A Practical Scheme to Improve User Satisfaction with Reduced Power in Wireless Networks

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Abstract—**Most known DSA(Dynamic Spectrum Access) methods in wireless network aim at enhancing the total system utility. As such, spectrum wastage may arise when the system-wise optimal allocation falls outside the desired region for QoS provisioning. The goal of this paper is to develop QoS-aware distributed DSA schemes using a game-theoretic approach. We devise a DSA solution which provides QoS level within preset range to as many users as possible. For this, we define it as a price for QoS level to escape beyond the preset range. Our scheme increases the number of satisfied users by 30% while reducing power consumption by 11%, compared with a state-of-the-art algorithm which is developed for maximum system utility.**

Keywords-power control, cognitive radio, ADP algorithm, Quality of service, DSA

I. INTRODUCTION

The Dynamic spectrum allocation is proposed for re-using frequencies and managing resources in wireless networks [1]-[2]. Equipped with cognitive radios, users in a network can check and utilize available spectrum opportunistically [1]. The spectrum utilized by users requires trade-off between avoiding interference and resources efficiency. The trade-off and managing resources are complicated, so efficient strategy is necessary.

From an information-theoretic viewpoint, the utility of a radio for each user depends on the received SINR(Signal to Interference and Noise Ratio). In a network system, each user decides on its transmission power and bandwidth based on the radio environment. Its decision affects SINR of all users in a network. Thus, radio resource allocation is an interactive decision making process, which can be modeled as a multi-player game.

The game theoretic approach has been proposed for distributed DSA problem [3]-[8]. A variety of game-theoretic approaches have been applied to network resource allocation, as surveyed in [8]. N.Nie et al[4] propose a game theoretic formulation of the adaptive channel allocation problem for cognitive radios. Single and multi channel asynchronous distributed pricing that consider user's interference price during spectrum sharing are shown to outperform disregarding interference prices [5]-[7]. Other tools such as the genetic algorithm have also been investigated for the DSA problem.

Most existing DSA methods aim at increasing the network efficiency, defining the figure of merit to be the total system utility achieved by all users. Due to this purpose of DSA, wireless resources are distributed unfairly by spectrum efficiency. In addition, wastage of wireless resources is caused by the unfair distribution

To address this unfairness and waste of resource propose a distributed DSA solution which provides QoS level within preset range to as many users as possible. For this, we define it as a price for QoS level to escape beyond the preset range. Our scheme increases the number of satisfied users by 30% while reducing power consumption by 11%, compared with the approach in [5] which is developed for maximum system utility.

In section II, system modeling to obtain network benefit with exploiting user's utility is explained. By considering interference, we obtain network benefit in section III. We suggest the solution to obtain network benefit with considering interference and QoS in section IV. In section V, we evaluate the performance and verify the decreasing meaningless power and increasing the number of users that meet the QoS range. Finally, we draw conclusion in section VI.

II. SYSTEM MODEL

System modeling through [6] and [9] for user's utility is described as following. The cognitive radio networks we consider consist of a set of spectrum agile users $\mathrm{N} = \{1, \cdots, N\}$ that seek to share a set of $\mathrm{K} = \{1, \cdots, K\}$ available orthogonal channels. The transmission power of each user is restricted within the range $[P_{i,\min}, P_{i\max}]$, which is determined by the radio design of the transmitter. Each user corresponds to a dedicated pair of transmitting and receiving nodes. Each transmitter of user i T_i , $1 \le i \le N$, communicate with only one receiver R_i. Each transmission interferes to other receivers using the same channel. The distance between transmitter of user i and receiver of user j is represented by d_{ij}.

The value of the transmission by user i is characterized by utility function $u_{tot-i}(\mathbf{p})$, which is the function of the received

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SINR. The equation of SINR received by user i on channel k is given by

$$\gamma_i^k\left(\mathbf{p}^k\right)=\frac{p_i^k \times h_{ii}}{n_0+\sum_{j\neq i} p_j^k \times h_{ji}} \tag{1}$$

, where n_0 is the background noise power and h_{ij} is the link gain between T_i and R_i determined by the distance d_{ij}. User i allocates power p_i^k for transmission over channel k, while $p_i^j=0$ means that channel j is not selected. $\mathbf{p}=\langle \mathbf{p}_1,\mathbf{p}_2,\cdots,\mathbf{p}_N\rangle$ is the vector of the user's transmission powers. Power used for channel k is defined as $\mathbf{p}^k=\langle p_1^k,p_2^k,\cdots,p_N^k\rangle$. In this game, $\mathbf{p}_i=\langle p_i^1,p_i^2,\cdots,p_i^k\rangle$, is the vector of the user's transmission power across all channels. The user i's opponents is defined to be $\mathbf{p}_{-i}=\langle \mathbf{p}_1,\cdots,\mathbf{p}_{i-1},\mathbf{p}_{i+1},\cdots,\mathbf{p}_N\rangle$, so that $\mathbf{p}=(\mathbf{p}_i,\mathbf{p}_{-i})$.

