Bandwidth Allocation Methods Based on Quality of Experience Considering Users' Characteristics for Web-based Services

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To my parents and my husband, thanks for their love and encouragement.

To my son, thanks for coming in my life.

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Abstract

The constant increase of Internet services as well as the rapid improvement and support from software and hardware devices have allowed users to easily access many types of Internet services such as news, email services, social networking, and even entertainment with audio and video anywhere and anytime. As a result, huge information exchanged among users has generated a large quantity of traffic on the Internet. While the network resource is limited, users always expect the better level of satisfaction. This poses the challenges of network resource allocation for not only network providers but also network planning and system design.

There is no doubt that the Internet and its services are becoming an important role in people life. However, there are two difficult problems for network providers in allocating and distributing the internet bandwidth resource: how to allocate reasonably the limited network resource to users and still guarantee the perceived quality of users. In other words, the fairness in allocation and users satisfaction is the most important consideration in solving the resource distribution problem. The problem has motivated intensive research in the past few years to find the ways to balance the fairness in allocation among users while keeping a reasonable network performance.

To address the above problems, in the dissertation I propose novel approach for bandwidth resource allocation schemes based on the quality of experience (QoE) for web-based services. Web-based services, one of the typical Internet services, which are widely used by Internet users, have been growing with a tremendous speed in the recent years. From the viewpoint of users, the proposed approach clearly shows the

level of users satisfaction and the objective information, i.e., network metrics. In particular, this dissertation includes the following main points.

First, I proposed a bandwidth resource allocation scheme which is based on the fair QoE viewpoint to allocate the bandwidth to users. This scheme is based on the fact that users can experience the same satisfaction level even in the different network resource environment. It is caused by the effect of subjective factors such as users' situation, demands, or degree of relaxation. The main point of the proposed scheme is the applicability to multi-user types in real systems. In the dissertation, I analyzed the proposed method in case of two, three, four and generalized user situations. The numerical results show that the proposed method successfully allocates a fair QoE to users and improves the QoE for dissatisfied users.

Secondly, I proposed a hybrid allocation method for three user types. The proposed method is based on the methodology that bandwidth consumption can be negotiated among users. It means that the proposed method tries to keep a similar level of users' satisfaction under the bandwidth limitation. The aim of this method is to find a trade-off solution for the bandwidth allocation issues. The numerical results show that the proposed bandwidth allocation method can improve the QoE for some user groups and remain a suitable average QoE for all users. In addition, the method also proposes a bandwidth threshold for users. By using the bandwidth threshold, it enables to realize the proposed method in real system.

Finally, I proposed a theory of the participatory service that is a solution to realize the proposed bandwidth allocation schemes. Since user classification seems to be the most difficult to realize for the proposal, i.e., how to determine or classify users' behavior and characteristics. To treat this issue, I consider a participatory service in bandwidth allocation. The participatory service is used to connect users' requirements with the allocation policy. The methodology of the participatory service is that bandwidth usage or consumption is negotiable between network providers and users. Some users can share or give their bandwidth resources to others at this time, and next time, when they want to use more bandwidth resources, they can ask to receive bandwidth from others. It is expected that this service will bring the benefit for both network providers and users.

Contents

List of Abbreviations

HTTP	The Hypertext Transfer Protocol
ISP	Internet Service Provider
ITU	International Telecommunication Union
LTE	Long Term Evolution
MOS	Mean Opinion Score
MMF	Max-Min Fairness
OFDMA	Orthogonal Frequency-Division Multiple Access
PDA	Personal Digital Assistant
PF	Proportional Fairness
QoE	Quality of Experience
QoS	Quality of Service
UCD	User-Centered Design
3G	Third Generation
4G	Fourth Generation

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Chapter 1

Introduction

This chapter introduces an overview about bandwidth resource allocation. I discuss the typical challenges in network resource distribution problems and the objectives of allocation schemes. This chapter also points out why the previous approaches are not enough to tackle these challenges. Finally, this chapter presents the contributions and structure of the dissertation.

1.1 Bandwidth Resource Allocation Problem

Currently, the Internet and its services play an important role in our daily life. The wide development of networks allows flexibility in accessing Internet services at almost any place. In addition, with the growing up of the mobile devices such as personal digital assistant (PDA), smart phone, and tablet computer (tablet PC), people can easily enjoy multimedia applications for entertainment with audio and video as well as use the devices in their business anytime. The spread of the Internet can be easily observed from the increasing number of Internet users. According to the statistics from the International Telecommunication Union (ITU), it is estimated that the number of Internet users was 3.2 billion in 2015 [1], up from 400 million in 2000, and is currently still increasing. There will be nearly 3.9 billion global users by 2019, as shown in the visual networking index forecasted by Cisco [2]. Undoubtedly, networks have become an essential part of people's lives. However, there are many challenges for Internet service providers (ISPs) and network planning and design because of the popularity of the Internet and its services as well as the rapid growth of Internet traffic. The demand of users is continuously increasing, while network resources are limited. As a result, distributing limited network resources to meet users' requirements and retaining reasonable network performance are mandatory. To address this issue, this study focuses on the bandwidth resource allocation.

For the above reason, distributing the limited network resource to meet users' requirements and retaining reasonable network performance have attracted much attention from research community. Many approaches are introduced based on the various viewpoints to solve the bandwidth allocation issue: how to allocate the limited network resource to users.

Network resource allocation is interested in many previous studies. The typical factors considered in allocation schemes are fairness and how to achieve the fairness. There are several definitions for fairness from many viewpoints, but they are generally categorized to two main viewpoints: objective and subjective.

From objective viewpoint, there are some typical approaches including max-min fairness, rate-proportional fairness. In these approaches, the fairness is considered based on equal rate, equal throughput or equal network resource. This type of fairness is called quality of service (QoS) [3]. The QoS schemes can be easily applied into real systems because the objective factors are feasible to measure and control. However, users can experience different satisfaction level even in the same network conditions. It is because the levels of users' satisfaction are different depending on various subjective factors such as users' situations, individual characteristics, and other psychological factors. Therefore, the objective metrics are difficult to guarantee the perceived quality of users.

To overcome the limitation of objective viewpoint, allocation methods based on the viewpoint of the quality of experience (QoE) are introduced. According to ITU, the quality of experience or user satisfaction is defined as the overall acceptability for applications or services and affected by all end-to-end factors [4]. Following this definition, QoE consists of both subjective and objective factors. In addition, ITU-T G.1031 defines that there are three main factors influencing the web-QoE: user, context, and system influence factors [5]. Therefore, considering the users satisfaction based on only objective metrics as previous studies has a challenge: users can experience different level of satisfaction even in the same network resource metrics, and it is expected that considering the fairness from QoE viewpoint can find the solution.

QoE becomes an important topic in many field of science community, and network resource allocation has also attracted attention in many literature with a long history [34, 48, 49, 53]. With the explosion of the Internet and its services, the challenge for resource allocation policies are raising quickly. For this reason, the dissertation focuses on the bandwidth resource allocation based on QoE. All experiments in the dissertation are applied for a web-based service, which is one of the typical Internet services widely used by Internet users [57].

1.2 Challenges

As mentioned above, network providers are nowadays facing a problem in allocating network resources due to the constant increase of Internet services. While the network resource is limited, users always desire the best quality of experience (QoE) with the huge information exchange [37, 41]. 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 consumption is different among individual users and directly depends on users' behavior. For instance, the demands for bandwidth from relax users are usually lower than those from busy users. Thus, allocating the same amount of resources to all users might not meet their expectations.

Considering the network resource allocation schemes from users' viewpoint is vital to guarantee a real fair allocation among users. However, there are some challenges for user-based allocation approaches. Therefore, the fairness of allocation schemes and users' satisfaction or expectation are the most challenge for network resource allocation policies nowadays.

For the fairness problem, in general, there are two main challenges for bandwidth resource allocation: How to define fairness and how to achieve fairness. For users' satisfaction, the challenge comes for the evaluation of users' satisfaction level.

First, I consider the fairness problem. For the computer networks, fairness is an important criterion. Although there are many factors which affect the performance, fairness can be considered regarding several statements such as fairness based on response time, fairness based on throughput, fairness based on power, and fairness of variable window flow control [30].

In [25], the authors present a tutorial for rate adaption, congestion control and fairness. Some typical fairness approaches were mentioned in this study such as max-min fairness, proportional fairness, and utility fairness [23, 25, 29, 32, 35]. These approaches are based on the rate to obtain a fair allocation. The methodology of the max-min fairness is as follows. First, the method tries to grow up all rates together from the equal rate until one or some link capacity limits are hit. Then the rates for the sources that use these links are not increased, and the rates are only increased for other sources. Increasing the rate continues until the end of network resource. The method tries to put emphasis on the smallest rates. For the proportional fairness, the methodology is as follows: "Any change in the allocation must have a negative average change." [25]. The study also introduces the concept of rate proportional fairness as an extended version of the proportional fairness when the allocation policy maximizes a weighted sum of logarithms. In addition, the proportional fairness is considered as an example of the utility approach, and the max-min fairness is as a limited case of a utility fairness.

Depending on situation, the different allocation scheme is applied to optimize the performance. However, these objective allocation methods, which are only based on the objective metrics and should be the equal in bandwidth amount or the same other network resources indexes, are difficult to achieve a satisfactory compromise for end users. When QoE becomes an important index for the success of services, the real perceived quality of users becomes more important than all of other network parameters such as data rate, video rate, delay, and throughput [24, 51]. Therefore, it is necessary to consider both the fairness in real perceived quality of users as well as the fairness of network resources such as bandwidth in traditional approaches. As a result, not only the fairness of network resources but also the fairness of user satisfaction should be considered and studied. In other words, considering of the fairness problem tends to be the fairness of users' satisfaction or QoE level among users.

In [50], the authors proposed two allocation algorithms for OFDMA systems. The first approach is based on the methodology of the max-min method to maximize the minimum MOS. The second approach introduces a trade-off between the spectral efficiency and the appropriate level of user satisfaction. The proposed method got some achievements since it represented the real user perceived quality in term of MOS and achieved a fair distribution of capacity among users.

In recent studies, QoE fairness is mentioned to consider the end users' QoE [28, 54]. All of them try to apply different algorithms and technique to consider user perceived quality for HTTP streaming video services. In general, all of these studies try to keep balancing or improve the fairness among users. In addition, the fairness concept in these studies leads to the real user experience and satisfaction.

[60] is based on previous user history to allocate the resource. The authors try to make a different priority in allocation, and then they can save the resource for other users. Therefore, they can achieve the least difference in QoE among users and guarantee the QoE fairness.

For the users' satisfaction problem, there are some difficulties to realize and deploy a QoE-based approach in general and a QoE-based bandwidth allocation method in particular. As mentioned above, the QoE is subjective and depends on each individual end user as well as the specific application or service [4]. Therefore, a difficulty of QoE implementation is on the users' satisfaction measurement. A question is how to evaluate users' satisfaction level. It requires information about all users. Some objective and subjective approaches were studied, but a common solution or standardization is still expected [6, 22, 33, 39, 44, 55].

1.3 Objectives

Motivated by the above problems, the main goal of the dissertation is to find the answer for a fair allocation. From my viewpoint, network resource allocation schemes should be considered from users' viewpoint because it can reflect real users' consumption and guarantee a real fair in perceived quality of users. Although users' QoE is subjective, it is possible to evaluate by using the subjective method as the mean opinion score method (MOS) [7, 8, 9, 10]. In the dissertation, user satisfaction is evaluated by using utility values referring to previous studies [45, 46, 59]. In this study, QoE fairness is defined as the similar in satisfaction level of end users regarding the perceived quality for an application or service. By this meaning, when QoE is measured by MOS or utility functions, the QoE fairness can know as: provide a service quality to guarantee the same MOS or utility values for users.

In general, the objectives of the dissertation are as follows:

- Network resource allocation schemes should be based on users' viewpoint: users are centric in the new network design. I believe that resource allocation schemes should be user-centric and considered from the subjective viewpoint. This idea was originally based on the effect of psychological factors, such as users' characteristics, situations, behavior and degree of relaxation, on users' waiting time tolerance [26, 27, 41, 42, 43]. In these studies, the obtained results showed the significant effects of subjective factors on users' level of tolerance and satisfaction. Therefore, the methodology of the user-centric bandwidth allocation method should consider the effect of psychological factors and other subjective factors of users on QoE. The allocation method from this viewpoint can overcome the challenge of the fair QoS method: QoE may be different even under the same network resource conditions.

- The consideration of fair allocation should focus on the fair QoE among users and the average QoE of all users in the network system. To overcome the challenge of the objective viewpoint, an allocation based on the fair

QoE is introduced. However, some users may lose much more bandwidth resources to share with others in this method. This problem leads to the decreases in average QoE of all users, and it does not seem really fair for users. Therefore, another approach to consider the fairness in a trade-off solution to balance the QoE of each users and the average QoE of users is required.

- The relationship between users' satisfaction or QoE and the allocated bandwidth of users is described by using the utility functions. Currently, the QoE from the users' perspective can be evaluated by using the mean opinion score (MOS) method [7, 8, 9, 10, 11]. MOS is a typical subjective measurement indication, which is used to obtain the users' view of service quality. Then, a utility function could be used to represent or map the relationship between the objective QoS metrics and the users' QoE [31, 52]. In the concept of utility, user satisfaction could be controlled under the system conditions and users' requirements. For this reason, user satisfaction is presented by using utility values in my proposed allocation methods. Although it is also based on the same consideration of the utility function as that of previous studies, my proposal is significantly different from previous works. My proposed methods provide a novel bandwidth allocation that considers users' situations to allocate suitable bandwidth based on the real resource consumption of users.

1.4 Contributions of the Dissertation

As mentioned above, the objectives of the proposed methods in the dissertation are to find a fair allocation method as well as the ways to balance the fairness in allocation among users while keeping a reasonable network performance. Therefore, the allocation methods should exactly reflect users' feeling, users' satisfaction level, and the fairness considered from the viewpoint of real perceived quality of users. In the study, I propose two bandwidth allocation methods by classifying users into different groups based on their psychological factors. 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 amount of 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, my proposal tends toward a fair allocation as well as an efficient management of the network resources.

Consequently, the contributions of the dissertation are as follows:

First, I propose a bandwidth resource allocation scheme that is based on the fair QoE viewpoint to allocate the bandwidth to users. In this scheme, all users can experience the same satisfaction level or QoE level even in the different network resource environment. It is caused by the effect of psychological factors such as users' situation, demands, or degree of relaxation. The main point of the proposed scheme is to be applied to multi-user types in real systems. To illustrate this point of the proposal in the dissertation, I analyze the proposed method in various contexts of two, three, four, and general user situations. The numerical results show that the proposed method successfully provides a fair QoE allocation to users and improves the QoE for dissatisfied users.

Secondly, I propose a hybrid allocation method for three user types. Currently, the allocation methods based on the viewpoint of QoS and QoE have their limitations. However, considering the QoE in the network resource control schemes is mandatory to guarantee a real perceived experience of users. For this reason, I propose a new bandwidth resource allocation method based on the satisfaction level of users. The proposed method is based on the methodology in which bandwidth consumption can be negotiated among users. It means that the proposed method tries to keep a similar level of users' satisfaction under the bandwidth limitation. Since a win-no lose approach is difficult to achieve, the aim of this proposal is to find a trade-off solution between the QoE level of each user group and the average QoE of all users. The numerical results show that the proposed bandwidth allocation method can provide an adaptable bandwidth allocation and a proper QoE level for users.

Finally, I propose a theory of a participatory service. Considering the participatory service in bandwidth allocation is necessary to realize my proposed bandwidth allocation schemes. User classification, i.e., how to determine and classify users' situations as relaxed, normal, and pressured, seems to be the most difficult to realize the proposal. To treat this issue, the participatory service is used to connect users' requirements with the allocation policy. In the participatory service, bandwidth usage or consumption should be negotiable between network providers and users. Some users can share or give their bandwidth resources to others at this time, and next time, when they want to use more bandwidth resources, they can ask to receive bandwidth from others. It is expected that this service will bring the benefit for both network providers and users. For convenience, the participatory service will be optional for users.

1.5 Structure of the Dissertation

The dissertation includes six main parts divided into six chapters. It starts out with the introduction on the bandwidth allocation method and the quality of experience. Then, the specific challenges for distributing network resource in web-based services are discussed. I also consider the typical problem in previous solutions that motivate the proposed methods in the dissertation.

Chapter 2 Bandwidth Allocation Based on QoE Viewpoint. This chapter describes the original theory, the relevant model to specify and analyze the proposals in the dissertation. All proposed methods in this study are based on the viewpoint of users to allocate the bandwidth. Therefore, this chapter focuses on describing in detail the related works such as user classification and utility functions as well as how to implement an allocation method based on the QoE viewpoint. A specific experimental model to find the utility functions on mobile devices is also introduced.

Chapter 3 Fair QoE Bandwidth Allocation Method. In this chapter, I focus on the fairness problem in bandwidth resource allocation. Fairness from the QoS viewpoint does not completely solve the problem in previous studies because of psychological effects. Considering fairness from QoE viewpoint is mandatory because it can exactly reflect the perceived quality of users. Therefore, this chapter presents a bandwidth allocation method based on the fair QoE. The method guarantees that all users experience the same perceived QoE level. The numerical results are obtained from various case studies with different user classifications. For each specific situation, I introduce a simple computing solution. In particular, I introduce a general solution to apply the proposed method in the general situation.

Chapter 4 Hybrid Bandwidth Allocation Method. This chapter focuses on the bandwidth allocation method for three user types. Therefore, the proposed method classifies users as relaxed, normal, and pressured users. Users in the normal situation are considered as the threshold for the others. It means that the normal users keep their bandwidth and QoE level, and the bandwidth exchange is realized only between relaxed and pressured users. The bandwidth negotiation rules are as follows: The pressured users can improve their QoE, but their QoE should not become higher than the normal users' QoE. On the other hand, the relaxed users experience a lower level of QoE to share their resource with others, but their QoE should be always better than the QoE of normal users. Since a win-no lose approach is difficult to achieve, the goal of this proposal is to find a trade-off solution for bandwidth resource allocation problems.

Chapter 5 Theory of Participatory Service in Bandwidth Allocation. In this chapter, I focus on an implementation of my proposed bandwidth allocation methods: How to apply these methods in real system effectively. I propose a theory of a participatory service that allows network providers to collect information from users about their real bandwidth consumption or demands. By sharing or contributing their bandwidth resources to others, users can receive some benefit next time. For convenience and easy understanding, a unit point system is introduced to exchange between users and bandwidth policy. Depending on the network condition, the allocation policy will decide the equivalence rate between a point and the bandwidth amount.

