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Co-opetition Strategy for Collaborative Multiuser Multimedia Resource Allocation

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***Abstract*—This paper focuses on using the mindset of co-opetition for collaborative multimedia resource allocation. The co-opetition suggests a judicious mixture of competition and cooperation. We present a novel co-opetition strategy based on the Kalai-Smorodinsky Bargaining Solution (KSBS), and apply it to video rate allocation. The proposed strategy makes satisfied users stop competing for resources such that QoS of unsatisfied users can be improved. Our strategy is evaluated through comparing to existing competition-based strategies. Numerical results indicate that, the co-opetition strategy can result in an improved number of satisfied users. Algorithm with low complexity is also presented.**

***Index Terms*—Co-opetition, KSBS, collaborative multimedia, resource allocation.**

I. Introduction

Multiuser resource allocation has long been an important topic of research. As emergences of many novel multimedia services, it again attracts much attention of research.

In previous research, fairness criterion was always employed to allocate resources among multiple users. For instance, RSVP allocates resources based on multimedia services' traffic specifications (TSPECs) [1]. However, the fairness does not consider the resulting impact on the multimedia QoS. So they are unsuitable for content-aware multimedia transmissions.

To address above limitation, game theory has been introduced into resource allocation in communications. As opposed to conventional mechanisms which operate in resource domain, game theory allows to allocate resources in utility domain. As thus, the utility function can be used to built a bridge between resources and QoS. In [2], the Nash Bargaining Solution (NBS) and the KSBS are respectively applied to video rate allocation. The mindset of co-opetition is a new but successful concept from economic area [3]. It introduces a judicious mixture of competition and cooperation in social resource allocation. Similarly, co-opetition can also be applied to communication resource allocation. [4] employs co-opetition for decentralized resource allocation over spectrum agile networks. However so far, no literature could be found out that applies the co-opetition to collaborative resource allocation.

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This paper presents a novel co-opetition strategy for collaborative multiuser multimedia resource allocation. Since co-opetition is the combination of competition and cooperation, we need to choose a criterion, under which users compete for resources. Several criteria are available, such as Sum Utility Maximization (SUM)[1], the KSBS. In this paper, we choose the KSBS as the fairness criterion. The justification of the choice will be illustrated later. During the competition, users whose QoS requirements have been satisfied, could temporarily stop competing, such that those unsatisfied users can be improved in QoS. In the sense of stopping competing, users also work cooperatively, and as thus they work in the way of co-opetition.

The novelty of this paper lies in the fact that we employ the co-opetition for communication resource allocation and construct it based on the KSBS. The KSBS is quite suitable to multimedia resource allocation, as it allows users to achieve the same percentage of their maximum utilities achievable. Also, unlike other competition criteria (e.g., SUM), the KSBS has a simple mathematical formulation. Thus it is very easy for us to construct the co-opetition strategy. Moreover, the algorithms in previous research also apply to the construction of co-opetition [2]. However it is worth to mention that, although the KSBS has been used in previous research, they use the KSBS simply as a competition fairness. In this paper, the KSBS is used as one component of co-opetition strategy.

Rest of the paper is organized as follows. In Section II, we review the competition strategy. In Section III, we describe the proposed co-opetition strategy. In Section IV, we apply the co-opetition strategy to video rate allocation. Conclusion is drawn in Section V.

II. Competition Criterion: KSBS

In this section, we briefly review the basic definition about the KSBS and show how it can be used for users to compete.

