Novel Coopetition Paradigm Based on Bargaining Theory for Collaborative Multimedia Resource Management

Zhangyu Guan, Dongfeng Yuan and Haixia Zhang
Wireless Mobile Communications and Transmission Lab (WMCT)
Shandong University, Jinan, Shandong, China, 250100
Email: {zhangyuguan, dfyuan, haixia.zhang}@sdu.edu.cn

***Abstract*—This paper presents a novel *coopetition* paradigm based on bargaining theory for collaborative multimedia resource management. The paradigm consists of a judicious mixture of competition and cooperation. For competition, the well-known Kalai-Smorodinsky Bargaining Solution (KSBS) is adopted as the fairness criteria, and for cooperation each user stops competing for resources as long as it achieves a predefined threshold of Quality of Service (QoS). We apply the proposed paradigm to rate allocation amongst multiple video users and compare its performance to other two schemes, traditional KSBS, and generalized KSBS for similar video quality. Results indicate that our paradigm adapts the best to the variation of resources as well as the user number. Also, importantly, our paradigm can result in an improved number of satisfied users while simultaneously avoid penalizing same users in the case of scarce resources. Complexity of the proposed paradigm is also analyzed.**

***Index Terms*—*Coopetition*, Kalai-Smorodinsky Bargaining Solution (KSBS), collaborative multimedia, resource allocation.**

I. Introduction

Resource management in multimedia systems is of increasing importance to support the recently emerging multimedia services (e.g., multicamera surveillance and multiuser enterprise streaming) over time-varying and bandwidth-constrained networks. As opposed to static reservation-based resource allocation [1], [2], resources can be allocated dynamically based on currently available resources, participating users and multimedia content characteristics. In this case, if resources available are insufficient to satisfy the Quality of Service (QoS) constraints of all users, fairness should be adopted to allocate resources amongst them. For example, the notion of proportional fairness was introduced in [3], and successfully deployed in [4]. However, it does not consider the resulting impact on video quality, and as thus it is unsuitable for content-aware multimedia transmissions.

To address this limitation, game theory has been applied to allocate resources in utility domain, and has been shown to lead to improved performance. [5] proposes to use mechanism design for resource management for noncollaborative wireless multimedia. In [6], [7], bargaining theory is applied to rate allocation in multiuser video and speech transmission systems, respectively. *Coopetition* is a new concept from economic area [8], and it suggests that a judicious mixture of competition and cooperation is often advantageous in competitive environments [9]. [10] designs different *coopetition* strategies that converge to distinct Nash equilibriums for wireless multimedia in spectrum agile networks and shows that *coopetition* results in an improved number of satisfied users. However, as we know, there is yet no *coopetition* paradigm developed for collaborative multimedia systems.

This paper proposes a novel *coopetition* paradigm based on bargaining theory for resource management for collaborative multimedia transmission. In the paradigm, the bargaining solution is used as fairness criteria under which users compete for resources. On one hand, in bargaining, users are assigned with the same bargaining power, and in this sense, users operate in a competitive manner. On the other hand, users having achieved satisfied QoS stop competing for resources temporarily until all other users are satisfied, and thus users also operate in cooperative way.

The novelty of this paper lies in the fact that we develop the *coopetition* paradigm based on the Kalai-Smorodinsky Bargaining Solution (KSBS) for video transmissions. Unlike other resource allocation using bargaining theory, such as the Nash Bargaining Solution (NBS) [11], the KSBS is especially useful for multiuser video communications as it ensures that all users be penalized the same percentage of the maximum utility increment with respect to the disagreement point, at which users allocate resources without collaboration. As thus, the KSBS allows to develop the *coopetition* paradigm by changing the disagreement point during resource allocation. Moreover, the proposed *coopetition* paradigm scales to the number of users and it has very low complexity such that it is very suitable for allocating resources in real time.

Rest of the paper is organized as follows. In Section II, we review the definition of the KSBS. Section III describes the proposed *coopetition* paradigm. In Section IV, we apply the paradigm to video rate allocation, and finally, we conclude this paper in Section V.