Chapter 6 Conclusion and Future Work. This chapter summaries all works in the dissertation. The contributions of the study are also discussed.

Finally, the dissertation ends with future work in this chapter.

Chapter 2

Bandwidth Allocation Based on QoE Viewpoint

This chapter introduces in detail the bandwidth allocation schemes based on QoE viewpoint. 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 consumption is different among individual users and directly depends on users' behavior. For instance, the network resource demands of busy users are usually higher than those of relaxed users. Thus, allocating the same amount of resources to all users might not meet their expectations. To overcome the challenge, finding a justice of network resource allocation based on the user experience is mandatory. This means that future bandwidth allocation methods should refocus their targets from the objective network perspective to the users' perspective. To achieve this, some information about the user classification and the relationship between the allocated bandwidth and QoE for each user group is required. Therefore, I explain some typical user classifications based on users' characteristics and the in corresponding utility functions. The classification and utility functions will be used in the next part of my dissertation.

2.1 Methodological Assumptions

The section introduces some basis definition and assumptions regarding the proposed methods in the dissertation. First, the dissertation classifies the allocation methods based on the objective and subjective point of view. In the dissertation, the objective viewpoint or the perspective of engineering is called as the QoS viewpoint while the subjective viewpoint or the perspective of users is known as the QoE viewpoint. The allocation method based on the fair QoS viewpoint will distribute the same bandwidth to users. On the other hand, the allocation method which allocates the bandwidth based on the satisfaction of users, is based on the QoE viewpoint.

In addition, the experimental results are obtained in the study by using mobile devices. As a result, the study is able to apply for mobile systems with users using the data networks such as 3G, 4G, and LTE. In the systems, the network can be over load when many users access in the same time because of the limited capacity. In this situation, it is mandatory to apply the allocation policy. Based on the perspective, the proposal in the dissertation is studied for mobile systems.

Finally, there are many factors affecting QoE of users such as users' characteristics, application, context, and system [4, 5]. Users' characteristics or psychological factors show a significant effect on the satisfaction of users. Therefore, the dissertation focuses on the effect of users' factors such as users' behavior, users' situation and demands on QoE.

The next section will describe in detail the methodology for the proposed bandwidth allocation methods in the dissertation.

2.2 User Classification

The methodology to consider the network resource allocation schemes from subjective viewpoint was originally based on the effect of psychological factors, such as users' behavior, degree of relaxation, and situations on users' waiting time tolerance [21, 26, 41, 43].

Nah in [41] states that waiting time is the most important factor on the decision of web users. The study suggests that the tolerable waiting time for users is two seconds. However, there are many factors affecting on users' level of tolerance. Therefore, it is important to understand users' waiting behavior in accessing the web because the perceived waiting time of users is more important than the true waiting time. This problem is introduced in [21] and an in-depth understanding of the problem is studied in [26]. It is clearly shown that the perceived waiting time directly affects users' decision and can be different from the true waiting time because of the impact from psychology on human time perception. [43] introduces in detail the effect of waiting time on users' QoE in terms of MOS under different psychological conditions.

The first step to allocate bandwidth based on QoE viewpoint is to understand users' behavior or psychological factors which influence users' decision. In other words, users should be classified into groups based on their characteristics. There are some typical classifications proposed in previous studies that present the finite set of user types.

Based on the users' viewpoint, Yamazaki and Miyoshi proposed a QoE-driven bandwidth allocation method for multiple user types [59]. In this study, two user types were analyzed: busy and relaxed. The amount of allocated bandwidth is calculated for users by using the quadratic equation. 31 respondents joined these experiments.

In [31], the authors consider three types of users as excellent, good, and fair. Excellent users expect the service quality more than the service cost. In contrast, fair users prefer the low-price service to the service quality. Finally, a good user keeps a balance between the service quality and price. The utility functions are decomposed in the study into four components for both technical and non-technical attributes of real time and non-real time applications. The experimental results are obtained by simulations.

In [58], the authors propose to classify users based on their psychological situations as pressured, relaxed, and normal situations. These experiments were implemented for Web service. 48 respondents answered their QoE about the network delay inserted randomly between two questions. In the pressured situation, examiners were asked to answer the questions quickly and remaining time was shown on experience. In contrast, users in the relaxed situation answered the questions while enjoying other services. For the normal situation, examiners answered the questions naturally without any special instructions. The results in the study are also used to illustrate my proposed methods in next chapter.

In [43], the authors focus on the user tolerance problem for waiting time in various case studies. The state of mind or degree of relaxation is considered as a factor influencing the subjective evaluation results in the experiments. The results were categorized into four classes based on users' replies as very relaxed, relaxed, neutral, and not relaxed. The numbers of participants in four classes were 94, 197, 71, and 38, respectively. Even though the results in the experiment were obtained with the plain-text e-mail service, it is possible to use for other web access services because the effect of waiting time to QoE in these applications is very similar [43]. Therefore, I will use the same settings as the study, i.e., four user types for the next part of the dissertation.

From the same viewpoint with previous studies, I propose to classify users according to their demands into best-effort, normal, and high speed. In real systems, users may get confused to decide their situations and tend to demand about the downloading speed because downloading speed will directly affect to users' waiting time. The waiting time is thus one of the main factors affecting the users' satisfaction level in web-based services. In previous studies, the network resource allocation depends on the degree of users' relaxation (user characteristics). However, users may have no time to answer about their degree of relaxation when they are busy. In other words, users may be confused about their state. In addition, although users are relaxed, they still want to experience high speed. Therefore, the classification based on users' requirements about their speed demand is suitable and reasonable.

In my approach, users are classified into best-effort if they can accept the downloading speed according to the network condition and network providers' policy. They are almost free at that moment and they can spend more time to use services. On the contrary, a high speed user expects as short waiting time as possible. They want to obtain the results quickly. And normal users do not accept to wait for long time but do not require a high speed. These users do not have any specific requirements for the down loading time.

2.3 Utility Function

The second step is to find the relationship between allocated bandwidth and the QoE of users. To evaluate users' satisfaction, subjective methods are the best solution although this method requires users' interaction with annoying users and with some delay. The mean opinion score (MOS) method is widely used as a subjective measurement [7, 8, 9, 10]. A five-grade MOS scale is used to show the quality from 1 (bad) to 5 (excellent). From the same methodology as the MOS method, utility functions are used to show the QoE level of users. In the concept of utility, user satisfaction could be controlled under the system conditions and users' requirements. For this reason, user satisfaction is presented using utility values in my proposed allocation methods. In the study, the utility value is used with the corresponding MOS value. When the utility value is 60, users can accept the service quality. In this case, it means that the waiting time for web site loading is under users' tolerance.

In previous studies, there are many approaches of a resource allocation method based on utility functions [56, 58, 59]. Authors in [59] introduce the utility functions for relaxed (R) and busy (B) users as follows:

$$U_t = C_t e^{\frac{-Q_t S}{B_t}}, \tag{2.1}$$

where $C_R = 81.045$, $Q_R = 0.076$, $C_B = 74.218$, and $Q_B = 0.174$, S is data size [Mbits], and B_t and U_t are allocated bandwidth and utility values for users. The authors assumed that the allocated bandwidth for users is a simple linear function of the waiting time.

In [58], based on the measurement results of QoS and QoE in three situations obtained from the experiments, I confirmed that the same utility functions as in Eq. (2.1) can be used to show the relationship between QoE and the allocated bandwidth for relaxed (R), normal (N), and pressured (P). In this situation, C_R = 75.62, Q_R = 0.07, C_N = 77.29, Q_N = 0.14, C_P = 71.86, and Q_P = 0.16.

Based on the experimental results in [43], the utility functions for very relaxed (VR), relaxed (R), neutral (N), and not-relaxed (NR) are as follows:

$$U_t = C_t ln \frac{S}{B_t} + Q_t, \tag{2.2}$$

where C_{VR} = -1.48, Q_{VR} = 5.88, C_R = -1.45, Q_R = 5.73, C_N = -1.31, Q_N = 5.32, C_{NR} = -1.29, and Q_{NR} = 5.12.

In the next chapter, I also use this kind of utility function to apply the proposed methods.

2.4 An Example of Implementing QoE Experiments

In the study, I set up an experiment for mobile users in an android mobile device. The purpose of this kind of experiment is to find out the relationship between users' behaviors and their satisfaction level. The experiment allows users to experience a various kind of web-based services in real system and sends their feedback to the server. From users' information and network conditions, the relationship between the users' satisfaction level and the bandwidth is obtained.

Figure 2.1 shows the process of the QoE assessment program. The detail of experiment is as follows:
Step 1: At the first time, users will register their information.
Step 2: Users can access the application.

- Users can choose to access some web-based services such as google, yahoo, gigazine, and train scheduler [12, 13, 14, 15, 16].
- When users open web pages, they need to wait for loading the contents.

Step 3: Users interact with services.

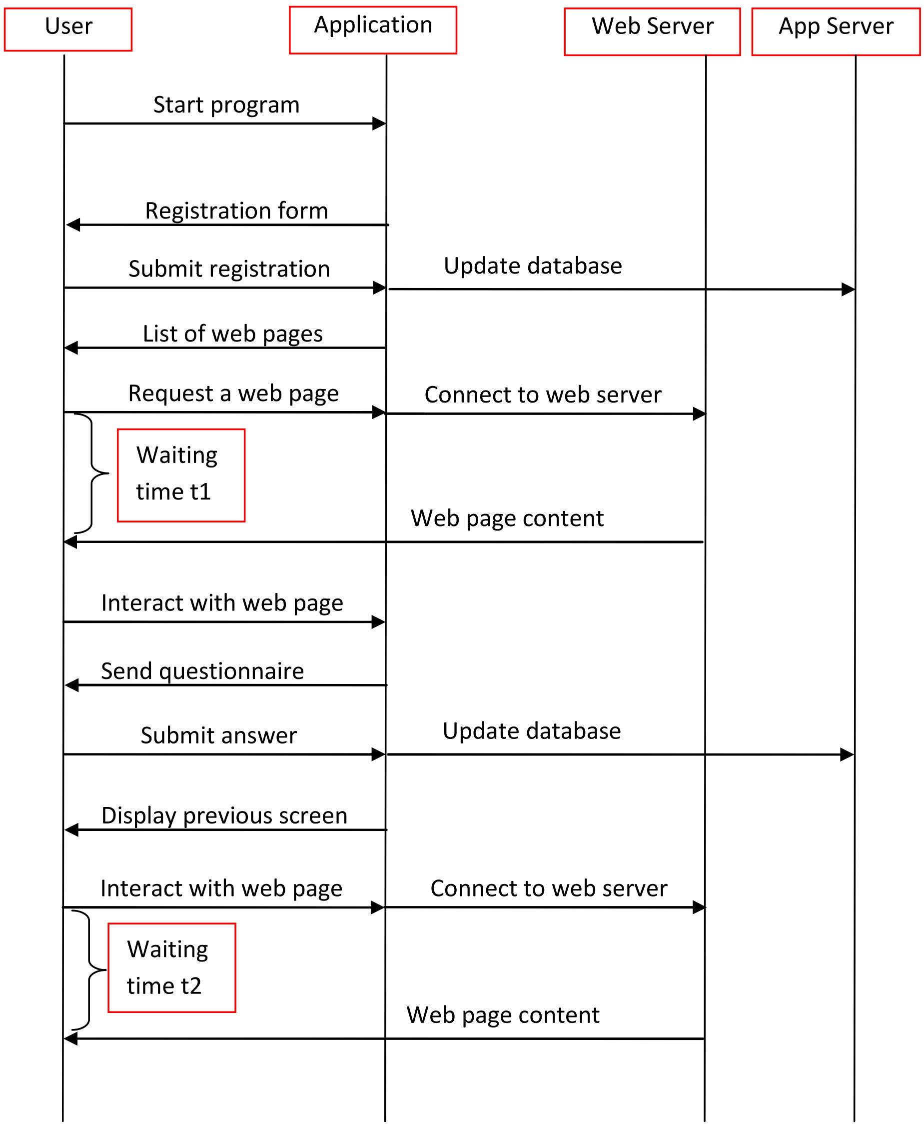


Figure 2.1: The diagram of the QoE assessment program.

- When users click to access to another content, a questionnaire will be sent to users. The questionnaire asks users some information about their locations, their demand, and their satisfaction corresponding to the waiting time.
- Users answer the questionnaire. The result will be sent to the server and they can click again to display the contents.

Step 4: Users continue to use services.

- Step 2 and step 3 will be repeated.

A question is asked to users whether they want to continue or not after several questionnaires. The experiment will continue until users want to stop experiments by clicking the exit button.

A registration form is used in the experiments including some main information as follows:

- User ID: this is automatically distributed when users install the software.
- User's age
- User's gender
- User's history

The detail of the questionnaire form used in the experiments is as follows:
Question 1: What is your current situation for communication speed?

- High speed is desirable
- Usual speed is OK
- Best effort is acceptable

Question 2: Place of use

- Home

- School
- Station
- Car or train
- Others

Question 3: Compared with the usual, how do you feel about the waiting time until the web-page is displayed on the screen after pressing the link?

- Shorter
- Slightly shorter
- Same as usual
- A little longer
- Longer

Question 4: User satisfaction

In question 2, if users choose the place of use as others, they can fill out their specific place such as shopping and walking. In question 4, a seek bar is displayed for users. They can touch on the seek bar to show their level of satisfaction from 0 to 100 corresponding with dissatisfied at all, dissatisfied, acceptable, satisfied, and very satisfied levels.

2.5 Conclusion

In this chapter, I explained the methodology of a bandwidth allocation method based on the viewpoint of users. Since the real perceived quality and users' satisfaction play important roles in the success of deploying services, it is mandatory to consider the QoE of users in network resource allocation policies. Therefore, I focus on the real fairness in allocation among users based on their QoE. To achieve this, some statistical information about users' behavior and the relationship between their QoE and the allocated bandwidth are required. These theories and description will become the background and basic parameters of my research that will be described in detail in the remaining part of the dissertation.

Chapter 3

Fair QoE Bandwidth Allocation Method

As described above, the allocation methods based on the QoS viewpoint are difficult to solve the fairness problem completely. In addition, the realization of a user-centric view will play an important role in future networks. For this motivation, this chapter focuses on the first solution to achieve the allocation fairness from user-centric view. In this chapter, I propose to allocate the feasible bandwidth resource to guarantee that all users can experience the same perceived QoE. For each type of user classification, the mathematical solutions are different. To demonstrate each solution, various kinds of examples are introduced in the chapter. Then, a general solution is proposed to solve the problem in a general case study in which there is no specific number of users' groups. It means that the solution is applicable independent of the number of users' groups.

3.1 Introduction

In user-centric view or paradigm, the fairness problem in resource allocation should be seen from the viewpoint of users. The first solution can be seen as the same QoE of users or a fair QoE bandwidth allocation method. Because the fair QoE allocation method is one kind of bandwidth allocation based on QoE viewpoint, it should follow the basic steps as shown in previous chapter.

The first step in the method, it requires the statistical information about users' characteristics. Depending on specific applications and services as well as the requirement of users, the users can be classified into groups. After that, the utility functions that express the relationship between the users' satisfaction and allocated bandwidth, are obtained by experiments. In the method, I control the relationship between utility values of users and the corresponding allocated bandwidth is calculated by using the relationship. As mentioned in the previous chapter, the utility values can be used to express the QoE or satisfaction level of users. It means that when all users receive the same utility values, they experience the same perceived quality or the same satisfaction level.

In this method, the fairness problem in network resource distribution is considered as the fair QoE bandwidth allocation. To verify the proposed allocation method, I apply some case studies where the users are categorized as two, three, four types, and a general situation. The obtained results show that the proposed method successfully allocates the fair QoE for users. A simple allocation method that allocates the same bandwidth to users, is commonly known as the fair QoS method, which is also mentioned in the chapter. The fair QoS method is seen as a conventional and basic allocation scheme for comparison with my proposal from two viewpoints: the perceived QoE of each user and the average QoE of all users. For the traditional method in evaluation of QoE, MOS is popular used as an ordinal scale from 1 to 5 score. The MOS scale, which is discrete, is very difficult to explain QoE in average meaning. The utility value, however, is a continuous range from 0 to 100. The average QoE expresses the average satisfaction level for all users in the system. Therefore, the average QoE is mentioned in the study.

The remainder of this chapter is organized as follows. The next section discusses the related work. Then Section 3.3 introduces the proposed method in detail for various case studies. In Section 3.4, I evaluate the proposed method and analyze the obtained results in detail. The last section is the conclusion and direction for the further work.

3.2 Related Work

Currently, the QoE from the users' perspective can be evaluated by using the mean opinion score (MOS) method [7]. MOS is a typical subjective measurement indication, which is used to obtain the users' view of service quality. Then, a utility function could be used to represent or map the relationship between the objective QoS metrics and the users' QoE [31, 52]. In the concept of utility, user satisfaction could be controlled under the system conditions and users' requirements. For this reason, user satisfaction is presented using utility values in my proposed allocation methods. Although it is also based on the same consideration of the utility function as that of previous studies, the proposal is significantly different from previous works. My proposed methods provide a novel bandwidth allocation that considers users' situations to allocate suitable bandwidth based on the real resource consumption of users.

First, the chapter reviews a simple bandwidth allocation method, which is based on the fair QoS viewpoint to allocate the bandwidth. The same bandwidth is allocated to all users based on the total bandwidth divided by the total number of users. From the QoS viewpoint, all users will obtain the same quality with the same bandwidth. The method adopts the same policy as the Max-Min fairness (MMF) and Proportional Fairness (PF) to allocation schemes [23, 29, 32, 35]. In these studies, fair allocation is considered based on technical parameters such as data rate, delay, and throughput. All users are supposed to receive the same satisfaction level when they have the same technical metric values. However, users satisfaction or QoE is the overall acceptability for applications or services and is affected by all end-to-end factors [4]. Only technical metrics are not enough to guarantee the perceived quality of users. As a result, these schemes are facing the problem since user's satisfaction is different depending on various subjective and objective factors.

To address the problem of the fair QoS method, it is required to consider both objective and subjective factors of users in the network resource allocation. An approach, which is discussed in many studies, is based on the QoE viewpoint to allocate the network resource to users [45, 47, 59]. Since users can experience the same satisfaction level even in the different network resource environment. It is caused by the effect of subjective factors such as users' situation, demands, or degree of relaxation [26, 41, 43, 58].