Denote N as the number of users, $R_{\max}$ as the maximum resources available. Monotonically increasing function, $U_n(r_n), r_n \geq r_{0n}$, represents user n's utility function. Here, r_{0n} is the minimum resource required by user n, i.e., $U_n(r_{0n}) = 0$. Therefore, each user can achieve non-negative utility with $r_n \geq r_{0n}$. We also assume the maximum resource

[1]The SUM can be viewed as a process, in which users compete based on the marginal utility. Larger marginal utility leads to more resource.

is much larger than the sum of minimum resources required by all users, i.e., $R_{\max} \gg \sum_{n=1}^{N} r_{0n}$. Thus, resources available to be allocated, denoted with R_{av}, writes

$$R_{\text{av}} = R_{\max} - \sum_{n=1}^{N} r_{0n}. \quad (1)$$

If allocate R_{av} to a single user, say user n, we obtain the maximum utility achievable, denoted with $U_{\max,n}$, i.e.,

$$U_{\max,n} = U_n(r_{0n} + R_{\text{av}}). \quad (2)$$

Then the KSBS allocates resources such that

$$\sum_{n=1}^{N} r_n^* = R_{\text{av}}, \quad (3)$$

and

$$\frac{U_1^*}{U_{\max,1}} = \cdots = \frac{U_N^*}{U_{\max,N}} \quad (4)$$

where $U_n^* = U_n(r_{0n} + r_n^*)$ denotes the utility of user n and $(r_{0n} + r_n^*)$ denotes corresponding resource allocated to it. Similarly as the definition in economic area [5], we call

$$\mathbf{U}_0 = \big(U_1(r_{01}), \cdots, U_N(r_{0N})\big), \quad (5)$$

$$\mathbf{U}_{\max} = (U_{\max,1}, \cdots, U_{\max,N}), \quad (6)$$

$$\mathbf{U}^* = (U_1^*, \cdots, U_N^*), \quad (7)$$

disagreement point, ideal point and solution point, respectively.

Equation (3) means that, at the solution point, all resource is allocated. In other words, at this point, no user could improve its utility without penalizing the others. All utility combinations that satisfy (3) form the utility boundary, denoted with $\mathbf{B}$, i.e.,

$$\mathbf{B} = \left\{ \big(U_1(r_1), \cdots, (U_N(r_N)\big) \middle| \sum_{n=1}^{N} r_n = R_{\max}, r_n \geq r_{0n}, \forall n \right\}. \quad (8)$$

Equation (4) means that, at the solution point, all users achieve the same percentage of their maximum utilities. Thus, resource allocation using the KSBS can be viewed as a process, in which users compete for resources based on their maximum utilities.

Resource allocation using the KSBS is illustrated in Fig. 1 in the case of two users. We observe that the solution point $\mathbf{U}^*$ is namely the intersection of the utility boundary $\mathbf{B}$ and the line connecting disagreement point $\mathbf{U}_0$ and ideal point $\mathbf{U}_{\max}$.

III. Co-opetition Strategy

In this section, we describe how to construct the co-opetition strategy using KSBS. Complexity of the proposed strategy is also analyzed.

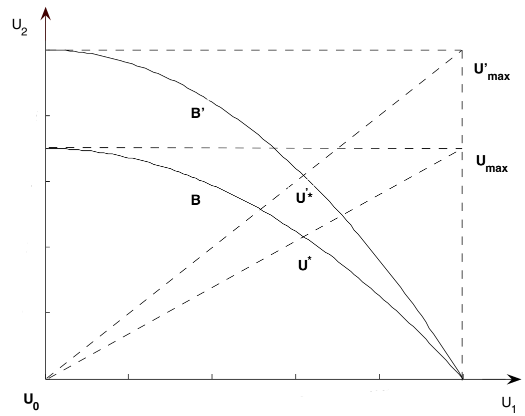


Fig. 1. A simple illustration of the resource allocation using the KSBS in the case of two users. Keeping user 1's utility function unchanged, user 2's utility at solution point is improved (from $\mathbf{U}^*$ to $\mathbf{U}'^*$) by strengthening its competition ability (from $U_{\max}$ to $U'_{\max}$).