We assume that the background noise level is the same on all channels, and the link gains are static within the transmission period. For each user using the Shannon capacity, we could adopt the total channel capacity gained by this user as its utility function, given by

$$u_{tot-i}(\mathbf{p})=C_i(\mathbf{p})=\sum_{k\in K}\log(1+\gamma_i^k(\mathbf{p}^k)),\quad i=1,\ldots,N. \tag{2}$$

In case of the single channel allocation, we denote $\varphi(i)$ as the channel selection of user i and utility function is

$$u_{tot-i}(\mathbf{p})=\log(1+\gamma_i^{\varphi(i)}(\mathbf{p}^{\varphi(i)})). \tag{3}$$

From a network perspective, the objective is to determine p that maximizes the total utility summed over all users.

$$\max_{\{\mathbf{p}\}} u_{tot}(\mathbf{p})=\sum_{i=1}^{N} u_{tot-i}(\mathbf{p}). \tag{4}$$

This is a centralized non-convex optimization problem subject to scalability issues. Now, we turn to the game theoretic approach to design simple distributed DSA algorithms.

III. Previous Approaches

Our solutions to QoS-aware DSA build upon the single-channel and multi-channel asynchronous distributed pricing algorithms SC-ADP and MC-ADP introduced in [6], [7]. In game-based DSA, each user strives to maximize its own local utility defined (1) or (2). In order to maximize the utility of system network, we increase the user's utility by raising user's power. While power is raised for user's utility, other neighboring users' utility is decreased by interference such as shown in Fig. 1. Thus, we can say that there is a trade-off between raise of user's utility and drop of other neighboring users' utility. We use interference price which is defined by Huang et al.[5] to consider interference that affects the neighboring users.

$$\pi_i^k=\left|\frac{\partial u_{tot-i}^k\left(\gamma_i^k\left(\mathbf{p}^k\right)\right)}{\partial \sum_{j\neq i} p_j^k \times h_{ji}}\right| \tag{5}$$

Each user collects the information of neighboring users through interference prices and chooses channels and allocates power to maximize network benefit, which is defined to subtract interference prices from the surplus of utility such as expressed in (6).

$$u_{sur-i}(\mathbf{p}_i,\mathbf{p}_{-i})=\sum_{i=1}^{N}\left(u_{tot-i}(\mathbf{p}_i,\mathbf{p}_{-i})-\sum_{k\in K}\left(p_i^k\times\sum_{j\neq i}\pi_j^k h_{ij}\right)\right) \tag{6}$$

We determine power which optimizes the network utility through (6), then, inform the updated interference price to neighbor. In this repetitive process, user chooses the power which becomes steady state.

IV. Proposed Scheme

Wireless networks call for ubiquitous access from heterogeneous users. User sharing the network resources may have application-specific QoS requirements, which translate into a set of user-specific predefined ranges of the desired utilities $R_i:[R_{i,\min},R_{i,\max}]$. Here $R_{i,\min}$ is the minimum utility required for user i to have a successful transmission, while $R_{i,\max}$ is the maximum utility for user i to support its application.

Most exist DSA methods which maximizes the network benefit through the value of utility has a problem which causes

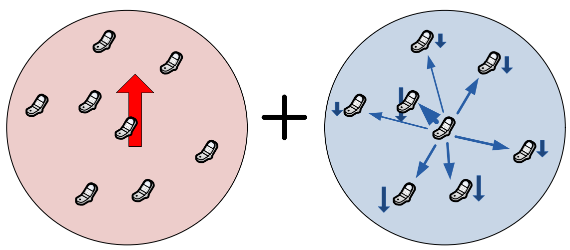

Fig 1. The increase and decrease of network benefit with SC/MC ADP algorithm.