Based on the users' viewpoint, Yamazaki and Miyoshi proposed a QoE-driven bandwidth allocation method for multiple user types [59]. In this study, two user types were analyzed: busy and relaxed. The amount of allocated bandwidth is calculated for users by using the quadratic equation. From the same viewpoint, the previous studies proposed bandwidth allocation solutions for three user types [45, 46]. The controlling parameters are used to allocate bandwidth with different weight to users. This means that users can obtain different priorities in allocation to acquire higher levels of QoE than others. The allocated bandwidth for each user group was calculated by using the cubic equation and the Newton-Raphson method [17, 18]. For the Newton-Raphson method, it is possible to apply for multiple user types within the convergent conditions of the method. In the dissertation, the results are expanded from the previous studies. Therefore, a general solution is proposed to apply for the system when the number of users' groups is not specific and it is independent on the type of utility functions (linear, logarithmic, or step function).

3.3 Proposed Method

3.3.1 Theory

- The total number of users: N_{ALL}.
- The total bandwidth: B_{ALL}.
- The number of user groups: n.
- The number of users in a group i: N_i.
- Each user in the same group i is allocated the same bandwidth B_i and experiences the same level of QoE U_i.

The total number of users N_{ALL} and the total bandwidth B_{ALL} are given by the equation:

$$N_{ALL} = N_1 + N_2 + ... + N_n, \tag{3.1}$$
$$B_{ALL} = N_1B_1 + N_2B_2 + ... + N_nB_n. \tag{3.2}$$

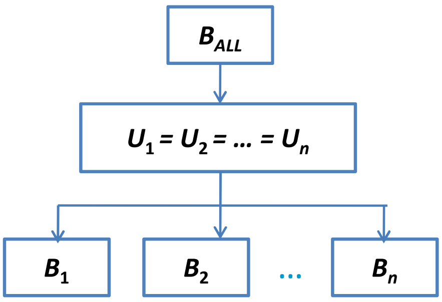


Figure 3.1: Fair QoE bandwidth allocation method.

The utility functions express the relationship between QoE and allocated bandwidth for each user group as follows:

$$U_1 = f_1(B_1), \tag{3.3}$$
$$U_2 = f_2(B_2), \tag{3.4}$$
$$\vdots$$
$$U_n = f_n(B_n). \tag{3.5}$$

In general, the utility function for users in group i can be expressed as follows:

$$U_i = f_i(B_i), \tag{3.6}$$

where $i = [1, n]$.

As shown in Fig. 3.1, the fair QoE allocation method distributes bandwidth based on the QoE relationship among user groups. The general relationship is presented as follows:

$$k_1U_1 = k_2U_2 = k_3U_3 = ... = k_nU_n, \tag{3.7}$$

where k_1, k_2, k_3, ..., k_n are the controlling parameters. Depending on the management policy, the proposed method can provide different QoE levels or give the priorities in allocation to certain users by changing the values of k_1, k_2, k_3, ..., k_n. When $k_1 = k_2 = k_3 = ... = k_n$, all of the users experience the same satisfaction levels.

From Eqs. (3.6) and (3.7), the following is conducted:

$$k_1 f_1(B_1) = k_2 f_2(B_2) = k_3 f_3(B_3) = ... = k_n f_n(B_n). \tag{3.8}$$

First, I present the relationship between users in group 1 and others. From Eq. (3.8), the following is obtained:

$$\begin{aligned} k_1 f_1(B_1) &= k_2 f_2(B_2), && (3.9) \\ k_1 f_1(B_1) &= k_3 f_3(B_3), && (3.10) \\ &\vdots \\ k_1 f_1(B_1) &= k_n f_n(B_n). && (3.11) \end{aligned}$$

The utility functions of users in group 2, 3, .., n are expressed as functions of users in group 1 as follows:

$$\begin{aligned} f_2(B_2) &= \frac{k_1}{k_2} f_1(B_1), && (3.12) \\ f_3(B_3) &= \frac{k_1}{k_3} f_1(B_1), && (3.13) \\ &\vdots \\ f_n(B_n) &= \frac{k_1}{k_n} f_1(B_1). && (3.14) \end{aligned}$$

Then the allocated bandwidth for users in group 2, 3, ..., n can be expressed as follows:

$$\begin{aligned} B_2 &= f_2^{-1}\Big(\frac{k_1}{k_2} f_1(B_1)\Big), && (3.15) \\ B_3 &= f_3^{-1}\Big(\frac{k_1}{k_3} f_1(B_1)\Big), && (3.16) \\ &\vdots \\ B_n &= f_n^{-1}\Big(\frac{k_1}{k_n} f_1(B_1)\Big), && (3.17) \end{aligned}$$

where f_2^{-1}, f_3^{-1}, ..., f_n^{-1} are inverse functions of f_2, f_3, ..., f_n, respectively. The right sides of Eqs. (3.15), (3.16), and (3.17) are equations of one variable B_1. Therefore, the following is obtained:

$$\begin{aligned} B_2 &= f_{12}(B_1), && (3.18) \\ B_3 &= f_{13}(B_1), && (3.19) \\ &\vdots \\ B_n &= f_{1n}(B_1), && (3.20) \end{aligned}$$

where

$$\begin{aligned} f_{12}(B_1) &= f_2^{-1}\Big(\frac{k_1}{k_2}f_1(B_1)\Big), && (3.21) \\ f_{13}(B_1) &= f_3^{-1}\Big(\frac{k_1}{k_3}f_1(B_1)\Big), && (3.22) \\ &\vdots \\ f_{1n}(B_1) &= f_n^{-1}\Big(\frac{k_1}{k_n}f_1(B_1)\Big). && (3.23) \end{aligned}$$

Based on Eqs. (3.18), (3.19), and (3.20), Eq. (3.2) is transformed as follows:

$$B_{ALL} = N_1 B_1 + N_2 f_{12}(B_1) + N_3 f_{13}(B_1) + \cdots + N_n f_{1n}(B_1). \tag{3.24}$$

Eq. (3.24) is an equation with one variable B_1. The solution of Eq. (3.24) can be lead by a using root-finding algorithm, which is known as the Newton-Raphson method. In some special situations, when the equations are in form of quadratic or cubic equations, the solution can be found by using quadratic formula or geometric interpretation formulae, respectively. However, in a general situation, the Newton-Raphson method is the best solution.

When repeating the process, the similar equations for allocated bandwidth of users in other groups are conducted.

In the method, there are some conditions to apply the Newton-Raphson method. First, it is possible to express an allocated bandwidth of any user as a function of another allocated bandwidth. Secondly, the relationship between

QoE and allocated bandwidth of users is a monotonic increasing function. The condition to guarantee the solution is possible to find the inverse functions in Eqs. (3.15), (3.16), and (3.17).

In the next section, I will introduce the Newton-Raphson method in detail.

3.3.2 Newton-Raphson Method

The Newton-Raphson method is popularly used to find the solution for complicated functions in mathematics [18]. The method uses an iterative process to estimate the root of a function.

It is assumed that there is a complicated function algebraically as follows:

$$f(x) = ax^{\alpha} + bx^{\beta} + cx^{\gamma} + d. \tag{3.25}$$

To find the solution for this kind of function, first it is assumed that the initial value x_0 is a good estimation of the real solution of Eq. (3.25). This value is randomly chosen according to conditions of a specific function. Then, the next estimation x_1 is given by

$$x_1 = x_0 - \frac{f(x_0)}{f'(x_0)}. \tag{3.26}$$

The next estimation x_2 is obtained in the same way,

$$x_2 = x_1 - \frac{f(x_1)}{f'(x_1)}. \tag{3.27}$$

The general form of the estimation x_{n+1} is given as follows:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}. \tag{3.28}$$

where x_n and x_{n+1} are current and next estimations of the root, respectively. By continuing the iteration, the obtained root of Eq. (3.25) is found r_0. Depending on the accuracy requirement, the error in computing of the method is applied. Therefore, the error in computing of Newton-Raphson method equals $f(r_0)$.

3.4 Experiments

In this chapter, I only mention the situation where $k_1 = k_2 = k_3 = ... = k_n$, all users experience the same satisfaction levels, but it can easily extend the idea to the general case of Eq. (3.7) by applying the above solution.

3.4.1 Two user types

(1) Experimental Scenario

In previous studies, authors introduce various utility functions based on their experiments. Authors in [59] introduce the utility functions for two user types as relaxed and busy users as follows:

$$U_R(B_R) = C_R e^{-Q_R \frac{S}{B_R}}, \quad (3.29)$$

$$U_B(B_B) = C_B e^{-Q_B \frac{S}{B_B}}, \quad (3.30)$$

where $C_R = 81.045$, $Q_R = 0.076$, $C_B = 74.218$, and $Q_B = 0.174$. The authors assumed that the allocated bandwidth for users is a simple linear function of the waiting time.

The total bandwidth is allocated to users as follows:

$$B_{ALL} = N_R B_R + N_B B_B, \quad (3.31)$$

where N_R and N_B are the number of users in relaxed and busy situations, respectively.

According to the rule of the fair QoE method, relaxed and busy users will experience the same QoE level, $U_R = U_B$. Based on this relationship and Eqs. (3.29) and (3.30), the following equation is derived:

$$\frac{Q_B}{B_B} - \frac{Q_R}{B_R} = \frac{1}{S} \ln(\frac{C_B}{C_R}). \quad (3.32)$$

The right side of Eq. (3.32) can be replaced as a constant value C_1,

$$C_1 = \frac{1}{S} \ln(k_1 \frac{C_B}{C_R}). \quad (3.33)$$

Then, based on Eqs. (3.31), (3.32), and (3.33), the formulae express the allocated bandwidth for relaxed and busy users as follows:

$$C_1 N_R B_R^2 + ((Q_R - Q_B)N_R + Q_B N_{ALL} - C_1 B_{ALL})B_R - Q_R B_{ALL} = 0, \tag{3.34}$$

$$C_1 N_B B_B^2 - ((Q_B - Q_R)N_B + Q_R N_{ALL} + C_1 B_{ALL})B_B + Q_B B_{ALL} = 0. \tag{3.35}$$

Equations shown in (3.34) and (3.35) have the form of quadratic equations. To solve this kind of function, it is possible to apply both the Newton-Raphson method or discriminant solution [19].

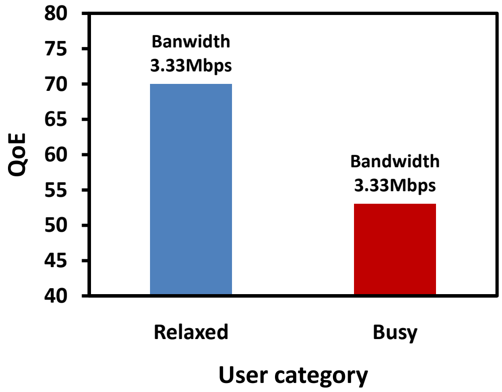
(2) Numerical Results

This section shows the numerical results obtained by the proposed method in case of two user types. It is assumed that users download the same content whose size is 6.44Mbits and share the total bandwidth 100Mbps.

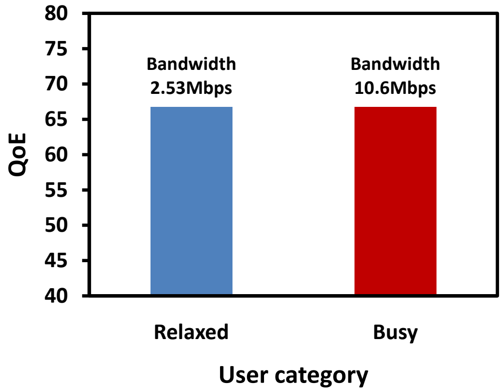
Table 3.1 shows the scenario in various case studies in the experiments.

Table 3.1: Experimental scenario for the fair QoE bandwidth allocation method in case of two user types.

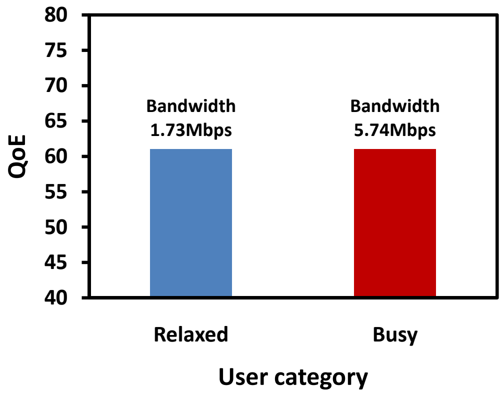
No.	B_{ALL} **[Mbps]**	S **[Mbits]**	N_{ALL}	N_R [%]	N_B [%]
1	100	6.44	30	90	10
2	100	6.44	30	60	40
3	100	6.44	20	[0,100]	[0,100]
4	100	6.44	30	[0,100]	[0,100]
5	100	6.44	40	[0,100]	[0,100]
6	100	6.44	50	[0,100]	[0,100]



(a) Fair QoS method.



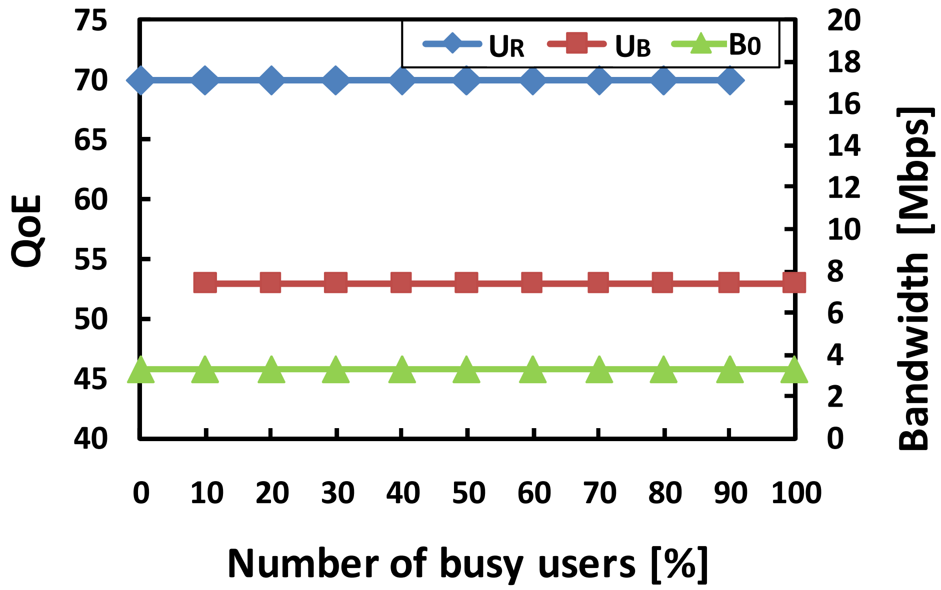
(b) Fair QoE method, 10% busy users.



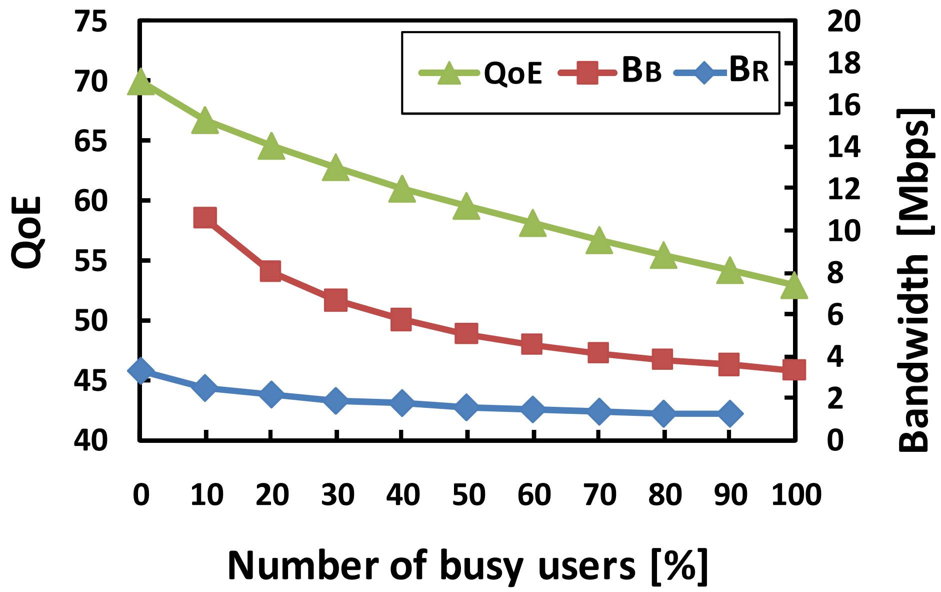
(c) Fair QoE method, 40% busy users.

Figure 3.2: Bandwidth allocation and users' QoE based on fair QoS and fair QoE methods in case of 30 users in total, and the number of users in busy situations is 10%, and 40%.

Figure 3.2 shows the bandwidth allocation and users' QoE based on the fair QoS and fair QoE methods. As shown in Fig. 3.2(a), although users are allocated the same bandwidth amount as the rule of fair QoS method, they experience the different satisfaction level. In this case, the busy users are not satisfied with the service quality. On the other hand, all users obtain the same satisfaction level as shown in Figs. 3.2(b) and (c).



(a) Fair QoS method.



(b) Fair QoE method.

Figure 3.3: Bandwidth allocation and users' QoE based on fair QoS and fair QoE methods in case of 30 users in total, and the number of users in relaxed and busy situations changes.

Figure 3.3 shows the bandwidth allocation and users' QoE based on both the fair QoS and fair QoE methods. In this case study, the number of users in relaxed and busy groups changes from 0 to 100%. As shown in Fig. 3.3(a), relaxed and busy users are allocated the same bandwidth $B_0 = B_{ALL} / N_{ALL}$, and the value does not vary as users' situations change. As a result, relaxed and busy users keep their QoE level when the number of busy users change in the fair QoS method. In Fig. 3.3(b), all users experience the same level of QoE. In this method, the allocated bandwidth and users' QoE of each user decrease when the number of busy users increases.

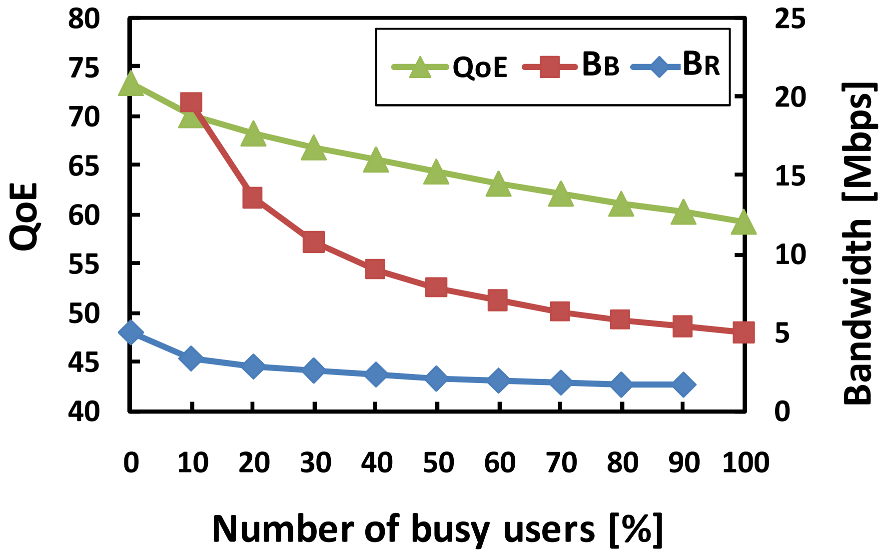


Figure 3.4: Bandwidth allocation and users' QoE based on fair QoE method in case of 20 users in total and the number of users in relaxed and busy situations changes.