A. Construction of the Co-opetition Strategy

As mentioned in Section I, satisfied users stop competing for resources in co-opetition strategy. Therefore, we first need to distinguish satisfied and unsatisfied users. Set a threshold of utility, denoted with U_{t}, such that if user's utility is above or equal to the threshold, we call it satisfied user, and unsatisfied user otherwise[2]. Taking video services as example, U_{t} can be set such that the Peak Signal-to-Noise Ratio (PSNR) equals 35 dB corresponding to good video quality.

Denote the number of satisfied users with N_{s}, then one of following three cases always happens in resource allocation.

1) $N_{\text{s}} = 0$. In this case, no user needs to stop competing, and the co-opetition reduces to absolute competition strategy.
2) $N_{\text{s}} = N$. This implies that the total resource $R_{\max}$ is able to satisfy all users. Denote the resource required by user n to reach U_{t} with $r_{\text{t}n}$, then the co-opetition strategy simply needs to allocate $r_{\text{t}n}$ to user n. Again it reduces to a competition strategy, in which N users compete for remains of resources.
3) $1 \leq N_{\text{s}} < N$. Part of N users can be satisfied in this case. Assume the satisfied users are known, and denote the set of all users and the set of satisfied users with $\mathcal{N}, \mathcal{S}$, respectively. Then the co-opetition strategy can first allocate $r_{\text{t}n}$ to user $n \in \mathcal{S}$, then make users in $\mathcal{N}/\mathcal{S}$ compete for remains of resources.

we observe that in above three cases, the most important thing is to determine how many and which users can be satisfied through co-opetition. Recall that the KSBS is employed as the competition criterion. Following observation results in an efficient way to know which users can be satisfied.

Observation 1: Two users compete based on the KSBS, say user n, m. Their maximum utilities achievable are denoted

[2]In this paper, we focus on same services. In the case of homogeneous services, users might have different utility functions and thresholds.

with $U_{\max,n}, U_{\max,m}$, respectively. If $U_{\max,n} > U_{\max,m}$, then user n is easier to achieve U_{t} than user m.

This observation can be interpreted as follows. Set the value of each fraction in (4) to be k and replace U_n^* with U_n, then we have

$$U_n = kU_{\max,n}, \forall n. \tag{9}$$

There exists $k = k^*$ corresponding to $\mathbf{U}^*$, i.e., all resources are allocated, and $k = 0$ corresponding to that no user achieves improvement of utility. As k increases from 0 to k^*, each user's utility increases at speed of $U_{\max,n}$ for user n. Thus, the larger the $U_{\max,n}$ is, the easier for user n to achieve U_{t}.

Based on above observation, we propose following method to determine satisfied users.

First, reorder N users in decreasing order of $U_{\max,n}$. Denote the utilities of reordered users as $U_{(1)}, \cdots, U_{(N)}$, where $(\cdot)$ maps new indices to original users such that,

$$U_{\max(n)} > U_{\max(m)}, \text{ if } m > n. \tag{10}$$

Assume $1 \le N_{\mathrm{s}} < N$. From Observation 1, the N_{s} satisfied users are user $(1), \cdots, (N_{\mathrm{s}})$, and they can achieve the same utility of U_{t}. Other users are unsatisfied, their utilities can be computed according to (4), e.g., for user $(m), m \in \{N_{\mathrm{s}} + 1, \cdots, N\}$,

$$U_{(m)} = \frac{U_{\max(m)}}{U_{\max(N_{\mathrm{s}})}} U_{\mathrm{t}}. \tag{11}$$

Denote respectively resources required by N users with

$$\underbrace{r_{\mathrm{t}(1)}, \cdots, r_{\mathrm{t}(N_{\mathrm{s}})}}_{\text{satisfied}}, \underbrace{r_{(N_{\mathrm{s}}+1)}, \cdots, r_{(N)}}_{\text{unsatisfied}}, \tag{12}$$

then the sum of required resources, denoted with r_{s}, can be written as

$$r_{\mathrm{s}} = \sum_{n=1}^{N_{\mathrm{s}}} r_{\mathrm{t}(N_{\mathrm{s}})} + \sum_{n=N_{\mathrm{s}}+1}^{N} r_{(n)}. \tag{13}$$

Theorem 1: r_{s} monotonically increases as N_{s} increases.