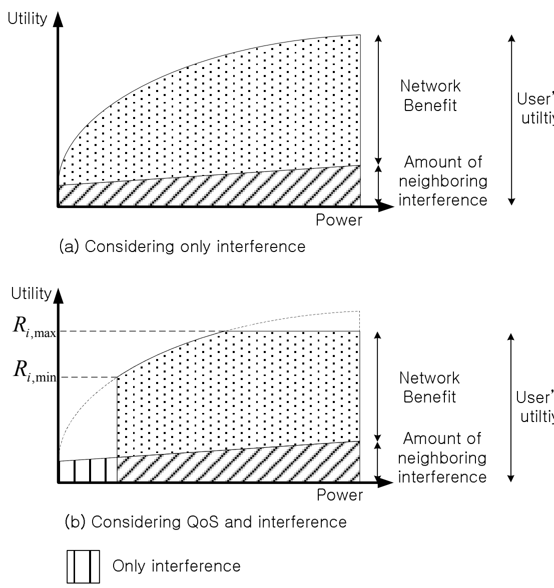

Fig 2. Comparison of network utility by user's power.

interference to neighbor users. This problem is solved by maximizing the network benefit through the interference price in ADP with considering interference which affects neighbor users such as shown in Fig 2 (a). However, ADP algorithm without considering QoS causes two problems. Now, let us solve this problem through Fig 2 (b).

First, some users decrease their utility to reduce the interference which affects other users. When the utility cannot meet $R_{i,\min}$ of its application, a transmission failure arises.

Another problem is that some users increase their utility to gain more than $R_{i,\max}$. The extra utility doesn't gain any contribution to the performance, but increases Neighboring interference. Neighboring interference means the interference given to neighboring users due to one user's power.

In order to solve these problems, DSA scheme is proposed with considering QoS. With exploiting interference suppression, only user's utility is considered without interference which affects other users in [9].

However, if we exploit interference suppression, interference which affects to other users and affects to myself should be excluded. In addition, there is a problem that SINR which includes the interference by equation (1), (2), (3) is exploited in [9]. In order to solve these problems, we propose the following equation which considers QoS and other users.

$$u_{pro-i}(\mathbf{p}_i,\mathbf{p}_{-i}) = \sum_{i=1}^{N}\Big(u_{tot-i}(\mathbf{p}_i,\mathbf{p}_{-i}) - \sum_{k\in K}\Big(p_i^k \times \sum_{j\neq i}\pi_j^k h_{ij}\Big) - \left(u_{tot-i}(\mathbf{p}_i,\mathbf{p}_{-i}) - R_{i,\max},0\right)^{+} - \left(\frac{R_{i,\min}}{u_{tot-i}(\mathbf{p}_i,\mathbf{p}_{-i})}-1\right)^{-1}\left(R_{i,\min} - u_{tot-i}(\mathbf{p}_i,\mathbf{p}_{-i}),0\right)^{+}\Big). \quad (7)$$

Let us divide into two cases which exceeds the $R_{i,\max}$ and less than $R_{i,\min}$.

[Case1] $u_{tot-i}(\mathbf{p}_i,\mathbf{p}_{-i}) > R_{i,\max}$

In this case, we put $\mathbf{p}'$ as the power that meets utility, $R_{i,\max}$.

$$\mathbf{p}_i' < \mathbf{p}_i$$

$$\begin{aligned} u_{pro-i}(\mathbf{p}_i,\mathbf{p}_{-i}) &= \sum_{i=1}^{N}\Big(u_{tot-i}(\mathbf{p}_i,\mathbf{p}_{-i}) - \sum_{k\in K}\Big(p_i^k \times \sum_{j\neq i}\pi_j^k h_{ij}\Big) - \left(u_{tot-i}(\mathbf{p}_i,\mathbf{p}_{-i}) - R_{i,\max},0\right)^{+}\Big) \\ &= u_{pro-i}(\mathbf{p}_i',\mathbf{p}_{-i}') - \alpha \qquad (\alpha > 0) \end{aligned} \quad (8)$$

$$u_{tot-i}(\mathbf{p}_i',\mathbf{p}_{-i}') = u_{tot-i}(\mathbf{p}_i,\mathbf{p}_{-i}) - \left(u_{tot-i}(\mathbf{p}_i,\mathbf{p}_{-i}) - R_{i,\max},0\right)^{+} \quad (9)$$

$$\alpha = \sum_{k\in K}\Big(p_i^k \times \sum_{j\neq i}\pi_j^k h_{ij}\Big) - \sum_{k\in K}\Big(\big(p_i^k\big)' \times \sum_{j\neq i}\big(\pi_j^k\big)' h_{ij}\Big) \quad (10)$$

When power of user is higher than $\mathbf{p}'$ in ADP algorithm considering interference, user gets higher utility than $R_{i,\max}$ such as shown in Fig 3(a). In Fig 3(b) and (8), we keep value of utility from exceeding $R_{i,\max}$ which is the maximum value of user's utility due to power increment and the value of utility which exceeds this is meaningless.