Figures 3.4, 3.5, and 3.6 show the similar numerical results to Fig. 3.3(b) when the total numbers of users are 20, 40, and 50 respectively. In these Figs., when the number of users in busy situation is small, much bandwidth is allocated to users in this group. In contrast, the allocated bandwidth for busy users decreases rapidly when the number of busy users increases.

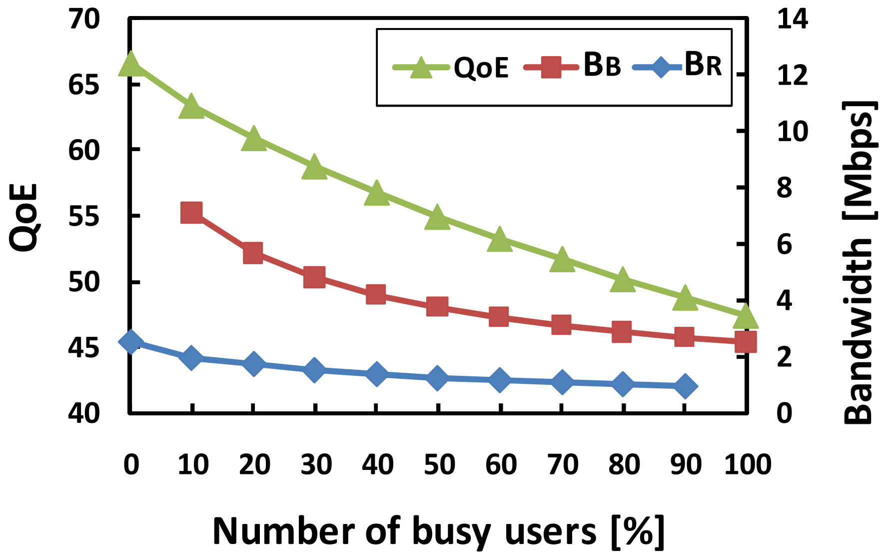


Figure 3.5: Bandwidth allocation and users' QoE based on fair QoE method in case of 40 users in total and the number of users in relaxed and busy situations changes.

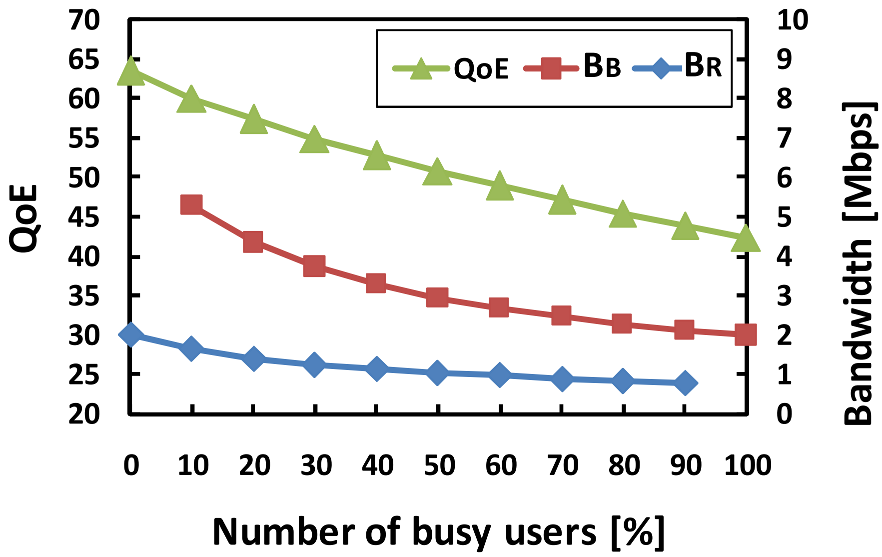


Figure 3.6: Bandwidth allocation and users' QoE based on fair QoE method in case of 50 users in total and the number of users in relaxed and busy situations changes.

3.4.2 Three user types

(1) Experimental Scenario

As mentioned above, the user classification and utility functions in this study are based on previous studies [58]. The utility functions show the relationship between the QoE and the allocated bandwidth of each user types as follows:

$$U_R(B_R) = C_R \mathrm{e}^{-Q_R \frac{S}{B_R}}, \tag{3.36}$$
$$U_N(B_N) = C_N \mathrm{e}^{-Q_N \frac{S}{B_N}}, \tag{3.37}$$
$$U_P(B_P) = C_P \mathrm{e}^{-Q_P \frac{S}{B_P}}, \tag{3.38}$$

where $C_R = 75.62$, $Q_R = 0.07$, $C_N = 77.29$, $Q_N = 0.14$, $C_P = 71.86$, $Q_P = 0.16$, S is data size [Mbits], B_R, B_N, and B_P are allocated bandwidth [Mbps], and U_R, U_N, and U_P are utility values for users in relaxed, normal, and pressured situations, respectively.

The total bandwidth B_{ALL} is distributed to users according to the following equation:

$$N_R B_R + N_N B_N + N_P B_P = B_{ALL}, \tag{3.39}$$

where N_R, N_N, and N_P are the numbers of users in relaxed, normal, and pressured situations, respectively.

As shown in Fig. 3.1, the fair QoE allocation method distributes bandwidth based on the QoE relationships among user groups. All users experience the same QoE level or utility value, $U_R = U_N = U_P$. Based on this relationship and Eqs. (3.36), (3.37), and (3.38), the relationship of bandwidth among users are expressed as follows:

$$\frac{Q_N}{B_N} - \frac{Q_R}{B_R} = \frac{1}{S}\ln\left(\frac{C_N}{C_R}\right), \tag{3.40}$$
$$\frac{Q_R}{B_R} - \frac{Q_P}{B_P} = \frac{1}{S}\ln\left(\frac{C_R}{C_P}\right), \tag{3.41}$$
$$\frac{Q_N}{B_N} - \frac{Q_P}{B_P} = \frac{1}{S}\ln\left(\frac{C_N}{C_P}\right). \tag{3.42}$$

The right sides of Eqs. (3.40), (3.41), and (3.42) can be regarded as constant values:

$$C_1 = \frac{1}{S}\ln(\frac{C_N}{C_R}), \tag{3.43}$$
$$C_2 = \frac{1}{S}\ln(\frac{C_R}{C_P}), \tag{3.44}$$
$$C_3 = \frac{1}{S}\ln(\frac{C_N}{C_P}). \tag{3.45}$$

First, I present the allocated bandwidth for normal and pressured users as functions of the allocated bandwidth for relaxed users. From Eqs. (3.40), (3.41), (3.43), and (3.44), the following equations are obtained:

$$B_N = \frac{Q_N B_R}{Q_R + C_1 B_R}, \tag{3.46}$$
$$B_P = \frac{Q_P B_R}{Q_R - C_2 B_R}. \tag{3.47}$$

Based on Eqs. (3.46) and (3.47), Eq. (3.39) is transformed as follows:

$$N_R B_R + N_N \frac{Q_N B_R}{Q_R + C_1 B_R} + N_P \frac{Q_P B_R}{Q_R - C_2 B_R} = B_{ALL}. \tag{3.48}$$

Eq. (3.48) is an equation with one variable B_R, and it is possible to solve the equation and find the B_R. By repeating the similar process, the following equations for normal and pressured users are obtained:

$$N_R \frac{Q_R B_N}{Q_N - C_1 B_N} + N_N B_N + N_P \frac{Q_P B_N}{Q_N - C_3 B_N} = B_{ALL}, \tag{3.49}$$
$$N_R \frac{Q_R B_P}{Q_P + C_2 B_P} + N_N \frac{Q_N B_P}{Q_P + C_3 B_P} + N_P B_P = B_{ALL}. \tag{3.50}$$

After the transformation, the function expressing the amount of bandwidth allocated to users has the form of a general cubic equation, as follows:

$$ax^3 + bx^2 + cx + d = 0 \qquad (a \neq 0), \tag{3.51}$$

where

$$
\begin{aligned}
a(B_R) &= C_1C_2N_R, && (3.52)\\
b(B_R) &= -C_1N_RQ_R + C_2N_RQ_R + C_2N_NQ_N \\
&\quad -C_1N_PQ_P - C_1C_2B_{ALL}, && (3.53)\\
c(B_R) &= -N_R(Q_R)^2 - N_NQ_NQ_R - N_PQ_RQ_P \\
&\quad +C_1Q_RB_{ALL} - C_2Q_RB_{ALL}, && (3.54)\\
d(B_R) &= (Q_R)^2B_{ALL}, && (3.55)\\
a(B_N) &= C_1C_3N_N, && (3.56)\\
b(B_N) &= -C_3N_RQ_R - C_1N_NQ_N - C_3N_NQ_N \\
&\quad -C_1N_PQ_P - C_1C_3B_{ALL}), && (3.57)\\
c(B_N) &= N_RQ_RQ_N + N_N(Q_N)^2 + N_PQ_NQ_P \\
&\quad +C_1Q_NB_{ALL} + C_3Q_NB_{ALL}, && (3.58)\\
d(B_N) &= -(Q_N)^2B_{ALL}, && (3.59)\\
a(B_P) &= C_2C_3N_P, && (3.60)\\
b(B_P) &= C_3N_RQ_R + C_2N_NQ_N + C_2N_PQ_P \\
&\quad +C_3N_PQ_P - C_2C_3B_{ALL}, && (3.61)\\
c(B_P) &= N_RQ_RQ_P + N_NQ_NQ_P + N_P(Q_P)^2 \\
&\quad -C_2Q_PB_{ALL} - C_3Q_PB_{ALL}, && (3.62)\\
d(B_P) &= -(Q_P)^2B_{ALL}. && (3.63)
\end{aligned}
$$

There are some solutions to solve the formula in Eq. (3.51). The first method is using the Newton-Raphson method as mentioned above. The second method is using the geometric interpretation formulae [17] as follows:

$$
\begin{aligned}
x_1 &= \frac{2\sqrt{\Delta}\cos\left(\frac{\cos^{-1}\mu}{3}\right) - b}{3a}, && (3.64)\\
x_2 &= \frac{2\sqrt{\Delta}\cos\left(\frac{\cos^{-1}\mu}{3} - \frac{2\pi}{3}\right) - b}{3a}, && (3.65)\\
x_3 &= \frac{2\sqrt{\Delta}\cos\left(\frac{\cos^{-1}\mu}{3} + \frac{2\pi}{3}\right) - b}{3a}, && (3.66)
\end{aligned}
$$

where

$$\Delta = b^2 - 3ac, \tag{3.67}$$

$$\mu = \frac{9abc - 2b^3 - 27a^2 d}{2\sqrt{|\Delta|^3}} \quad (\Delta \neq 0), \tag{3.68}$$

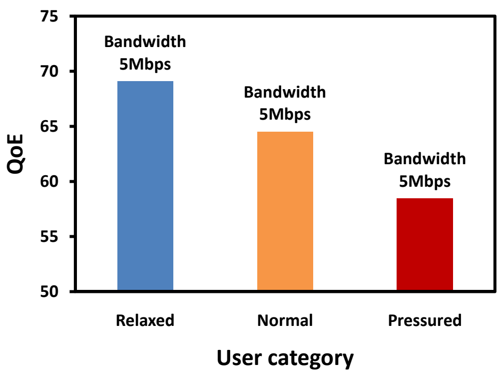
where $\Delta > 0$ and $|\mu| \leq 1$. By inserting the values of parameters a, b, c, and d from Eqs. (3.52)-(3.63) into Eqs. (3.64)-(3.66), the allocated bandwidth for users is obtained. For users in each group, three root values are calculated based on Eqs. (3.64)-(3.66). However, only one positive real root x_i, which satisfies the condition $0 \leq B_i \leq B_{ALL}$, is chosen as the allocated bandwidth B_i of users.

(2) Numerical Results

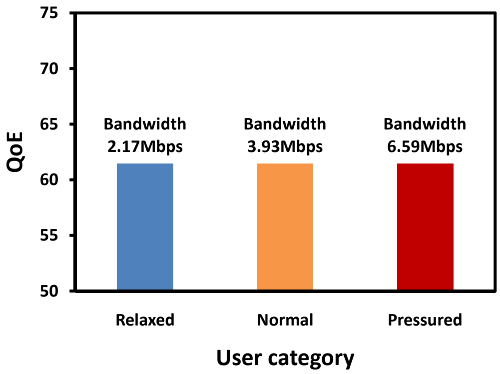
It is assumed that all users access the same service, i.e., Google news [12]. The average data size is 6.44Mbits. The total bandwidth of the access links is 100Mbps, which is distributed to 20 users in total, including 10% of users in the normal situation. The numbers of users in the relaxed and pressured situations change according to the case studies. Table 3.2 shows the scenario in various case studies in the experiments.

Table 3.2: Experimental scenario for the fair QoE bandwidth allocation method in case of three user types.

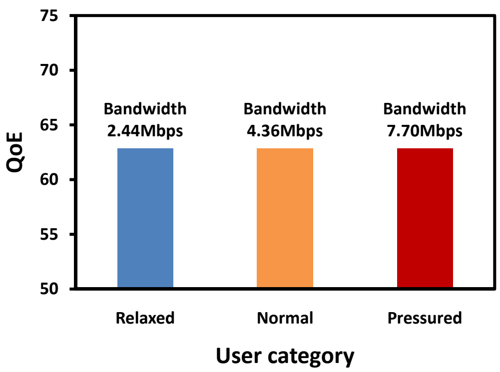
No.	B_{ALL} **[Mbps]**	S **[Mbits]**	N_{ALL}	N_R [%]	N_N [%]	N_P [%]
1	100	6.44	20	30	10	60
2	100	6.44	20	45	10	45
3	100	6.44	20	70	10	20
4	100	6.44	20	[0,90]	10	[0,90]
5	100	6.44	30	[0,90]	10	[0,90]



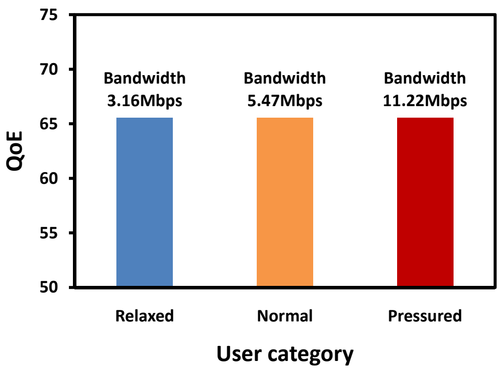
(a) Fair QoS method.



(b) Fair QoE method, 30%, 10%, and 60% users in relaxed, normal, and pressured situations, respectively.



(c) Fair QoE method, 45%, 10%, and 45% users in relaxed, normal, and pressured situations, respectively.



(d) Fair QoE method, 70%, 10%, and 20% users in relaxed, normal, and pressured situations, respectively.

Figure 3.7: Bandwidth allocation and users' QoE based on fair QoS and fair QoE methods in case of 20 users in total and the number of users in relaxed, normal, and pressured situations changes.

Figure 3.7 shows the bandwidth allocation and users' QoE based on the fair QoS and fair QoE methods when the total number of users is 20. When the numbers of users in relaxed, normal, and pressured situations change but the total number of users is constant, the allocated bandwidth to users based on the fair QoS method does not change, $B_0 = B_{ALL}/N_{ALL}$. As a result, their QoE level is also kept. In contrast, the allocated bandwidth to users in the fair QoE method changes when users change their situations. Therefore, all users always experience the same satisfaction level or the same QoE and the QoE value changes depending on the situations.

As shown in Fig. 3.7(a), the relaxed and normal users are satisfied with the service quality while the pressured users experience a lower QoE level even they are allocated the same bandwidth amount. In this case, the pressured users are not satisfied with the service quality when the network resource allocation policy is based on the fair QoS method.

On the other hand, the proposed fair QoE method can improve QoE for pressured users while the relaxed and normal users still experience good QoE as shown in Figs. 3.7(b), (c), and (d). It can be said that the pressured users are more difficultly satisfied than other user groups. Therefore, when the number of users in pressured situation increases, more bandwidth resource is required to satisfy users in the group. However, the total bandwidth resource is limited. As a result, the allocated bandwidth to users decreases when the number of pressured users increases as shown in the obtained results in Figs. 3.7(b), (c), and (d). In Fig. 3.7(b), when there exist 60% users in pressured situation, both relaxed and normal users decrease their QoE level compared with that in the fair QoE method. In contrast, both normal and pressured users can improve their QoE when the number of normal users is 70% in Fig. 3.7(d)

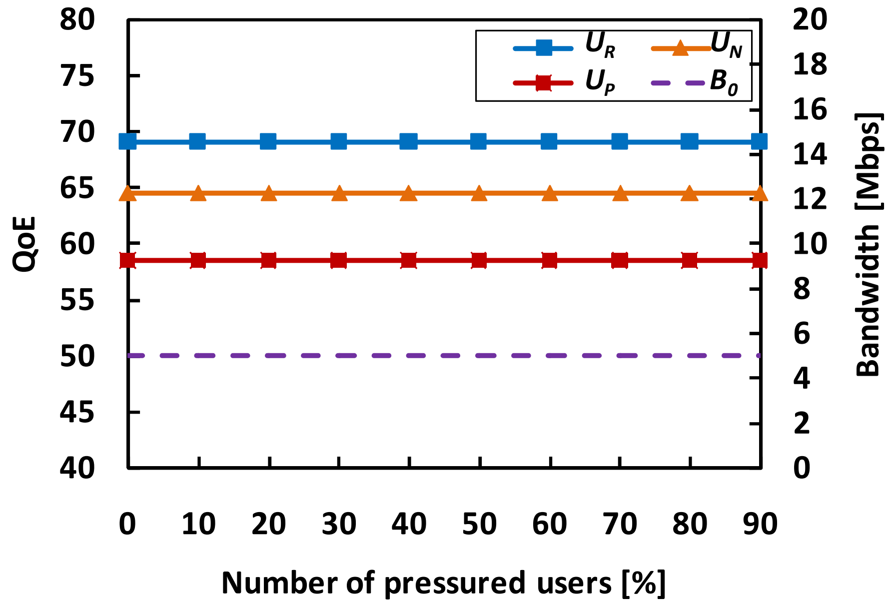


Figure 3.8: Fair QoS bandwidth allocation method.