Proof: Assume N'_{s} users can be satisfied and $N'_{\mathrm{s}} > N_{\mathrm{s}}$, then (12) can be rewritten as

$$\underbrace{r_{\mathrm{t}(1)}, \cdots, r_{\mathrm{t}(N_{\mathrm{s}})}}_{\text{satisfied}}, \underbrace{r_{\mathrm{t}(N_{\mathrm{s}}+1)}, \cdots, r_{\mathrm{t}(N'_{\mathrm{s}})}}_{\text{satisfied}}, \underbrace{r_{(N'_{\mathrm{s}}+1)}, \cdots, r_{(N)}}_{\text{unsatisfied}}. \tag{14}$$

User (m)'s utility corresponding to $r_{(m)}, m \in \{N'_{\mathrm{s}} + 1, \cdots, N\}$, denoted with $U'_{(m)}$, can be computed as

$$U'_{(m)} = \frac{U_{\max(m)}}{U_{\max(N'_{\mathrm{s}})}} U_{\mathrm{t}}. \tag{15}$$

Since $N'_{\mathrm{s}} > N_{\mathrm{s}}$, we have $U_{\max(N'_{\mathrm{s}})} < U_{\max(N_{\mathrm{s}})}$. Further, from (11) and (15), we have $U_{(m)} < U'_{(m)}$, $m \in \{N'_{\mathrm{s}} + 1, \cdots, N\}$, i.e.,

$$r_{(m)} < r'_{(m)}, m \in \{N'_{\mathrm{s}} + 1, \cdots, N\}. \tag{16}$$

Moreover, we have

$$r_{(m)} < r_{\mathrm{t}(m)}, m \in \{N_{\mathrm{s}} + 1, \cdots, N'_{\mathrm{s}}\}. \tag{17}$$

Algorithm: 1: Bisection method for determining satisfied users.

Input: lower bound $l = 0$, upper bound $u = N + 2$, $R_{\max}$.

Repeat:

1) Set $n = \lfloor \frac{l+u}{2} \rfloor$.
2) Compute $r_{\mathrm{s}}(n)$ and $r_{\mathrm{s}}(n+1)$ according to (11), (12), (13).
3) If $r_{\mathrm{s}}(n) > R_{\max}$, set $u = n$.
   If $r_{\mathrm{s}}(n+1) \le R_{\max}$, set $l = n$.

Until:

$\big(r_{\mathrm{s}}(n) \le R_{\max}$ and $r_{\mathrm{s}}(n+1) > R_{\max}\big)$ or $u = 0$.

Output: $N_{\mathrm{s}} = \min(N, n)$.

In (12) and (14), each user $(m), m \in \{1, \cdots, N_{\mathrm{s}}\}$, requires $r_{\mathrm{t}(m)}$. Thus, together with (16), (17), we have $r_{\mathrm{s}} < r'_{\mathrm{s}}$, where r'_{s} denotes the sum of all elements in (14). ■

Above theorem allows us to determine the number of satisfied users, N_{s}, by simply using the bisection method to solve

$$\begin{cases} r_{\mathrm{s}}(N_{\mathrm{s}}) \le R_{\max} \\ r_{\mathrm{s}}(N_{\mathrm{s}} + 1) > R_{\max} \end{cases}. \tag{18}$$

The method is illustrated in Algorithm 1[3]. Recall that user's utility function is assumed to be monotonically increasing. Thus it is easy to compute each resource in (12) from corresponding utility, e.g., by using the standard Newton bisection method.

So far, we have known how many and which users can be satisfied by co-opetition strategy. Corresponding to the three cases discussed aforehand in this section, the co-opetition strategy can be implemented in following steps.