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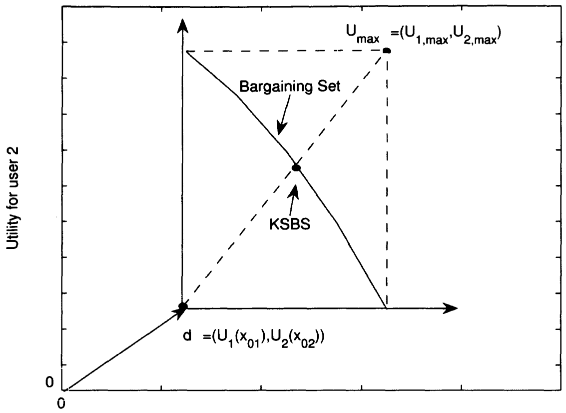

Fig. 1. Kalai-Smorodinsky Bargaining Solution (KSBS) for two-user case.

II. REVIEW OF THE KSBS

First, we briefly review the KSBS as follows since it is the base of our *coopetition* paradigm. In bargaining, N users allocate total resource X, and they each has its own utility $(U_n(x_n))$ with x_n being resource allocated. They each also desires a minimum utility $(U_n(x_{0n}))$ called disagreement point, which should be at least guaranteed. Thus, the resource available, X_{avai}, is actually $X - \sum_{n=1}^{N} x_{0n}$, and the maximum achievable utility, called the ideal point, can be written as $(U_{n,\max}) = U_n(x_{0n} + X_{\text{avai}})$. The maximum utility increment relative to the disagreement point $\mathbf{d} = (U_1(x_{01}), \cdots, U_N(x_{0N}))$ can be written as

$$\triangle\mathbf{U}_{\max} = ((U_{1,\max}) - U_1(x_{01}), \cdots, (U_{N,\max}) - U_N(x_{0N})).$$

Under constraints of $\sum_{n=1}^{N} x_n = X$ and $x_n \geq x_{0n}$, feasible utility pairs $\mathbf{U} = (U_1, \cdots, U_N)$ form the bargaining set $\mathbf{B}$ as

$$\mathbf{B} = \left\{ \mathbf{U} \middle| \mathbf{U} = (U_1(x_1), \cdots, U_N(x_N)), \sum_{n=1}^{N} x_n = X, x_n \geq x_{0n} \right\}.$$

At any pair in $\mathbf{B}$, no user is able to improve itself without penalizing the others. The KSBS sets the resource allocation in $\mathbf{B}$ at $\mathbf{U}^* = (U_1^*, \cdots, U_N^*)$ such that

$$\frac{(U_{1,\max}) - U_1^*}{(U_{1,\max}) - U_1(x_{01})} = \cdots = \frac{(U_{N,\max}) - U_N^*}{(U_{N,\max}) - U_N(x_{0N})}. \quad (1)$$

In other words, as mentioned in Section I, the KSBS can be used as fairness criteria that ensures all users be penalized the same percentage of the maximum utility increment with respect to the disagreement point. A simple example in the case of two users is depicted in Fig. 1, in which the KSBS is namely the intersection of the bargaining set and the line connecting the disagreement point $\mathbf{d}$ and ideal point $\mathbf{U}_{\max}$.

See [12] for details about the KSBS. In next Section, we develop a novel *coopetition* paradigm based on the KSBS.

III. PROPOSED *Coopetition* PARADIGM

As mentioned in Section I, *coopetition* is a judicious mixture of competition and cooperation. To allow *coopetition*, we propose to set a QoS threshold, Q_{th}, at which user achieves satisfying QoS and stops competing for more resources until all users achieve this threshold. Take an example of video transmission, Q_{th} can be set at Peak Signal-to-Noise Ratio (PSNR) equalling 35 dB corresponding to good video quality. After one or more users stop competing, other users proceed to compete. In the following, we describe the paradigm in detail and analyze its complexity.

A. Coopetition Paradigm based on the KSBS

Before resource allocation, we sort the ideal point $\mathbf{U}_{\max} = ((U_{1,\max}), \cdots, (U_{N,\max}))$ in decreasing partial order and denote the new ideal point with $\mathbf{U}_{\max}^{\text{new}} = ((U_{(1),\max}), \cdots, (U_{(N),\max}))$. Thus, user (i) is easier than user (j) to achieve better QoS if $i < j$, and (1) can be rewritten as

$$\frac{(U_{(1),\max}) - U_{(1)}^*}{(U_{(1),\max}) - U_{(1)}(x_{0(1)})} = \cdots = \frac{(U_{(N),\max}) - U_{(N)}^*}{(U_{(N),\max}) - U_{(N)}(x_{0(N)})}. \quad (2)$$