Figure 3.8 shows the allocated bandwidth and users' QoE of each user group in the fair QoS method when the number of pressured users changes from 0 to 90%. In Fig. 3.8, all users are allocated the same bandwidth, and this value does not vary as users' situations change. Thus, all users keep their levels of QoE when the number of users in the pressured situation changes in this method.

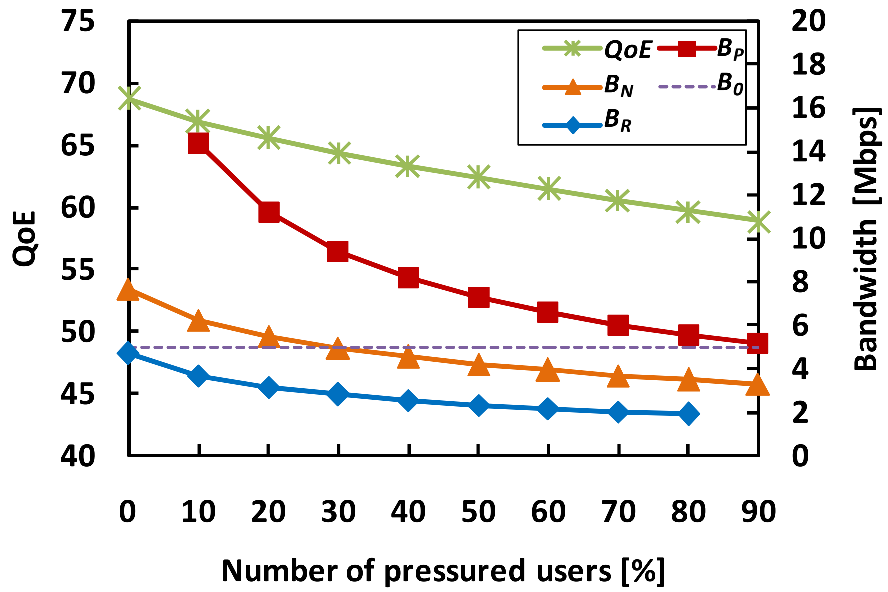


Figure 3.9: Fair QoE bandwidth allocation method.

Figure 3.9 gives the results of the fair QoE method when the number of total users is 20. The allocated bandwidth of each user decreases as the number of users in the pressured situation increases. Users in the normal situation can obtain higher bandwidth amounts than those in the fair QoS method when the number of pressured users is not more than 30%, while users in the pressured situation can always obtain a higher bandwidth resource amount. This means that the method always improves the QoE for users in the pressured situation. Moreover, when the number of users in the pressured situation is not more than 30%, this method also improves the QoE for the normal users.

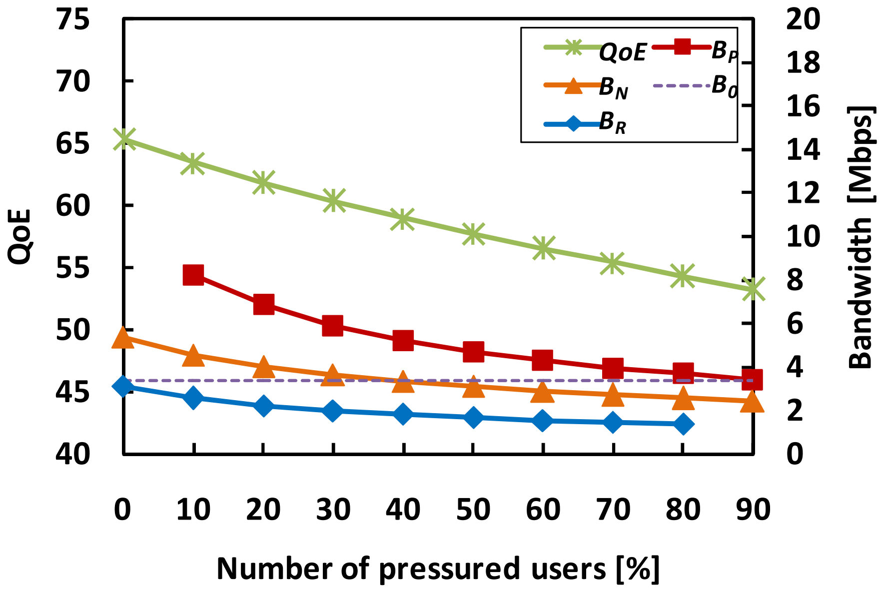


Figure 3.10: Fair QoE bandwidth allocation method.

Figure 3.10 presents the similar results of the fair QoE method to those in Fig. 3.9 when the number of total users is 30. When the number of users in the pressured situation is not more than 40%, this method can improves the QoE for both normal and pressured users. In contrast, only pressured users can get benefit from the proposal.

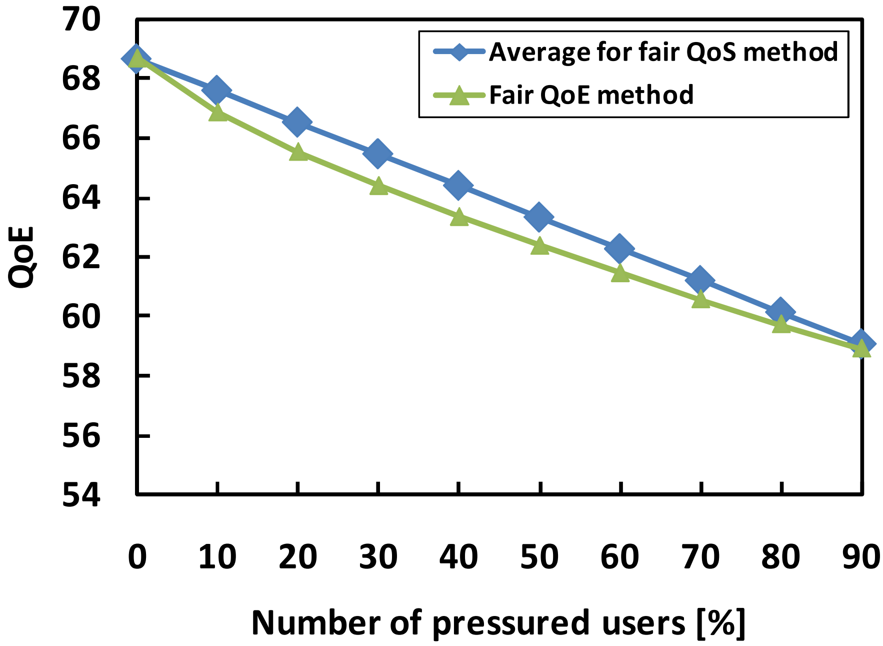


Figure 3.11: Average users' QoE based on fair QoS and fair QoE methods in case of 20 users in total.

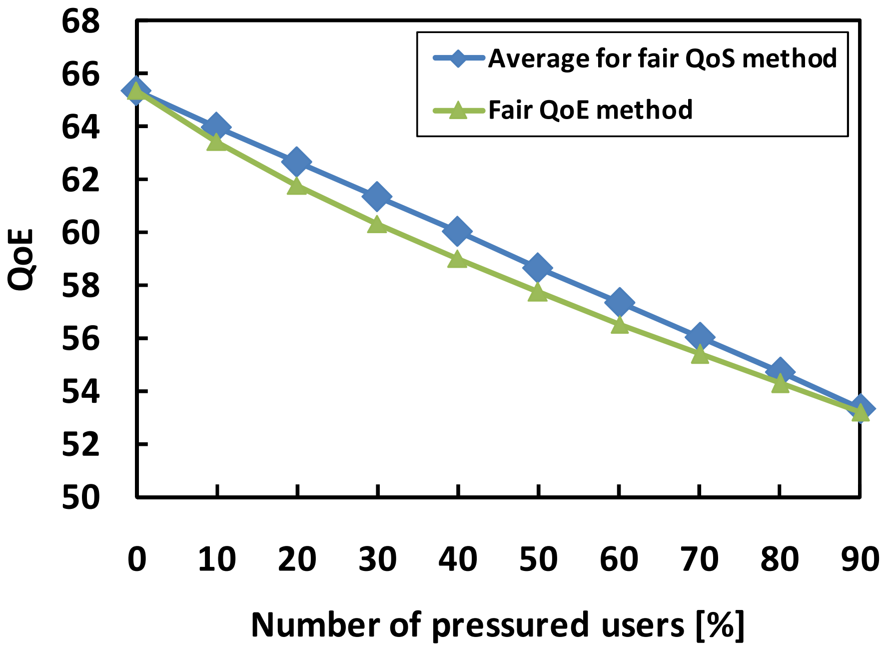


Figure 3.12: Average users' QoE based on fair QoS and fair QoE methods in case of 30 users in total.

Figures 3.11 and 3.12 show the average QoE of users for the two allocation methods when the number of normal users is 10% and that of pressured users changes from 0 to 90%. The total numbers of users in this case study are 20 and 30. As shown in these figures, the average QoE for the fair QoE method becomes a little smaller than that for the fair QoS method.

3.4.3 Four user types

(1) Experimental Scenario

This section is based on the experimental results in the previous study [43]. Therein, users are categorized very relaxed (VR), relaxed (R), neutral (N), and not-relaxed (NR) situations. The utility functions for users are as follows:

$$U_{VR} = C_{VR} \ln \frac{S}{B_{VR}} + Q_{VR}, \tag{3.69}$$

$$U_{R} = C_{R} \ln \frac{S}{B_{R}} + Q_{R}, \tag{3.70}$$

$$U_{N} = C_{N} \ln \frac{S}{B_{N}} + Q_{N}, \tag{3.71}$$

$$U_{NR} = C_{NR} \ln \frac{S}{B_{NR}} + Q_{NR}, \tag{3.72}$$

where C_{VR} = -1.48, Q_{VR} = 5.88, C_R = -1.45, Q_R = 5.73, C_N = -1.31, Q_N = 5.32, C_{NR} = -1.29, and Q_{NR} = 5.12.

Based on the rule of the fair QoE method, $U_{VR} = U_R = U_N = U_{NR}$, the following are derived:

$$U_{VR} = U_R, \tag{3.73}$$

$$U_{VR} = U_N, \tag{3.74}$$

$$U_{VR} = U_{NR}. \tag{3.75}$$

From Eqs. (3.73),(3.74), and (3.75), the following relationships are derived:

$$\ln((\frac{S}{B_{VR}})^{C_{VR}} \times e^{Q_{VR}}) = \ln((\frac{S}{B_R})^{C_R} \times e^{Q_R}), \tag{3.76}$$

$$\ln((\frac{S}{B_{VR}})^{C_{VR}} \times e^{Q_{VR}}) = \ln((\frac{S}{B_N})^{C_N} \times e^{Q_N}), \tag{3.77}$$

$$\ln((\frac{S}{B_{VR}})^{C_{VR}} \times e^{Q_{VR}}) = \ln((\frac{S}{B_{NR}})^{C_{NR}} \times e^{Q_{NR}}). \tag{3.78}$$

After the transformation based on Eqs. (3.76), (3.77), and (3.78), the allocated bandwidth for relaxed, neutral, and not-relaxed users can be expressed as functions of the allocated bandwidth for the very relaxed users as follows:

$$
\begin{aligned}
B_R &= B_{VR}{}^{\frac{C_{VR}}{C_R}} \times W_1{}^{\frac{1}{C_R}}, && (3.79)\\
B_N &= B_{VR}{}^{\frac{C_{VR}}{C_N}} \times W_2{}^{\frac{1}{C_N}}, && (3.80)\\
B_{NR} &= B_{VR}{}^{\frac{C_{VR}}{C_{NR}}} \times W_3{}^{\frac{1}{C_{NR}}}, && (3.81)
\end{aligned}
$$

where

$$
\begin{aligned}
W_1 &= \frac{S^{C_R} e^{Q_R}}{S^{C_{VR}} e^{Q_{VR}}}, && (3.82)\\
W_2 &= \frac{S^{C_N} e^{Q_N}}{S^{C_{VR}} e^{Q_{VR}}}, && (3.83)\\
W_3 &= \frac{S^{C_{NR}} e^{Q_{NR}}}{S^{C_{VR}} e^{Q_{VR}}}. && (3.84)
\end{aligned}
$$

The total bandwidth is allocated to users according to the following equation:

$$B_{ALL} = N_{VR}B_{VR} + N_R B_R + N_N B_N + N_{NR} B_{NR}. \quad (3.85)$$

By changing B_R, B_N, and B_{NR} from Eqs. (3.79), (3.80), and (3.81) into (3.85), the following is obtained:

$$
\begin{aligned}
N_{VR}B_{VR} + N_R W_1{}^{\frac{1}{C_R}} B_{VR}{}^{\frac{C_{VR}}{C_R}} + N_N W_2{}^{\frac{1}{C_N}} B_{VR}{}^{\frac{C_{VR}}{C_N}} + \quad (3.86)\\
+ N_{NR} W_3{}^{\frac{1}{C_{NR}}} B_{VR}{}^{\frac{C_{VR}}{C_{NR}}} - B_{ALL} = 0.
\end{aligned}
$$

Equation (3.86) is a one variable equation of B_{VR}. The equation has the form as follows:

$$ax + bx^{\alpha} + cx^{\beta} + dx^{\gamma} + e = 0, \quad (3.87)$$

where

$$
\begin{aligned}
a(B_{VR}) &= N_{VR}, && (3.88)\\
b(B_{VR}) &= N_R (W_1)^{1/C_R}, && (3.89)\\
c(B_{VR}) &= N_N (W_2)^{1/C_N}, && (3.90)\\
d(B_{VR}) &= N_{NR} (W_3)^{1/C_{NR}}, && (3.91)\\
e(B_{VR}) &= -B_{ALL}, && (3.92)\\
\alpha &= C_{VR}/C_R, && (3.93)\\
\beta &= C_{VR}/C_N, && (3.94)\\
\gamma &= C_{VR}/C_{NR}. && (3.95)
\end{aligned}
$$

By repeating the similar process, the similar equations expressing the amount of the allocated bandwidth to relaxed, neutral, and not-relaxed users are obtained with the parameters for relaxed users as follows:

$$a(B_R) = N_R, \tag{3.96}$$

$$b(B_R) = N_{VR}(W_1)^{1/C_{VR}}, \tag{3.97}$$

$$c(B_R) = N_N(W_2)^{1/C_N}, \tag{3.98}$$

$$d(B_R) = N_{NR}(W_3)^{1/C_{NR}}, \tag{3.99}$$

$$e(B_R) = -B_{ALL}, \tag{3.100}$$

$$\alpha = C_R/C_{VR}, \tag{3.101}$$

$$\beta = C_R/C_N, \tag{3.102}$$

$$\gamma = C_R/C_{NR}, \tag{3.103}$$

$$W_1 = \frac{S^{C_{VR}}e^{Q_{VR}}}{S^{C_R}e^{Q_R}}, \tag{3.104}$$

$$W_2 = \frac{S^{C_N}e^{Q_N}}{S^{C_R}e^{Q_R}}, \tag{3.105}$$

$$W_3 = \frac{S^{C_{NR}}e^{Q_{NR}}}{S^{C_R}e^{Q_R}}. \tag{3.106}$$

The parameters for the neutral users are as follows:

$$a(B_N) = N_N, \tag{3.107}$$

$$b(B_N) = N_{VR}(W_1)^{1/C_{VR}}, \tag{3.108}$$

$$c(B_N) = N_R(W_2)^{1/C_R}, \tag{3.109}$$

$$d(B_N) = N_{NR}(W_3)^{1/C_{NR}}, \tag{3.110}$$

$$e(B_N) = -B_{ALL}, \tag{3.111}$$

$$\alpha = C_N/C_{VR}, \tag{3.112}$$

$$\beta = C_N/C_R, \tag{3.113}$$

$$\gamma = C_N/C_{NR}, \tag{3.114}$$

$$W_1 = \frac{S^{C_{VR}}e^{Q_{VR}}}{S^{C_N}e^{Q_N}}, \tag{3.115}$$

$$W_2 = \frac{S^{C_R}e^{Q_R}}{S^{C_N}e^{Q_N}}, \tag{3.116}$$

$$W_3 = \frac{S^{C_{NR}}e^{Q_{NR}}}{S^{C_N}e^{Q_N}}. \tag{3.117}$$

The parameters for the not-relaxed users are as follows:

$$
\begin{aligned}
a(B_{NR}) &= N_{NR}, && (3.118)\\
b(B_{NR}) &= N_{VR}(W_1)^{1/C_{VR}}, && (3.119)\\
c(B_{NR}) &= N_R(W_2)^{1/C_R}, && (3.120)\\
d(B_{NR}) &= N_N(W_3)^{1/C_N}, && (3.121)\\
e(B_{NR}) &= -B_{ALL}, && (3.122)\\
\alpha &= C_{NR}/C_{VR}, && (3.123)\\
\beta &= C_{NR}/C_R, && (3.124)\\
\gamma &= C_{NR}/C_N, && (3.125)\\
W_1 &= \frac{S^{C_{VR}}e^{Q_{VR}}}{S^{C_{NR}}e^{Q_{NR}}}, && (3.126)\\
W_2 &= \frac{S^{C_R}e^{Q_R}}{S^{C_{NR}}e^{Q_{NR}}}, && (3.127)\\
W_3 &= \frac{S^{C_N}e^{Q_N}}{S^{C_{NR}}e^{Q_{NR}}}. && (3.128)
\end{aligned}
$$

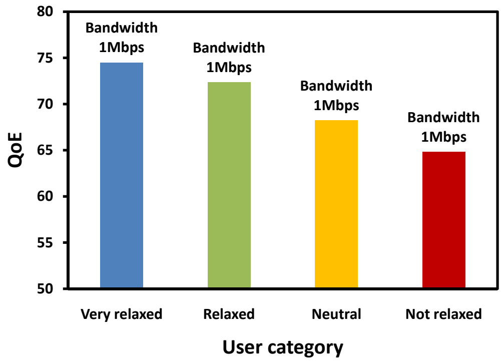
Since Eq. (3.87) is a complicated function algebraically, it can be solved by the Newton-Raphson method as mentioned above.