1) Determine N_{s} using Algorithm 1.
2) If $N_{\mathrm{s}} = 0$, resources can be allocated by maximizing k at the constraint of total resource $R_{\max}$, such that
$$U_n = kU_{\max n}, n \in \mathcal{N}. \tag{19}$$
3) If $N_{\mathrm{s}} = N$, resources can be allocated by maximizing k at the constraint of total resource $R_{\max}$, such that
$$U_n - U_{\mathrm{t}} = kU_{\max n}, n \in \mathcal{N}. \tag{20}$$
4) If $1 \le N_{\mathrm{s}} < N$, resources can be allocated by maximizing k at the constraint of total resource $R_{\max}$, such that
$$U_n = U_{\mathrm{t}}, n \in \mathcal{S}, \tag{21}$$
and
$$U_n = kU_{\max n}, n \in \mathcal{N}/\mathcal{S}. \tag{22}$$

In (19), all users compete for resources based on their maximum utilities achievable (*competition*). In (20), all users are first guaranteed the threshold utility (*co-opetition*), and then they compete based on their maximum utilities (*competition*). (21) guarantees part of users threshold utilities (*co-opetition*), and (22) makes other users compete for resources based on their maximum utilities achievable (*competition*).

In (19), (20) and (22), maximizing k can be solved by again applying bisection method. In the method, the lower and upper

[3] For the sake of computation, we define $r_{\mathrm{s}}(0) = 0, r_{\mathrm{s}}(N+1) = R_{\max}$ and $r_{\mathrm{s}}(N+2) = +\infty$.

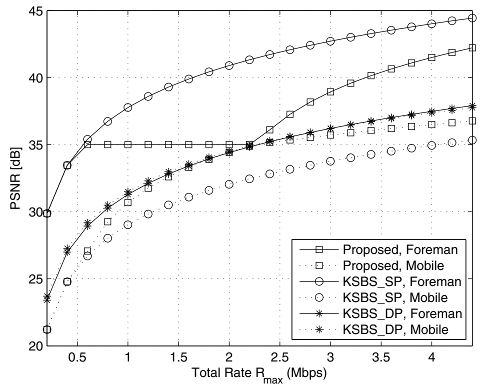


Fig. 2. Individual PSNRs achieved by Proposed, KSBS_SP and KSBS_DP. User 1: Foreman (CIF, TL=4, 30Hz), user 2: Mobile (CIF, TL=4, 30Hz)

TABLE I
TEST VIDEO SEQUENCES

ID	Video Sequence	μ	D_0	R_0
1	Foreman (CIF, TL=4, 30Hz)	5232400	0	0
2	Coastguard (CIF, TL=4, 30Hz)	6329700	4.3	0
3	Mobile (CIF, TL=4, 30Hz)	38230000	1	44040
4	Foreman (QCIF, TL=4, 30Hz)	2653300	0	19614
5	Foreman (CIF, TL=4, 15Hz)	2760000	1	20720
6	Foreman (CIF, TL=2, 30Hz)	4610000	3	55080

bounds of k can be set to be 0 and 1, respectively. For each k, we need to check whether it is feasible or not for the constraint of $R_{\max}$, i.e., the sum of resources allocated to users is no more than $R_{\max}$.

B. Complexity Analysis

Algorithm 1 needs at most $\log_2(N+2)$ iterations. Denote the number of operations required by each user and summation with S_1 and S_2, respectively. Since there are no more than N unsatisfied users, the maximum operations is $(S_1+S_2)N$. All iterations require no more than $(S_1+S_2)N\log_2(N+2)$ operations. The complexity of solving (19), (20) and (22) is $O(N)$. Therefore, the complexity of the co-opetition strategy is $O\big(N(1+\log N)\big)$.

IV. VIDEO RATE ALLOCATION EMPLOYING CO-OPETITION STRATEGY

In this section, we apply the co-opetition strategy to video rate allocation, and present some numerical results for performance evaluation.