$R_{i,\max}$ is the maximum utility for user i to support its application, so that it can eliminate the extra power in (9). By

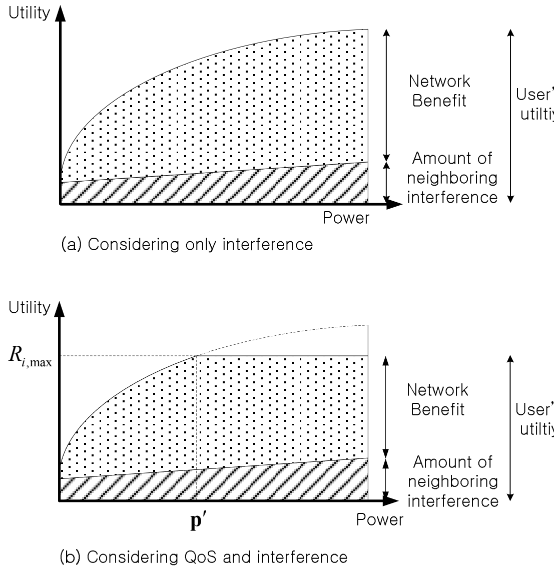

Fig 3. Case 1: Comparison of network utility by user's power.

increased power, neighboring interference becomes severe and efficiency of network becomes worse

Hence, if the value of user's utility exceeds $R_{i,\max}$ through the proposed equation, minus weight will be given. We keep value of user's utility which is increased due to minus weight from exceeding the $R_{i,\max}$.

Therefore, the proposed value of user's utility is limited up to $R_{i,\max}$ in (7), and the range of power is limited, either. We, therefore, decrease the interference and wastage of meaningless power. $R_{i,\max}$ is the maximum utility for user i to support its application, so that it can eliminate the extra power in (9). By increased power, neighboring interference becomes severe and efficiency of network becomes worse

Hence, if the value of user's utility exceeds $R_{i,\max}$ through the proposed equation, minus weight will be given. We keep value of user's utility which is increased due to minus weight from exceeding the $R_{i,\max}$. Therefore, the proposed value of user's utility is limited up to c in (7), and the range of power is limited, either. We, therefore, decrease the interference and wastage of meaningless power.

[Case2] $u_{tot-i}(\mathbf{p}_i,\mathbf{p}_{-i}) < R_{i,\min}$

In ADP algorithm, power which maximizes the network benefit is selected even though user's utility is less than $R_{i,\min}$. When user's utility is less than $R_{i,\min}$, transmission failure arises. Neighbors, however, are received interference by user's power. Thus, actual network benefit by the user's power becomes minus. In order to resolve this problem, we propose (7). According to our proposed algorithm through (7), user's utility becomes (11) and (12) when user's utility is less than $R_{i,\min}$.

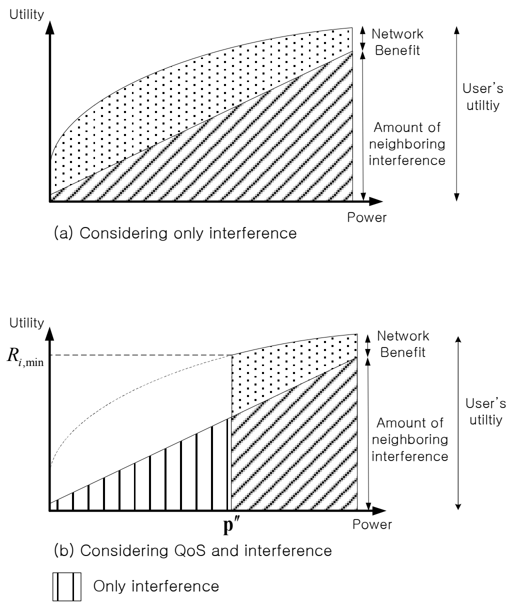

Fig4. Case 2: Comparison of network utility by user's power.