(2) Numerical Results

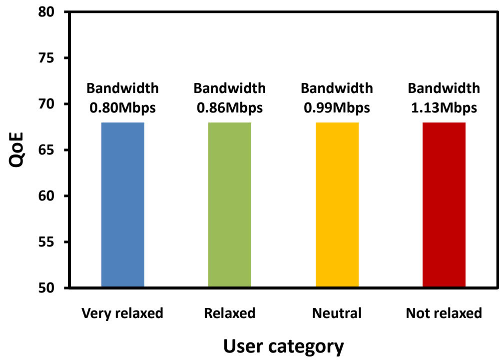
In this experiment, it is assumed that all users access the same service, Yahoo news [13]. The average data size, measured on an android smart phone, SONY EXPERIA C5303 model, is 4.29Mbits. The total bandwidth is 100Mbps. Many case studies are used in this experiment as shown in table 3.3.

Table 3.3: Experimental scenario for the fair QoE bandwidth allocation method in case of four user types.

No.	B_{ALL} **[Mbps]**	S **[Mbits]**	N_{ALL}	N_{VR} [%]	N_R [%]	N_N [%]	N_{NR} [%]
1	100	4.29	100	10	20	30	40
2	100	4.29	120	10	20	30	40
3	100	4.29	130	10	20	30	40
4	100	4.29	150	10	20	30	40

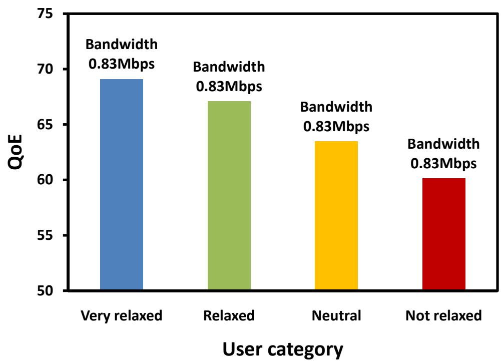


(a) Fair QoS method for 100 users.

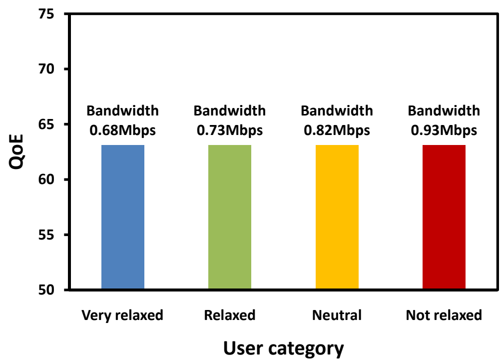


(b) Fair QoE method for 100 users.

Figure 3.13: Bandwidth allocation and users' QoE based on fair QoS and fair QoE methods in case of 100 users in total and 10%, 20%, 30%, and 40% users in very relaxed, relaxed, neutral, and not relaxed situations, respectively.



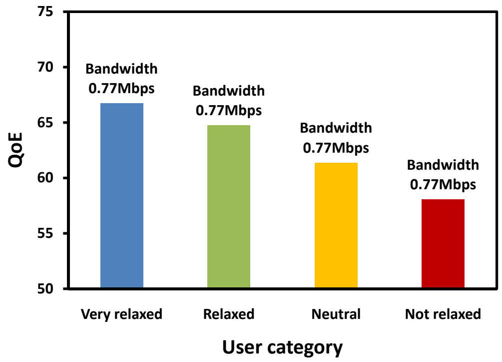
(a) Fair QoS method for 120 users.



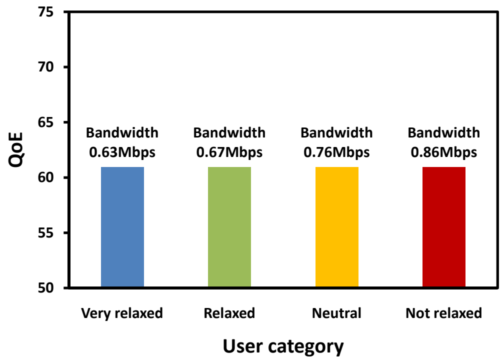
(b) Fair QoE method for 120 users.

Figure 3.14: Bandwidth allocation and users' QoE based on fair QoS and fair QoE methods in case of 120 users in total and 10%, 20%, 30%, and 40% users in very relaxed, relaxed, neutral, and not relaxed situations, respectively.

Figures 3.13, 3.14, 3.15, and 3.16 show the obtained results in the fair QoS and fair QoE methods when the total numbers of users are 100, 120, 130, and 150, respectively. As shown in Fig. 3.13(a), users experience the different QoE levels even they are allocated the same bandwidth amount. On the other hand, all users experience the same satisfaction level when the proposed fair QoE allocation method is applied as shown in Fig. 3.13(b). The similar results are shown in Fig. 3.14. In these case studies, all users are satisfied with the service quality in

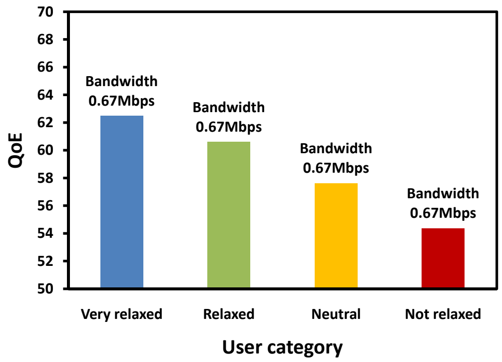


(a) Fair QoS method for 130 users.

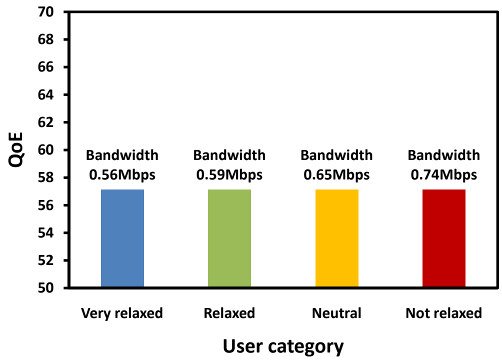


(b) Fair QoE method for 130 users.

Figure 3.15: Bandwidth allocation and users' QoE based on fair QoS and fair QoE methods in case of 130 users in total and 10%, 20%, 30%, and 40% users in very relaxed, relaxed, neutral, and not relaxed situations, respectively.



(a) Fair QoS method for 150 users.



(b) Fair QoE method for 150 users.

Figure 3.16: Bandwidth allocation and users' QoE based on fair QoS and fair QoE methods in case of 150 users in total and 10%, 20%, 30%, and 40% users in very relaxed, relaxed, neutral, and not relaxed situations, respectively.

both fair QoS and fair QoE methods.

In the third case study as shown in Fig. 3.15, very relaxed, relaxed, and neutral users are satisfied with the service quality in the fair QoS method. Not-relaxed users, however, experience a lower QoE level. In this situation, the fair QoE method can allocate a fair QoE level for all users. Therefore, the proposed method achieves an improvement for not-relaxed users.

In the last case study, the very relaxed and relaxed users experience an acceptable QoE level as shown in Fig. 3.16(a). In contrast, neutral and not-relaxed users are not satisfied. In this case study, there are many users in the network (150 users in the total), but the bandwidth resource is not enough. In addition, the ratio of not-relaxed users reaches 40%, and these users require more bandwidth amount than others to be satisfied. As a result, although the not-relaxed users can improve their QoE, the QoE level is not enough to be satisfied as shown in Fig. 3.16(b).

3.5 Conclusion

In this chapter, I proposed a bandwidth allocation method that considers not only the network resource but also the real perceived quality of users. The proposed method reallocates the bandwidth from the redundant users to others based on users' psychological factors. The method guarantees the QoE fairness for all users by applying the Newton-Raphson method. In some special situations, where the allocated bandwidth for users has the form of a special equation such as the quadratic or cubic functions, it is possible to apply the quadratic or cubic solution simply. On the other hand, in the general situation, the proposed method based on the Newton-Raphson method is the best solution. Comparing with the conventional method, the proposed method can achieve the purpose: improving QoE for the dissatisfied users while keeping good QoE for others. The positive numerical results show that it is possible to implement a bandwidth allocation method that allocates the really fair perceived quality to users.

Although the proposed method can overcome the challenge from the conventional method, there remain some issues in the proposal. First, the proposed method can achieve good results and effectively be applied to real systems just in some specific cases: There are both satisfied and dissatisfied users in the network. In contrast, if all users are satisfied with the service quality, the fair QoS method is simple and valuable. Secondly, the proposed method slightly decreases the average QoE of users. These problems motivate us to find out a new allocation method that combines the conventional fair QoS method and the proposed fair QoE method. Therefore, the following chapters will find a solution to improve the proposed method as well as to apply the proposed method effectively to a real system.

Chapter 4

Hybrid Bandwidth Allocation Method

In this chapter, I propose a bandwidth allocation method that is based on the viewpoint of QoE to allocate the bandwidth. The previous proposed method allocates the bandwidth by considering the same users' satisfaction in terms of QoE with respect to all users in the system. The method, however, decreases the average QoE of users compared to that in the fair QoS method. To cope with this issue, I propose another bandwidth allocation policy namely the hybrid bandwidth allocation method. The purpose of the second proposed method is to provide a flexible solution to reasonably allocate the limited network resources to users. Based on the statistical characteristics of users' situation, the proposed method can provide a trade-off approach to users. The numerical results of the proposed method, which are obtained in various case studies and verified by comparison to the traditional method, show a positive impact on the QoE of dissatisfied users.

4.1 Introduction

The wide development of networks allows flexibility in accessing Internet services almost any place and anytime. Challenges of the network resource control scheme are also increasing with the popularity of the Internet and Internet services. The crucial issue is coming since the network resource allocation method has to meet the users' requirement and still optimize the network performance. Many approaches are introduced based on the various viewpoints to solve the bandwidth allocation issue. The first approach is based on the fair objective quality of service (QoS) metrics to allocate the bandwidth. However, the levels of users' satisfaction are different depending on various subjective factors such as users' situations, individual characteristics, and other psychological factors. Therefore, the objective metrics are difficult to guarantee the perceived quality of users. To overcome the limitation, another approach based on the viewpoint of the quality of experience (QoE) is introduced. Although the fair QoE method can successfully solve the problem in the fair QoS method, as shown in previous studies [45, 46], it is faced with the following problem: the proposed method slightly decreases the average QoE of users.

Currently, considering QoE in network resource control schemes is mandatory to guarantee a real perceived QoE of users, while the allocation methods based on the fair QoS and fair QoE methods have their limitations. For this reason, I propose the second allocation method, namely a hybrid method, which considers fairness from another viewpoint. The hybrid method tries to combine the advantages of the fair QoS method and fair QoE method while reducing their limitations. This method focuses on remaining at a similar level of users' satisfaction based on a bandwidth limitation. Because a win-no lose approach is difficult to achieve, the aim of this proposal is to find a trade-off solution to the bandwidth allocation issues.

To achieve this aim, the proposed method first categorizes users into groups according to their situations: pressured, normal, and relaxed [58]. Each user group has a specific utility function to map the relationship between the allocated bandwidth and users' QoE. The method then allocates bandwidth to users with respect to each group. As a result, users in the same group will be allocated the same network resource.

As mentioned above, the goal of the proposed method is to find a trade-off solution, which gives the similar level of QoE for users. The hybrid method tries to follow the natural rule between users' behaviors and requirements, between required bandwidth and the satisfaction level. It can be said that the relaxed users are more easily satisfied than others and the pressured users are more difficultly satisfied than other user groups. In this chapter, the proposed method follows this rule to allocate the bandwidth. Therefore, users in the normal situation are considered as the threshold for users in other situations. It means that the pressured users can improve their QoE, but their QoE levels should not become higher than those of the normal users. On the other hand, the relaxed users can accept a lower level of QoE to share their bandwidth resources with others, but their QoE levels should be always better than or equal to the QoE of normal users.

The rest of this chapter is organized as follows. The next section introduces the related works. Section 4.3 then describes the proposed bandwidth allocation method in detail. Section 4.4 shows some numerical results in various case studies to illustrate the proposed method. Finally, the conclusions and future work are presented in the last section.

4.2 Related Work

The fairness is mentioned in many previous studies and has a long history of development [25, 30, 38]. There are various approaches for the fairness problem to solve a specific issue. Although the fairness has various definitions, all literature state that the fairness implies the equality of the network resource: it can be equal delay, throughput, or power depending on the application.

In the chapter, the fairness is considered as the balance between the QoE of each user and the average QoE of all users. The previous studies show that both the fair QoE and fair QoS methods have their limitations. Therefore, the proposed method tries to allocate the proper network resource for users with the different requirements. While some users require more network resource than others, some users can accept a lower bandwidth amount. The hybrid approach tries to follow the natural mappings between the real users' consumption and their satisfaction level. In other words, the proposed method tries to lead to a relative fairness in distributing network resource while it still guarantees the benefit of users.

4.3 Proposed Bandwidth Allocation Method

In this method, the relaxed and pressured users will be given different amounts of bandwidth. The relaxed users will share their bandwidth with the pressured users. If there are many users in the relaxed situation, at least one relaxed user can help one pressured user to improve the bandwidth. In this case, the bandwidth for pressured users can be significantly improved. In contrast, when there are many users in the pressured situation in the network, one relaxed user must help many pressured users to improve their bandwidth. It is difficult to improve the bandwidth for the pressured users.

The satisfaction level of users can be expressed in the concept of utility. Based on this consideration, previous studies have proposed utility functions to estimate the QoE model for the web application under the different psychological situations [58]. From the same perspective, in this study, I continue to use the settings of the previous work, i.e., three user types. Therefore, the study categorizes users into groups according to their situations: relaxed (R), normal (N), and pressured (P) [58]. Each user type has a specific utility function, which is obtained based on the previous study results [58] to map the relationship between users' QoE and the allocated bandwidth as follows:

$$
\begin{aligned}
U_R(B_R) &= C_R \mathrm{e}^{-Q_R \frac{S}{B_R}}, & (4.1)\\
U_N(B_N) &= C_N \mathrm{e}^{-Q_N \frac{S}{B_N}}, & (4.2)\\
U_P(B_P) &= C_P \mathrm{e}^{-Q_P \frac{S}{B_P}}, & (4.3)
\end{aligned}
$$

where $C_R = 75.62$, $Q_R = 0.07$, $C_N = 77.29$, $Q_N = 0.14$, $C_P = 71.86$, $Q_P = 0.16$, S is data size [Mbits], B_R, B_N, and B_P are allocated bandwidth [Mbps], and U_R, U_N, and U_P are utility values for the relaxed, normal, and pressured users, respectively.

In addition, the total bandwidth (B_{ALL}) is distributed to users according to the following equation:

$$N_R B_R + N_N B_N + N_P B_P = B_{ALL}, \tag{4.4}$$

where N_R, N_N, and N_P are the numbers of users in relaxed, normal, and pressured situations, respectively.

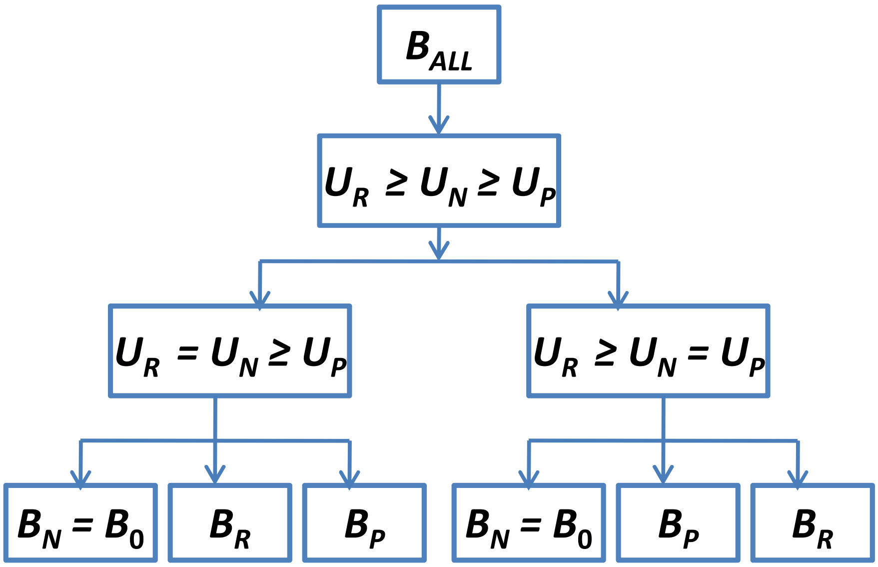


Figure 4.1: Flow diagram of the hybrid bandwidth allocation method.

Figure 4.1 shows the allocation process in this method. The normal users retain the same satisfaction levels and the bandwidth B_0 as those in the fair QoS method. B_0 is derived as follows:

$$B_N = B_0 = \frac{B_{ALL}}{N_{ALL}}. \tag{4.5}$$

From Eqs. (4.1), (4.2), (4.3), and (4.5), the following is derived:

$$U_R(B_0) > U_N(B_0) > U_P(B_0). \tag{4.6}$$

The users in the relaxed and pressured situations change their levels of QoE, but the order must be kept such that $U_R(B_R) \geq U_N(B_N) \geq U_P(B_P)$ based on the concept of the hybrid method. Therefore, users in the pressured situation can receive the bandwidth from others to improve the satisfaction level but their QoE should not be greater than those of the normal users. On the other hand, users in the relaxed situation will share their bandwidth but their satisfaction level should be equal or greater than those of users in the normal situation. There are two case studies corresponding to this rule as follows:

$$U_R = U_N \geq U_P, \tag{4.7}$$

$$U_R \geq U_N = U_P. \tag{4.8}$$

Case study 1: The case study corresponds to the situation shown in Eq. (4.7). From Eqs. (4.1), (4.2), and (4.7), the following is obtained:

$$C_R \mathrm{e}^{-Q_R \frac{S}{B_R}} = C_N \mathrm{e}^{-Q_N \frac{S}{B_N}}. \tag{4.9}$$

From Eq. (4.9), the allocated bandwidth for the relaxed users is derived as follows:

$$B_R = \frac{Q_R B_0}{Q_N - C_1 B_0}, \tag{4.10}$$

where $C_1 = \frac{1}{S} \ln \frac{C_N}{C_P}$.

From Eq. (4.4) the allocated bandwidth for the pressured users is derived as follows:

$$B_P = \frac{B_{ALL} - N_R B_R - N_N B_0}{N_P}. \tag{4.11}$$

Case study 2: The case study is based on the relationship expressed in Eq. (4.8). Repeating the process and based on Eqs. (4.2), (4.3), (4.4), and (4.8), the following are derived for the relaxed and pressured users:

$$B_P = \frac{Q_P B_0}{Q_N - C_2 B_0}, \tag{4.12}$$

$$B_R = \frac{B_{ALL} - N_N B_0 - N_P B_P}{N_R}, \tag{4.13}$$

where $C_2 = \frac{1}{S} \ln \frac{C_N}{C_R}$.

