific situation and application. In our opinion, the LT busy users should receive less utility than relax and ST busy users.

B. Method 2

Figures 6, 7, and 8 show the results obtained with the method 2. As mentioned above, the second bandwidth allocation method is based on the correlation among three user groups represented by (22). The parameters l_1 and l_2 are utilized to control the relationships among the groups. The information is denoted by the horizontal and vertical axes like those in the previous method. From the results, both the utilities and the allocated bandwidth for users depend on the ratio of ST busy users.

Figure 6 presents the statistical results when l_1 = 1 and l_2 = 1.2. In this case, the utilities will be the same value for ST busy and relax users. Furthermore, they are 20% more than that of LT busy users. When a few users belong to the ST busy user group, the allocation should distribute more resource for ST busy users.

Figures 7 and 8 describe the utilities and allocated bandwidth with other controlling parameter values. In Fig. 7, the utility of relax users is assigned 20% more than ST busy users and 40% more than LT busy users. The allocated bandwidth for relax users increases rapidly when the number of ST busy users decreases.

In Fig. 8, the relax users receive the utility 10% higher than ST busy users and 30% higher than LT busy users. In Figs. 7 and 8, the utility of relax users is higher than other users. In this case, however, the much bandwidth is allocated to ST busy users as the number of ST users is small.

In general, both the proposed methods show that it is possible to allocate bandwidth based on user characteristics. The first method focuses on the relationship of QoE between relax group and busy group or among users in busy group. The second method considers the relationship among three groups. In our opinion, the second method is more convenient than the first method in allocation in spite of slightly complicated computing.

IV. Conclusion

In this paper, we proposed two methods for the network resource allocation based on the utility functions for three groups of users. The first method allows to control the correlation of QoE between relax and busy groups, and then consider to distribute into ST and LT busy groups. The second method is based on the correlation of QoE among three user groups. By considering the QoE of users, the network resource allocations are derived for users. In the study, some simplistic cases were introduced to demonstrate the results with two proposed methods. The results prove that it is possible to implement a fair allocation of QoE level, which is based on the utilities of users.

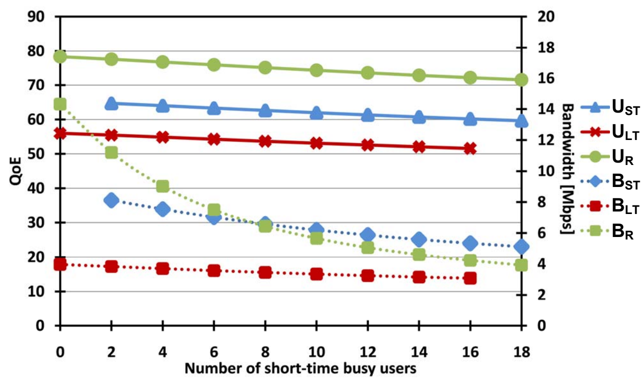

Fig. 7. Computation results with method 2, l_1=1.2, l_2=1.4.

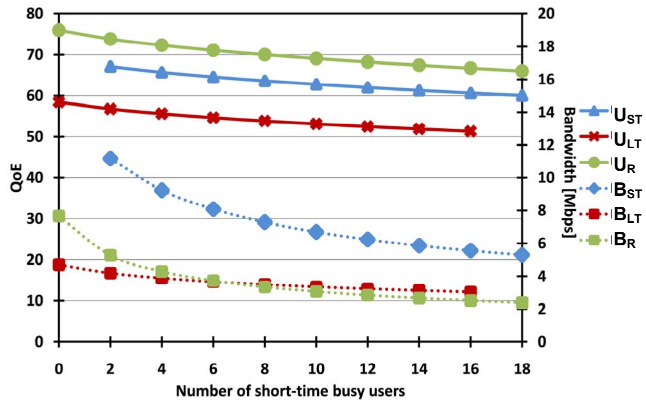

Fig. 8. Computation results with method 2, l_1=1.1, l_2=1.3.

Some challenges remain in current implementation. First, the user classification in the study is just relative. In fact, it depends on the application, situation, and the past experience of users. In particular, users may have different expectations depending on psychological effects. In the future, we will analyze the proposed methods in various case studies reflecting real situations. Moreover, in existing studies, the user classification is based on the users' answers about their degree of relaxation. It causes annoyance to users, and it is hard to apply in real applications. Therefore, it is necessary to find a new solution to predict users' behavior without or reducing the disturbance/irritation to users. Future works also study to find a solution for this problem, which will be invisible with users.

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