A. System Setup

Total rate supported by the network is allocated among N video users. In this paper, the network is assumed to be error free. At application layer, several Rate-Distortion (RD) models have been proposed to describe video's rate-distortion behavior [6], [7]. We employ the model in [7] as it suits well for the average rate-distortion behavior of the state-of-the-art video coders [8]. In the model, user's distortion D is defined as

$$D = D_0 + \frac{\mu}{R-R_0}, R \geq R_0, \tag{23}$$

where R is the allocated rate, and R_0, D_0 and μ are sequence parameters [7]. We employ the same test sequences as those in [2] for comparison. For reader's convenience, we list the parameters in Table I. User's utility is defined as

$$U = \frac{255^2}{D} = \frac{255^2(R-R_0)}{D_0(R-R_0)+\mu}, \tag{24}$$

and the PSNR is given by $\mathrm{PSNR} = 10\log_{10} U$.

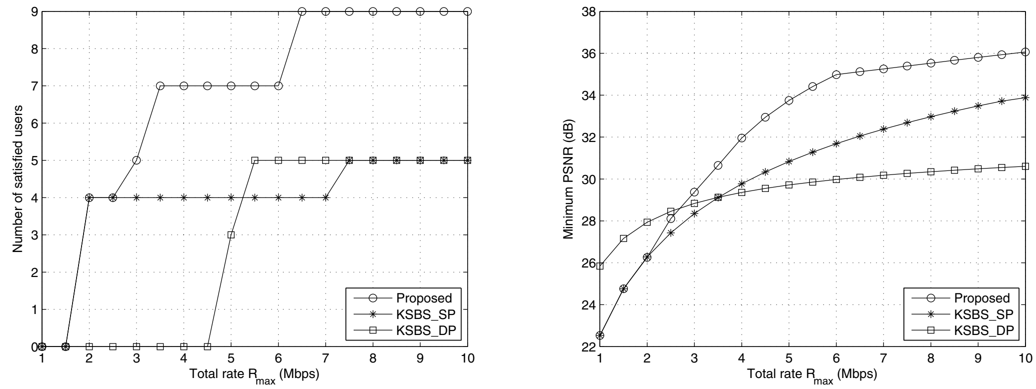
The minimum rate required equals to R_0 and the threshold utility is set such that PSNR = 35 dB, corresponding to good video quality. We compare the proposed strategy (Proposed) to three competition-based strategies: KSBS with same (KSBS_SP) and different (KSBS_DP) bargaining power, Nash Bargaining Solution (NBS) [2]. KSBS_SP is namely the KSBS introduced in Section II in this paper, and KSBS_DP assigns different bargaining power to users to achieve similar PSNRs. The NBS maximizes the sum PSNRs.

B. Numerical Results

1) Comparison to the KSBS in Terms of Individual PSNRs: Figure 2 shows the individual PSNRs achieved by KSBS_SP, KSBS_DP and Proposed. The Proposed coincides with the KSBS_SP in the case of scarce rate, e.g., $R_{\max} \leq 0.5$ Mbps. When there is sufficient rate, e.g., $R_{\max} \geq 4$ Mbps, all of them can guarantee satisfying video quality. Besides, in the case of moderate rate, $0.5 < R_{\max} \leq 2$ Mbps, the KSBS_SP makes the user 1 to be satisfied, however, no user can be satisfied by KSBS_DP. In this case, the Proposed decreases the user 1's PSNR to 35 dB to improve the user 2's PSNR. Consequently, user 2 can achieve comparable or almost the same video quality as KSBS_DP. Additionally, when $2.5 < R_{\max} \leq 4$ Mbps, KSBS_DP leads to system-wide good performance and both of the two users can be satisfied. The Proposed keeps this good performance while the KSBS_SP still penalizes the user 2.