In a real case study, using the relationship of Eq. (4.7) or (4.8) depends on the specific conditions and situations. The suitable values, which are obtained using Eqs. (4.10)-(4.13) and satisfy the condition $0 \leq B \leq B_{ALL}$, are chosen as the allocated bandwidth of users.

4.4 Numerical Results

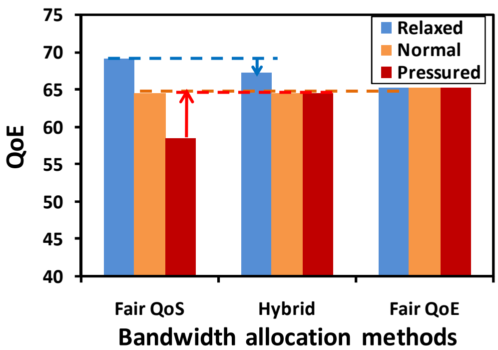
Table 4.1: Experimental scenario for the hybrid bandwidth allocation method.

No.	B_{ALL} **[Mbps]**	S **[Mbits]**	N_{ALL}	N_R [%]	N_N [%]	N_P [%]	**Results**
1	100	6.44	20	40	50	10	Fig. 4.2
2	100	6.44	20	20	50	30	Fig. 4.2
3	100	6.44	20	30	10	60	Fig. 4.3
4	100	6.44	20	70	10	20	Fig. 4.3
5	100	6.44	20	[0,60]	40	[0,60]	Figs. 4.4,4.5,4.8
6	100	6.44	20	[0,90]	10	[0,90]	Figs. 4.6,4.7,4.9
7	100	6.44	30	[0,90]	10	[0,90]	Fig. 4.10
8	100	6.44	50	[0,90]	10	[0,90]	Fig. 4.11

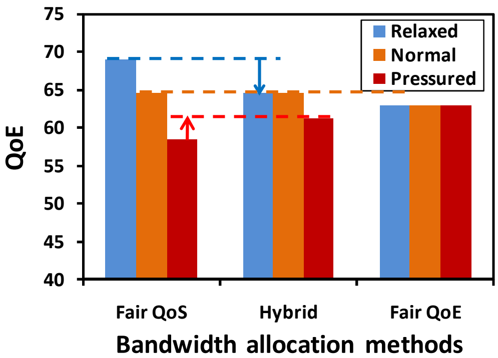
This section shows the numerical results in various case studies with the proposed method. The fair QoS and fair QoE methods are also mentioned as a conventional and basic allocation schemes for comparison with the proposed hybrid method from two viewpoints: the perceived QoE of each user and the average QoE of all users. Table 4.1 shows the scenarios used in the numerical experiments with the corresponding results.

In the chapter, it is assumed that all users access the same service, i.e., Google news [12]. The average data size is 6.44Mbits. The total bandwidth of the access links is 100 Mbps, which is distributed to 20 users in total. Note that the utility value is used to show the users' satisfaction, i.e., QoE. When the utility value is greater than or equal to 60, the service quality is acceptable. Otherwise, users are not satisfied with the perceived quality.

Figure 4.2 shows the bandwidth allocation and users' QoE based on the fair QoS, hybrid, and fair QoE methods. In this case study, the number of users



(a) Case study 1: 40% users in relaxed, 50% users in normal, and 10% users in pressured situations.



(b) Case study 2: 20% users in relaxed, 50% users in normal, and 30% users in pressured situations.

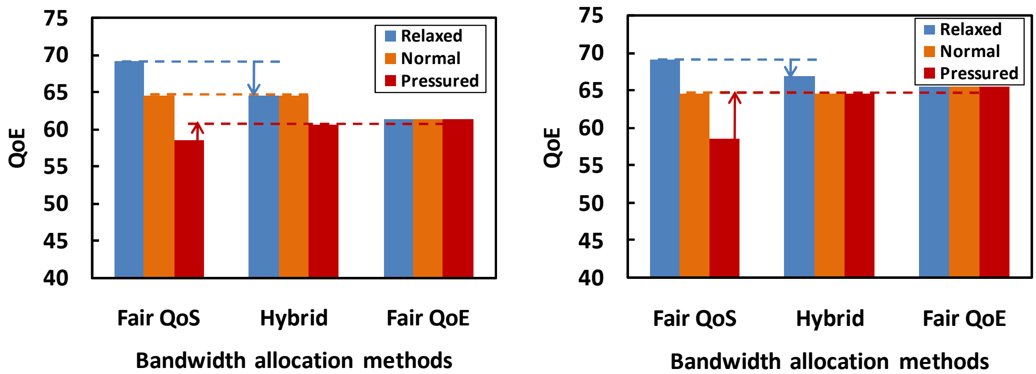
Figure 4.2: Bandwidth allocation and users' QoE based on fair QoS, hybrid, and fair QoE methods in case of 50% users in normal situation.

in normal situation is 50%. Figures. 4.2(a) and (b) show the results when the number of users in pressured and relaxed situation changes. In both figures, the allocated bandwidth for users in the fair QoS method does not change because the number of total users and the total bandwidth are constant.

As shown in Figs. 4.2(a) and (b), the relaxed and normal users are satisfied with the service quality while the pressured users experience lower level of QoE in the fair QoS method. On the other hand, the proposed method can improve QoE for the pressured users while the relaxed and normal users still experience good QoE.

Figure 4.2(a) shows the results when the number of users in pressured situation is 10% and that in the relaxed situation is 40%. In this case, many relaxed users can share their bandwidth with the pressured users. As a result, the pressured users can significantly improve their QoE level and achieve the same QoE with the normal users while the relaxed users slightly decrease their QoE levels. In this case study, the results are obtained by using Eqs. (4.7), (4.10), and (4.11).

In Fig. 4.2(b), the users in normal and relaxed situation experience the same level of satisfaction. The results are obtained when the number of users in pressured situation is 30% and that in the relaxed situation is 20%. In this case, many pressured users wish to improve their experience level while the amount of sharing bandwidth from relaxed users is limited. Therefore, the hybrid method can improve the QoE of the pressured users compared with that of the fair QoE method. However, their QoE level is less than that of the relaxed and normal users. In this case study, the results are obtained by using Eqs. (4.8), (4.12), and (4.13).



(a) Case study 1: 30% users in relaxed, 10% users in normal, and 60% users in pressured situations.

(b) Case study 2: 70% users in relaxed, 10% users in normal, and 20% users in pressured situations.

Figure 4.3: Bandwidth allocation and users' QoE based on fair QoS, hybrid, and fair QoE methods in case of 10% users in normal situation.

The similar results are shown in Fig. 4.3 in case of 10% users in the normal situation. The numbers of users in the relaxed and pressured situations change according to the case studies. As shown in Fig. 4.3(a), many users are in the pressured situation. As a result, the QoE of pressured users is slightly improved while the relaxed users should decrease much their QoE level. In contrast, there are many users in the relaxed situation in the case study 2 as shown in Fig. 4.3(b). The pressured users can significantly improve their QoE while the relaxed users just decrease a little.

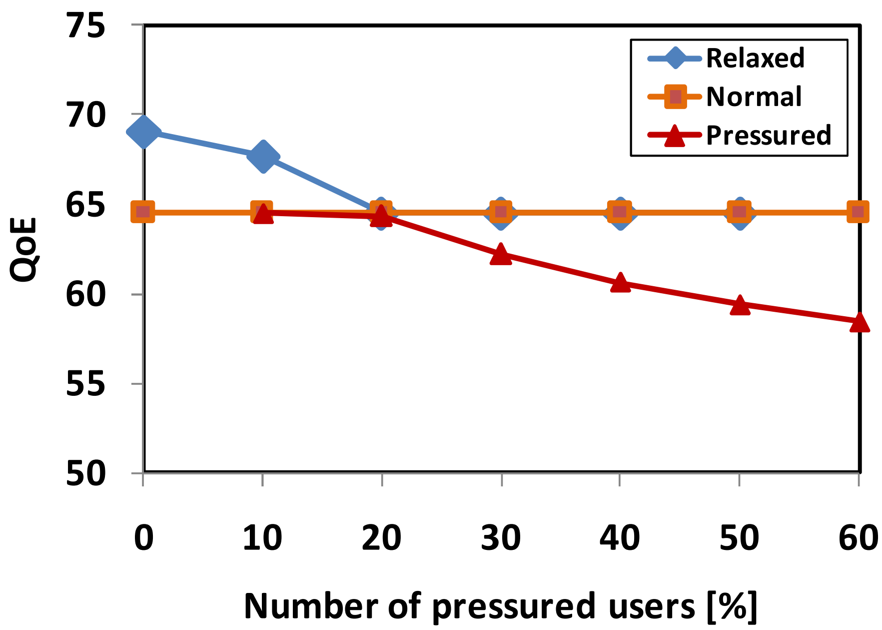


Figure 4.4: Users satisfaction based on the hybrid method when the number of users in pressured situation changes.

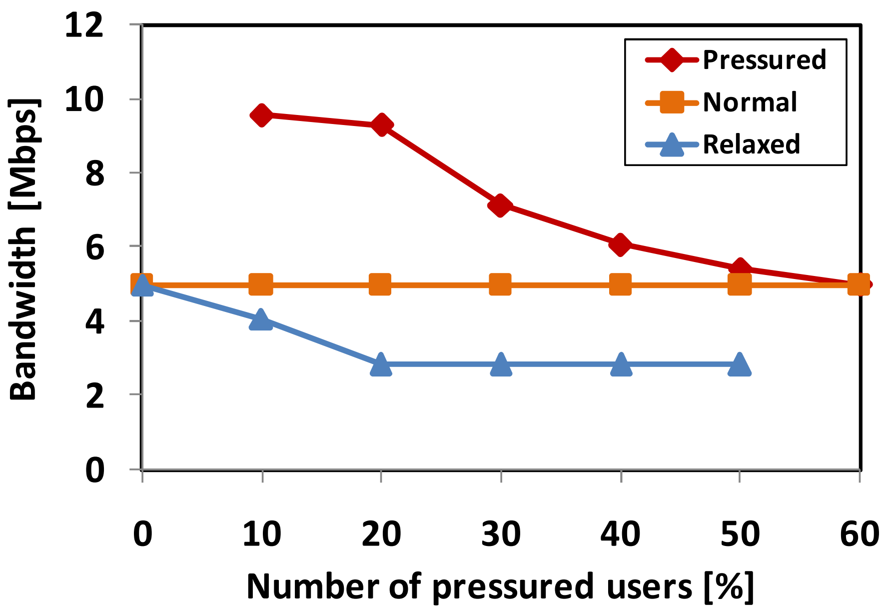


Figure 4.5: Bandwidth allocation based on the hybrid method when the number of users in pressured situation changes.

Figures 4.4 and 4.5 present the users' satisfaction and bandwidth allocation based on the hybrid method when the ratio of users in the normal situation is 40% and that in the pressured situation changes from 0 to 60%. According to the result shown in Fig. 4.4, users in the normal situation keep their QoE level when the number of users in the pressured situation changes. In addition, when the ratio of the pressured users is more than 20%, the relaxed and normal users experience the same QoE level, which is higher than that of the pressured users. In contrast, the relaxed users can obtain a better satisfaction level compared with that of the normal and pressured users.

As shown in Fig. 4.5, users in the normal situation receive the same bandwidth as shown in Eq. (4.5), and always experience the same level of QoE when the number of pressured users changes. In addition, the relaxed users also remain their bandwidth and QoE when the ratio of pressured users is not less than 20%.

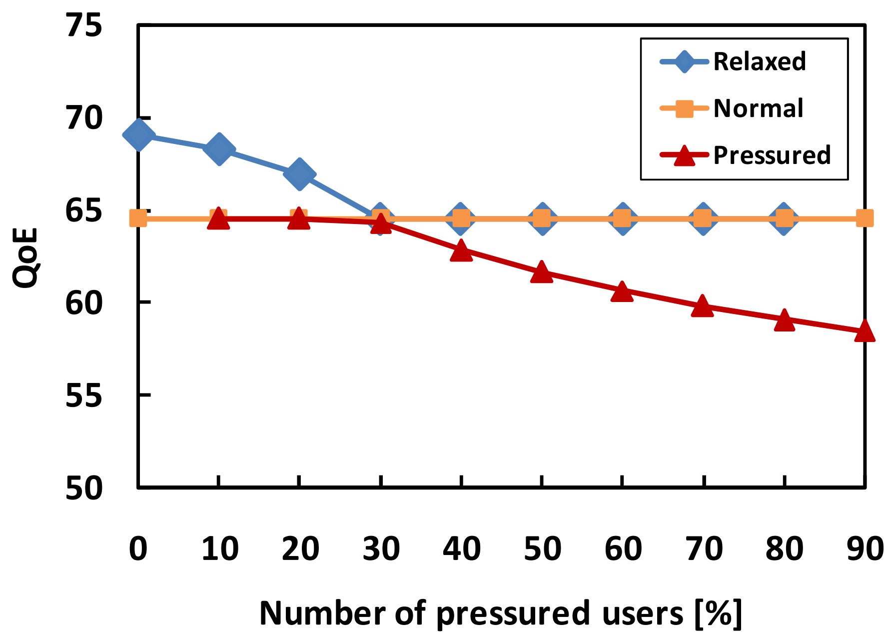


Figure 4.6: Users satisfaction based on the hybrid method when the number of users in pressured situation changes.

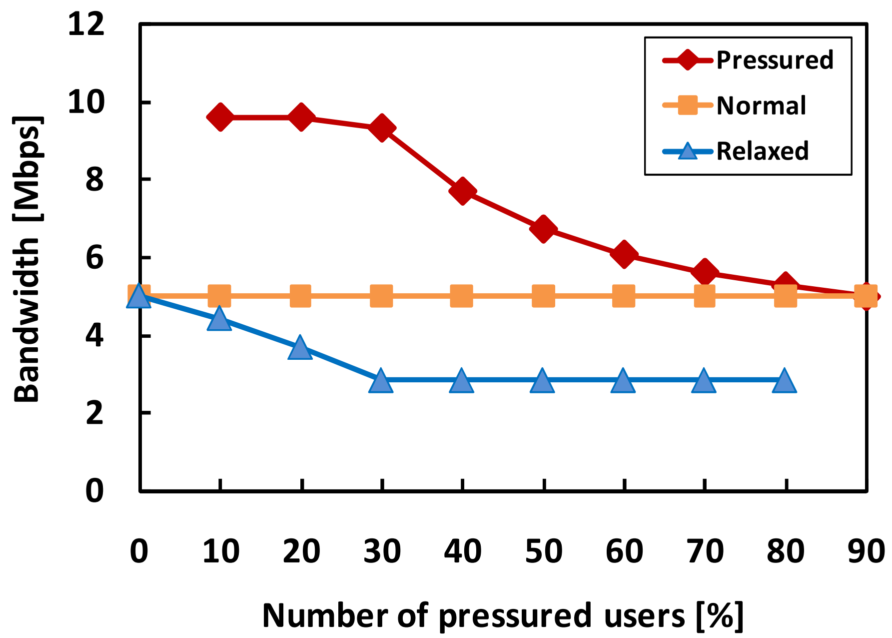


Figure 4.7: Bandwidth allocation based on the hybrid method when the number of users in pressured situation changes.

Figures 4.6 and 4.7 show the similar results when the ratio of normal users is 10% and the ratio of pressured users changes from 0 to 90%. When the ratio of the pressured users is more than 30%, the pressured users experience a lower QoE level than that of the relaxed and normal users. In contrast, the relaxed users can obtain a better satisfaction level compared with that of the normal and pressured users. In addition, in Fig. 4.7 the pressured users keep their bandwidth and QoE when the ratio of pressured users is less than 30%.

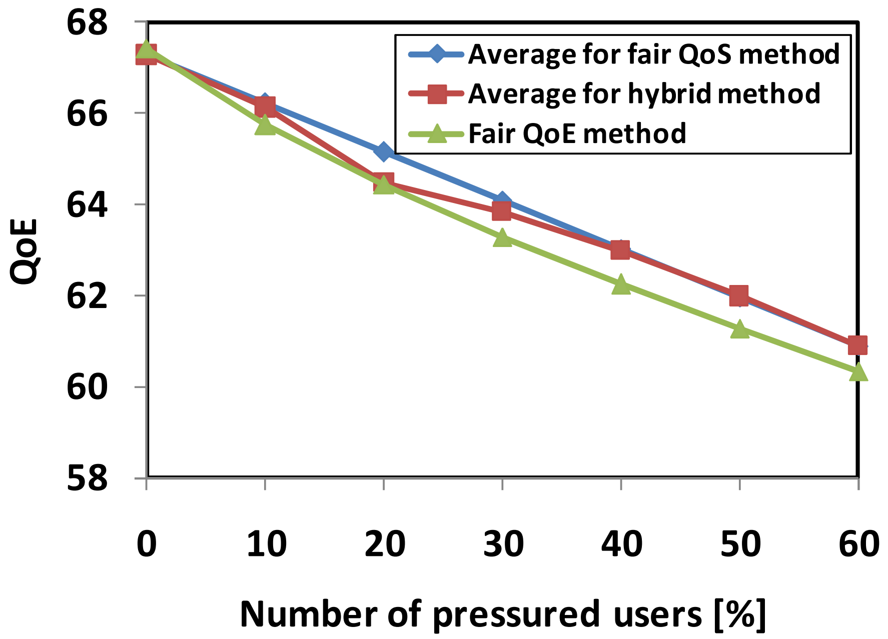


Figure 4.8: Users' satisfaction based on fair QoS, fair QoE, and hybrid methods in case of 50% users in normal situation and 20 users in total.

Figure 4.8 shows the average QoE of users in the fair QoS, proposed, and fair QoE methods when the ratio of the normal users is 40% and that of the pressured users changes from 0 to 60%. The QoE in the hybrid method becomes a little smaller than that in the fair QoS method. However, the hybrid method can improve the average QoE of users compared with the fair QoE method. It is noted that when the ratio of pressured users is around 20%, the average QoE of users in the proposed method is similar to that in the fair QoE method. This can be explained from the result in Fig. 4.4. At this point, the normal and relaxed users get the same QoE level, which is slightly higher than that of the pressured users. It means that the hybrid and the fair QoE methods become very similar when the ratio of pressured users is approximately 20%.