$$u_{pro-i}(\mathbf{p}_i,\mathbf{p}_{-i}) = \sum_{i=1}^{N}\Big(u_{tot-i}(\mathbf{p}_i,\mathbf{p}_{-i}) - \sum_{k\in K}\Big(p_i^k \times \sum_{j\neq i}\pi_j^k h_{ij}\Big) - \left(\frac{R_{i,\min}}{u_{tot-i}(\mathbf{p}_i,\mathbf{p}_{-i})}-1\right)^{-1}\big(R_{i,\min}-u_{tot-i}(\mathbf{p}_i,\mathbf{p}_{-i}),0\big)^{+}\Big) \quad (11).$$

$$u_{pro-i}(\mathbf{p}_i,\mathbf{p}_{-i}) = \sum_{i=1}^{N}\Big(u_{tot-i}(\mathbf{p}_i,\mathbf{p}_{-i}) - \sum_{k\in K}\Big(p_i^k \times \sum_{j\neq i}\pi_j^k h_{ij}\Big) - u_{tot-i}(\mathbf{p}_i,\mathbf{p}_{-i})\Big) \quad (12).$$

In our proposed algorithm through (11) and (12), we can verify that only neighboring interference is left when user's utility is less than $R_{i,\min}$. Let us denote that $\mathbf{p}''$ is the user's power when utility is $R_{i,\min}$. Through our proposed algorithm, user controls the power over $\mathbf{p}''$, then, meets the QoS.

V. SIMULATION RESULTS

In this section, we present some numerical results to illustrate the performance of QoS-aware DSA solution, with reference to ADP algorithms that are QoS-blind[6], [7]. In all tests, we set $n_0 = 10^{-2}$, $h_{ij} = d_{ij}^{-4}$, and the range of power for each user is $[P_{i\min}, P_{i\max}] = [10,200]$. The number of K channels are available and each has the same bandwidth. 100 transmitter are uniformly distributed within a 20m × 20m square area. The 30 corresponding receivers are randomly distributed within a 2m × 2m square area centered at their dedicated transmitters. Based on the network setup in our simulations and with reference to (2), we define the numerical QoS bounds for three types of network applications:

Web browsing : [0.5,0.6]
Stream audio : [0.6,0.8]
Stream video : [0.8,1.2]

30 users who use the same channel will be selected randomly, then simulation is processed. The result is followed as below.

In Fig.5, QoS is not considered and average of user's utility indicates 1.092 in a ADP algorithm which is object to maximize the network benefit. However, in the propose algorithm which considers QoS, when QoS requirements indicate [0.8, 1.2], which means between 0.8 and 1.2, average of user's utility is decreased by 10%. When QoS reqirement indicates [0.6, 0.8] and [0.5, 0.6], the average of user's utility is decreased by 28% and 42%, respectively. This reduction of utility is considered by user's requirement. Fig. 6 shows reduced waste of meaningless power by decreased QoS.

In Fig. 6, average power is decreased by 14%, 46% and 65% when QoS requirement indicates [0.8, 1.2], [0.6, 0.8] and [0.5, 0.6] , respectively. In Fig. 5, user's standard deviation indicates 0.44 when QoS is not considered. When QoS is considered, standard deviation indicates 0.24, 0.12 and 0.14 when QoS requirement indicate [0.8, 1.2], [0.6, 0.8] and [0.5, 0.6], respectively. Compared with the case which considers QoS, value of user's utility is concentrated within QoS requirement when considering QoS such as shown in Fig 7.

Fig 7. shows the comparison between case of considering QoS and case of not considering. We can verify that multi-user decreases or increases their own utility in order to meet the QoS requirement. Decreased utility reduces the wastage of meaningless power and interference. In addition, increased utility decreases the number of users who suffer transmission failure. Through this process, the number of users with QoS requirement increases such as shown in Fig. 8.

Fairness experiment is conducted by Shannon Evenness index E_H [10]. According to the requirement of the QoS increases, fairness is declined in Fig.9. This is because the users whose efficiency is 0 are increased by the transmission failure. We solve the problem by the proposed scheme with reducing the transmission failure and increasing fairness of network.

VI. CONCLUSION

In this paper, we present distributed DSA scheme with considering QoS. By game theoretic method, optimized power is chosen with meeting the user's QoS as a main purpose and reducing the interference that affects others as a secondary purpose. Considering QoS, we drop the power when it is above QoS requirement, we raise when it is below QoS requirement. In this process, we reduce the wastage of meaningless power and the number of users who suffer transmission failure by the lack of QoS requirement. By decreasing this power, interference is reduced either. When both objectives are optimized, the proposed schemes yield good performance in terms of both total network useful utility and interference suppression. Simulations confirm the effectiveness of our proposed schemes in efficiently sharing spectrum along with QoS provisioning.