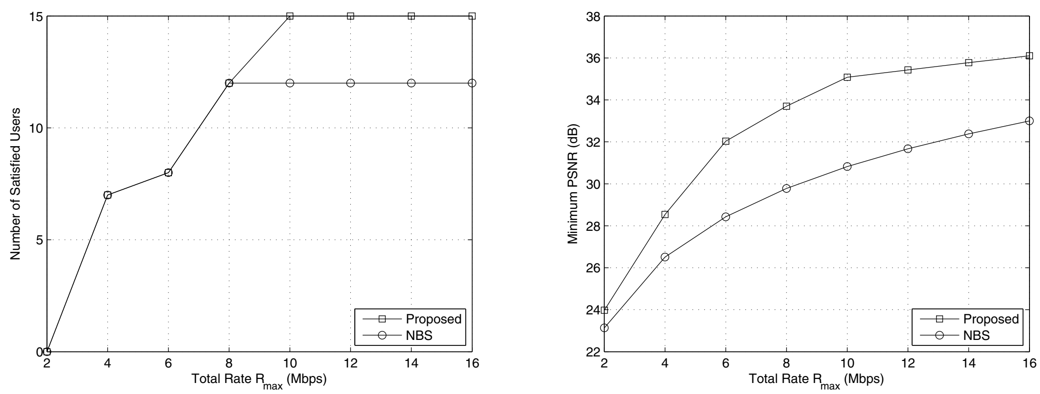
2) Comparison to the KSBS in Terms of Satisfied Users and Minimum PSNR: There are nine users transmitting a randomly selected sequence each. We can see from Fig. 3(a) that the Proposed has the best system efficiency, especially when $R_{\max} \geq 3$ Mbps. Proposed brings a system-wide satisfactory video quality when $R_{\max} \geq 6.5$ Mbps. But for KSBS_DP, only five users are satisfied. This means the KSBS_DP is not robust to the changes of total rate. This is due to the fact that KSBS_DP determines bargaining power in rate domain, but uses the them in utility domain. This might lead to high PSNR for those users not easy to achieve high PSNR, but low PSNR for others. Fig. 3(b) further verifies the robustness of our proposed scheme in terms of minimum PSNR. Since similar PSNR leads to a maximized minimum PSNR, the KSBS_DP only determines the bargaining power properly when the rate is low. We can see that both the Proposed and the KSBS_SP are robust. The Proposed leads the KSBS_SP in minimum PSNR.

3) Comparison to the NBS in Terms of Satisfied Users and Minimum PSNR: Fifteen sequences are employed which are also randomly selected. As shown in Fig. 4(a) and Fig. 4(b), the Proposed leads the NBS in terms of the number



(a) (b)

Fig. 3. Plot of the number of satisfied users (a) and minimum PSNRs (b) achieved by Proposed, KSBS_SP and KSBS_DP in the case of nine users. Video sequence Ids are 1, 6, 1, 3, 5, 1, 1, 2, 2.



(a) (b)

Fig. 4. Plot of the number of satisfied users (a) and minimum PSNRs (b) achieved by Proposed, NBS in the case of 15 users. Ids of video sequences are 3, 6, 1, 3, 5, 1, 1, 2, 2, 3, 5, 1, 1, 2, 2.

of satisfied users, and outperforms the NBS in terms of the minimum PSNR. In the case of total rate less than 8 Mbps, the Proposed and NBS can make the same number of satisfied users. However, in this case, the Proposed can result in an improvement of 1 dB to 4 dB in terms of the minimum PSNR compared to the NBS. If total rate is more than 8 Mbps, the Proposed can make all users satisfied, but only 12 users can be satisfied by the NBS. Moreover, more than 3 dB improvement can be achieved in terms of the minimum PSNR by the Proposed.

V. CONCLUSION

In this paper, we have presented a novel co-opetition strategy for collaborative multiuser resource allocation. The co-opetition strategy makes the satisfied users stop competing for resources, such that the QoS of unsatisfied users can be improved. Compared to existing competition-based strategies, the proposed strategy can result in an improved number of satisfied users, and improve the minimum utility. The co-opetition strategy also has low complexity.

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