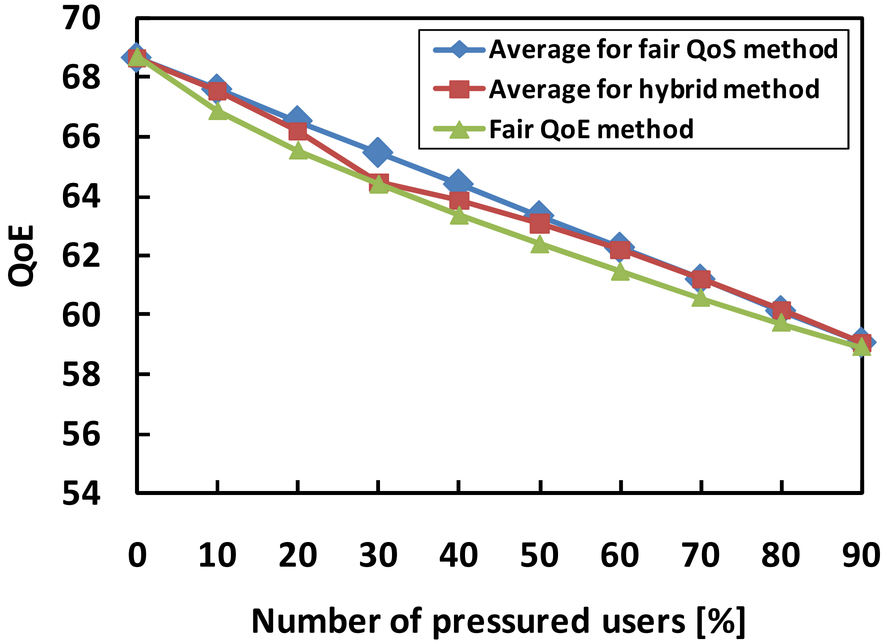


Figure 4.9: Users' satisfaction based on fair QoS, fair QoE, and hybrid methods in case of 10% users in normal situation and 20 users in total.

Figures 4.9, 4.10, and 4.11 present the similar results with those in Fig. 4.8. The results are obtained in these figures in the case where the ratio of normal users is 10% and that of the pressured users change from 0 to 90%. The total numbers of users in this case study are 20, 30, and 50, respectively. In all situations, the average QoE for the hybrid method is very close to that for the fair QoS method, while that for the fair QoE method becomes a little smaller. When the ratios of users in the pressured situation are 30%, 40%, and 50% as shown in Figs. 4.9, 4.10, and 4.11, respectively, the hybrid and fair QoE methods achieve similar average QoE.

In general, based on the above numerical results obtained in various case studies, the proposed allocation method successfully improves the QoE for the dissatisfied users. In addition, the proposed method maintains a similar QoE level among users compared with the fair QoE method and a similar average QoE compared with the fair QoS method.

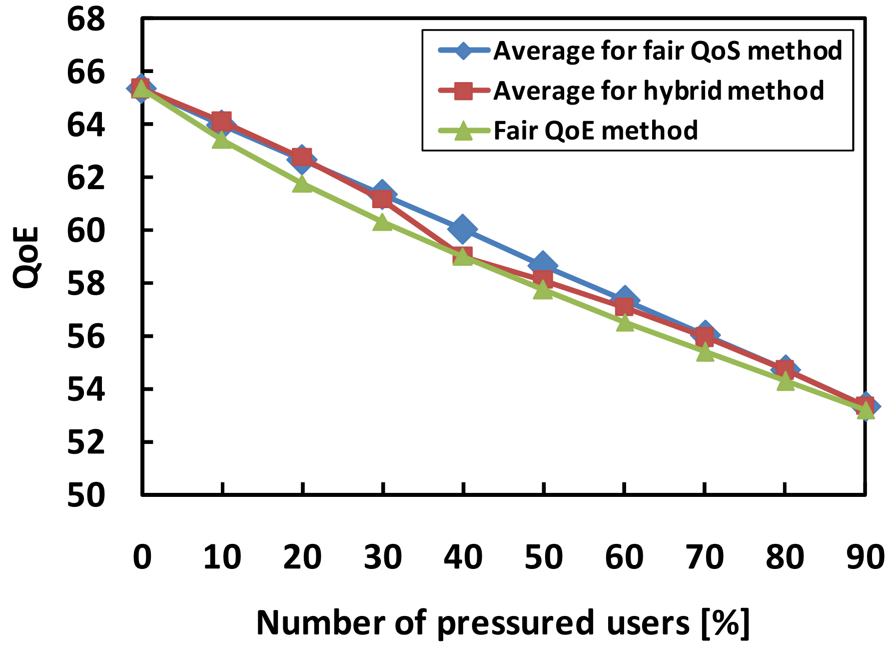


Figure 4.10: Users' satisfaction based on fair QoS, fair QoE, and hybrid methods in case of 10% users in normal situation and 30 users in total.

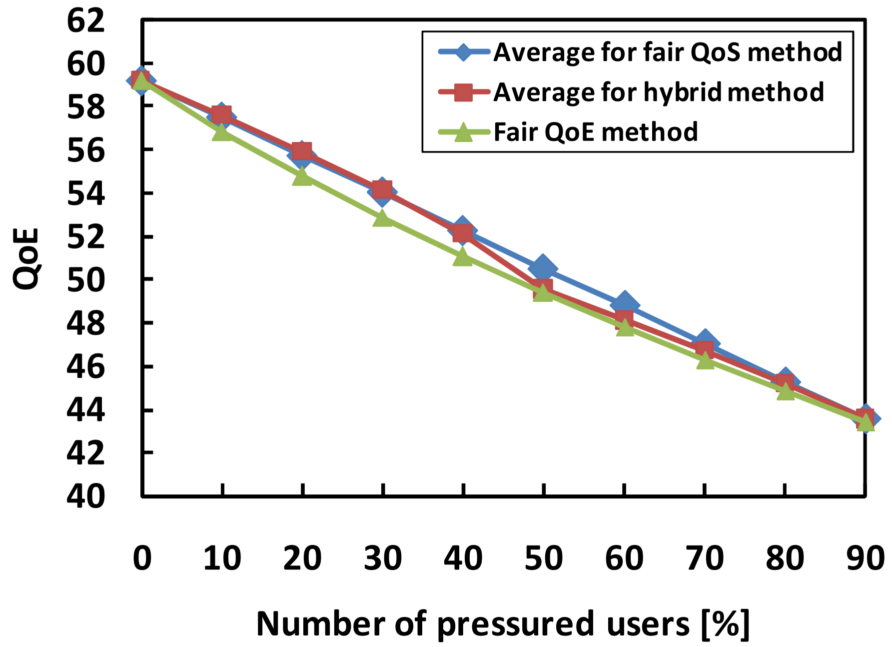


Figure 4.11: Users' satisfaction based on fair QoS, fair QoE, and hybrid methods in case of 10% users in normal situation and 50 users in total.

4.5 Conclusion

In this chapter, I proposed to consider the bandwidth allocation issue from the viewpoint of users to clearly show the level of users' satisfaction and the objective information, i.e., network metrics. The proposed method is based on the assumption that the bandwidth consumption is negotiable among users. It means that the proposed method tries to keep a similar level of users' satisfaction under the bandwidth limitation. The aim of the proposed method is to find a trade-off solution for the bandwidth allocation issues. To achieve this aim, the proposed method does not allocate a completely fair QoE level but achieves a similar level of QoE for users. Therefore, the proposed method improves the QoE level for users compared with the fair QoS method and decreases the difference in average QoE compared with the fair QoE method. The proposed method can be used as a trade-off solution between the viewpoints of fair QoS and fair QoE. In fact, a win-no lose solution, which can allocate the really fair quality to users and improve the average QoE of users, is difficult to achieve in reality. In that case, my proposed method is a good solution when it can combine the advantages and decrease the limitation of the previous studies.

The positive numerical results in the chapter show that it is potential to develop a trade-off allocation method as in the proposal. In the next chapter, I will try to find a solution to realize the proposal in real systems. This study, however, is performed only on the web-based service. It is necessary to test with other video, audio, and multimedia services. In further study, I will continue to improve the proposed method as well as expand this study for other services.

Chapter 5

Theory of Participatory Service in Bandwidth Allocation

In this chapter, I discuss the applicability of the proposed methods. User classification seems to be the most difficult to realize my proposed scheme, i.e., how to determine users' situations or classify users into groups. In other words, the question is how to collect the statistical information about users' characteristics. To treat this issue, I consider a participatory service in the bandwidth allocation. The participatory service is used to connect the users' requirements with the allocation policy. The methodology of the participatory service is that the bandwidth usage or consumption is to be negotiable between network providers and users. Some users can share or give their bandwidth to others at this time, and next time, when they want to use more bandwidth resources, they can ask to receive bandwidth from others.

5.1 Introduction

In the previous chapters, the study focuses on the bandwidth allocation methods based on the viewpoint of users to distribute the resource. The proposed methods are considered as the user-based policy, and it is necessary to find the solution to realize the proposed allocation methods in real system. As a result, a service that involves the users in development and implementation of the application is required. For this reason, this chapter introduces a theory of the participatory service. The participatory service is used to involve the users' requirements in bandwidth allocation policy.

The idea to build the participatory service is similar to the concept of the rewarding mechanism. For rewarding mechanism, it takes the subjective user factors into account and motivates the users to contribute resources to the system [61, 62]. In [62], the authors proposed to use an external evaluator and interactive learning agents to build a rewarding system. In the proposal, the system distributes the rewards based on user resource contributions and user states. The obtained results showed a positive trend when the average number of accepted users is improved.

Since users' satisfaction will decide the success of the services, the user-centric systems are becoming the next generation of the future networks [36, 40]. It is expected to offer the best user experience anytime and anywhere. The user-centered designs (UCD) are mentioned in the previous studies [20, 63]. These designs describe how end-users affect to or influence on systems. The user is in the center of focus during the development of these applications. The goal in the future is to make things visible, so users are able to look at an application and able to complete a task without disturbing to users. Therefore, user-centric design is an effective way to ensure a successful implementation of an application.

Since considering users' behavior plays an important role in the future network systems in general and in allocation policy in particular, user-based resource allocation methods are essential to apply in systems. Therefore, the theory of participatory service in bandwidth allocation is a first step to realize a user-based allocation policy. Next section shows a short discussion on a general model and some examples in the allocation policy.

5.2 General Model

A specific unit, i.e., *point*, can be used in the participatory service for communication among users. The participatory service will be based on system conditions such as the number of users and the total bandwidth to determine the relationship between *point* and allocated bandwidth. For example, when there are many people who can share their bandwidth, users can obtain more bandwidth with fewer points. In contrast, users may have to pay many points to increase their bandwidth when some people who are willing to give their bandwidth to others exit.

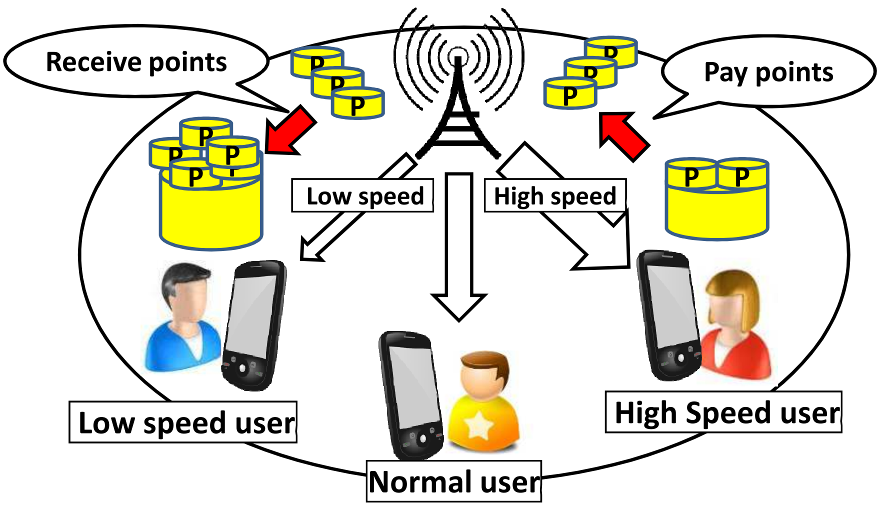


Figure 5.1: The concept of the participatory service.

Figure 5.1 shows an overview of the participatory framework. Therefore, users can be categorized in three groups such as low speed, normal, and high speed users. In general, the service acts as follows:

- At the start of process, all users are allocated the same bandwidth as in the fair QoS method.
- Some users wish to use higher bandwidth resource amount than normal $\Longrightarrow$ pay some points to obtain the benefit $\Longrightarrow$ increase their bandwidth.

- Some users can accept a lower bandwidth amount than normal $\Longrightarrow$ receive some points to give the resource $\Longrightarrow$ decrease their bandwidth.

Depending on the specific network conditions, the mapping or exchanging between points and allocated bandwidth is decided. For example, the policy based on time to decide can act as follows. If some users want to use high speed, they have to pay some points corresponding with the period of time such as 1 or 2 minutes. In addition, if some users are available to share their bandwidth resource, the received points are calculated based on their contributing period. Another policy can be used based on the speed. It means that if users want to improve their speed, i.e., 100kbps, they have to pay some points.

In addition, if there are many users want to use high speed mode, another problem occurs: how to decide which users can be improved. In a real system, there are some feasible solutions such as lottery (users are randomly chosen), first come first serve (users who send earlier requests will be served first), or auction (users who can pay higher points will be served).

The participatory service allows users to select their modes whether they use the service or not. If they do not use the service, the bandwidth will be allocated as in the fair QoS method. In contrast, they can obtain the benefit when they want to acquire more bandwidth resources. The service is still under studying period. Therefore, I continue to study the framework of such kind of services in the future, and I believe that it is feasible to apply it in real systems.

5.3 Conclusion

This chapter proposed a theory of the participatory service in the bandwidth allocation. The service allows network providers and network planning to collect information about users' requirements. From the obtained information, the bandwidth allocation policy can be applied to distribute the suitable bandwidth resource amount to users. The theory promises the benefit for both users and network providers when users can be satisfied with the service quality while the network resource is optimized. However, several future challenges remain. To realize the proposed scheme, more investigation in both users' behavior and system design are required. Furthermore, the investigation of the policy when calculating the bandwidth should be also taken into account.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

In the dissertation, I proposed two flexible resource allocation solutions, which allocate the bandwidth based on the network conditions (the total bandwidth and the total number of users) and users' conditions (users' situations). Compared with the fair QoS method, the proposed methods are briefly summed up as follows:

- The fair QoE method guarantees completely fair satisfaction to users.
- The hybrid method maintains a similar QoE among users and similar average QoE to that of the fair QoS method.

Depending on each case study with specific network and users' conditions, the proposed methods can achieve various improvements. Therefore, the dissatisfied users (pressured users) can always obtain benefit from the proposed methods because their satisfaction level is always improved. If many users can share their bandwidth, the pressured users can significantly improve their experience. In contrast, when many users wish to improve the bandwidth but only few users can contribute the network resource, the QoE of the pressured users can improve slightly. In the hybrid method, the normal users play a role as a threshold for others and do not contribute the bandwidth resource. The negotiation is done only between the relaxed and pressured users. In the method, the gains are distributed among the pressured users. The fair QoE method, however, is a little different. The normal users sometimes improve their QoE, and sometimes contribute their network resource depending on situations. Consequently, while the gains are always distributed to the pressured users, the normal users also in some cases obtain benefit in the method.

Based on the numerical results obtained with three bandwidth allocation methods in various case studies, I conclude that the proposed methods successfully improve the QoE of the dissatisfied users while relocating the network resources that are to be allocated to the satiated users. Therefore, I believe that it is possible to implement the bandwidth allocation method based on not only the technical metrics of the network resources but also the users' situations and satisfaction.

The proposed allocation methods are studied in the case where users are in different situations in the system. Some users are satisfied while some users are not satisfied with the service quality. This means that users' expectations of service quality are different. As a result, their levels of QoE are different even in the same network resource environment because of psychological effects. In these case studies, considering the bandwidth allocation method based on the users' situations is essential, and the proposed methods can achieve significant improvement for users. In contrast, if all users are satisfied with the service quality or are in the same situation, then the fair QoS method is simple and valuable.

The dissertation proposed two different resource allocation methods based on users' situations, considering QoE to solve the problem in the previous method: Users can experience different levels of QoE, even for the same bandwidth resource amounts. The proposed methods compute the allocated bandwidth with the understanding that the levels of satisfaction for users should be the same or similar among users. Compared with the conventional fair QoS method, the proposed methods can improve the QoE for the dissatisfied users while keeping good levels of experience for the others. The fair QoE method guarantees a completely fair user satisfaction. The hybrid method, meanwhile, decreases the difference in the average QoE compared with the fair QoE method. Moreover, this method successfully allocates closer levels of QoE to users compared with the fair QoS method. The hybrid method can be used as a trade-off solution between the viewpoints of the fair QoS and the fair QoE. In fact, a win-no lose solution, which can allocate the real fair quality to users and improve the average QoE of users, is difficult to achieve in reality. I believe that the hybrid method will give a good solution because it can combine the advantages and decrease the limitations of the previous studies.

6.2 Future Work

The proposed methods in the dissertation are based on users' psychological factors to categorize users into groups. It is easy to extend for another kind of classification depending on the real applications and services. To apply the proposed scheme, it is necessary to know the following two main factors:

- The statistics of users' behavior or characteristics to classify users into groups.
- The utility functions that show the relationship between the allocated bandwidth and users' satisfaction level.

Based on the above information, it is possible to apply the methodology in the proposed methods in the different network environments with various kind of services.

However, there remain several challenges that motivate the further study. In the future, I will continue to study the user-centric bandwidth allocation, which is closer to a win-no lose approach. Moreover, I am going to investigate the framework of the participatory services and to implement the proposed methods in a real system. The direction of future work is briefly outlined as follows:

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, I 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 situation. 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 and irritation from users. Future works also study to find a solution for this problem, which will be invisible with users.

Secondly, the investigation of the different services when applying the proposed methods should be also carefully taken into account. In the dissertation, I only focus on the web-based services, i.e., Yahoo news and Google news [12, 13] and it is assumed that all users access the same service. Therefore, it is necessary to consider the situation when users use the different services at the same time because it is close to the real situation. In addition, it is also vital to expand the proposed methods for other multimedia services with audio and video.

Besides, considering only the waiting time is not enough for measuring the performance of the applications as well as the bandwidth functions. In the future, many other metrics should be taken into account such as processing delay, propagation delay, delay at base stations, queuing delay, processing delay, etc. Although the bandwidth directly relates and significantly affects to QoE, it is necessary to consider other factors. Future work will investigate the delay model to find a real relationship between the allocated bandwidth and waiting time as well as the relationship between the QoE and the allocated bandwidth.

Finally, since the accuracy of the proposed methods depends on the users' classification and understanding of users' behavior, psychological study is also essentially required to complete the user-centric approach in the future.

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