VII. ACKNOWLEDGEMENT

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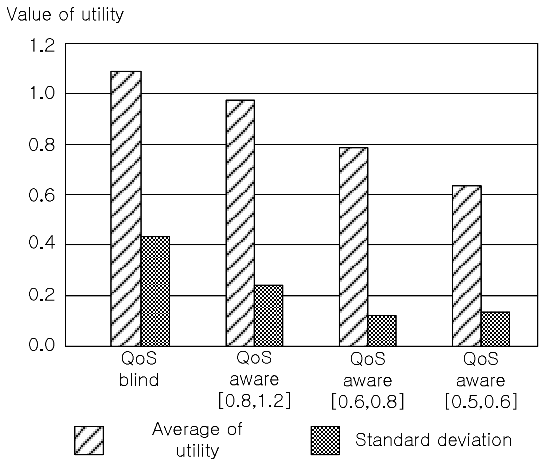

Fig 5. Average of utility and standard deviation.

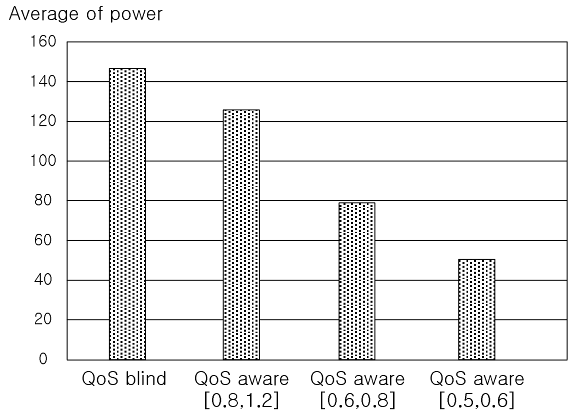

Fig 6. Average of power.

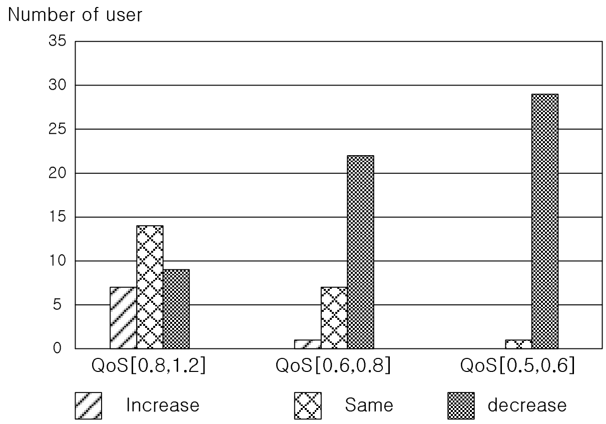

Fig 7. The number of users who has a changed value of utility.

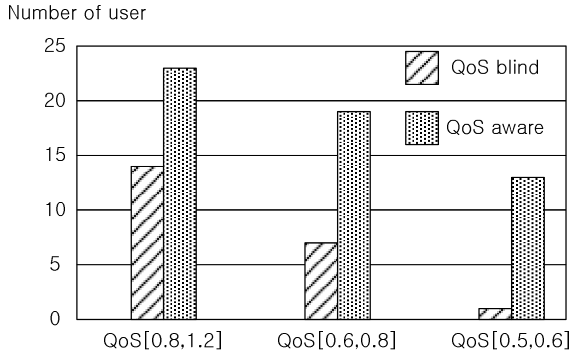

Fig 8. Number of users who meet QoS.

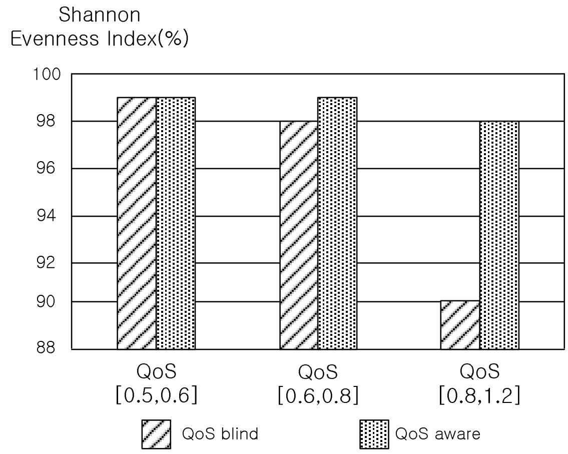

Fig 9. Comparison of fairness

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