X_{avai} can be allocated by several rounds. In each round, each user has a target utility $(U_{(n),\text{targ}})$ representing the utility that user (n) expects to achieve through this round. For instance, in the first round, the target utility vector $\mathbf{U}_{\text{targ}} = ((U_{(1),\text{targ}}), \cdots, (U_{(N),\text{targ}}))$ is initialized to be $(U_{\text{th}}, (U_{(2),\text{targ}}), \cdots, (U_{(N),\text{targ}}))$. Here U_{th} is the target utility of user (1) corresponding to QoS threshold Q_{th}. $(U_{(n),\text{targ}}), 2 \leq n \leq N$ can be computed such that

$$\frac{(U_{(1),\max}) - U_{\text{th}}}{(U_{(1),\max}) - U_{(1)}((x_{(1),\text{allo}}))} = \frac{(U_{(n),\max}) - (U_{(n),\text{targ}})}{(U_{(n),\max}) - U_{(n)}((x_{(n),\text{allo}}))}, \quad (3)$$

where $(x_{(n),\text{allo}})$ is the resource allocated to user (n) and equals $x_{0(n)}$ in the first round. Each user computes the total resource $(x_{(n),\text{tota}})$ required to achieve the target utility based on its utility function, and computes the extra resource $(x_{(n),\text{extr}})$ using $(x_{(n),\text{extr}}) = (x_{(n),\text{tota}}) - (x_{(n),\text{allo}})$. If following constraint

$$\sum_{n=1}^{N} (x_{(n),\text{extr}}) \leq X_{\text{avai}} \quad (4)$$

is unsatisfied, resource allocation is settled at $(U_{(1)}^*, \cdots, U_{(N)}^*)$ according to (2), namely directly using the KSBS (see [6] for detail algorithm). In this case, the resource allocation is completed in one round. Otherwise, allocate $(x_{(1),\text{extr}}), \cdots, (x_{(N),\text{extr}})$ to user $(1), \cdots, (N)$, respectively, and update the resource allocated, resource available and the ideal point as

$$(x_{(n),\text{allo}}) = (x_{(n),\text{allo}}) + (x_{(n),\text{extr}}), \quad (5)$$

$$X_{\text{avai}} = X - \sum_{n=1}^{N} (x_{(n),\text{allo}}), \quad (6)$$

$$(U_{(n),\max}) = U_n((x_{(n),\text{allo}}) + X_{\text{avai}}), \quad (7)$$

respectively. In this case, user (1) stops competing for resource[1] and the other $N-1$ users proceed to allocate X_{avai}. Note that in the second round of resource allocation, the target utility of user (2) is initialized to be U_{th} and thus the subindex $_{(1)}$ in (3) should be correspondingly substituted by $_{(2)}$.

Above procedures continue until having allocated all resource or all users having achieved the Q_{th}. In the latter case, all users proceed to compete for resource still available, X_{avai}, using the KSBS. Note that the disagreement point here becomes $(U_{\text{th}}, \cdots, U_{\text{th}})$. We also note that in this case, the resource can be allocated instead by first allocating to each user the resource required to achieve Q_{th} (*coopetition*), and then allocating the remains using the KSBS (competition).

Above *coopetition* paradigm is summarized in Algorithm 1, of which the complexity is analyzed in Section III-C.

Algorithm 1: *Coopetition* Paradigm Based on the KSBS

1: Sort the ideal point $\mathbf{U}_{\max}$.
2: Set user index $id = 1$.
Repeat:
3: Set target utility of user (id) to be U_{th}.
4: Compute $(U_{(n),\text{targ}})$ according to (3)*.
5: Compute $(x_{(n),\text{tota}})$ and $(x_{(n),\text{extr}})$ based on $U_{(n)}(x)$.
6: Check feasibility for the constraint $\sum_{n=id}^{N}(x_{(n),\text{extr}}) \leq X_{\text{avai}}$.
7: If feasible, allocate $(x_{(n),\text{extr}})$ to user (n), else, allocate X_{avai} using the KSBS. Go to step 9.
8: Update $\mathbf{X}_{\text{allo}}, X_{\text{avai}}, \mathbf{U}_{\max}$ according to (5), (6), (7). Update id using $id = id + 1$.
Until: $X_{\text{avai}} = 0$ or $id = N + 1$.
9: If $id = N + 1$, set $id = 1$ and allocate X_{avai} using the KSBS.

* Here, subindex $_{(1)}$ in (3) should be replaced by $_{(id)}$.

B. Example: coopetition for the Two-User Case

In this section, we analyze the case of two users. We assume the minimum resources desired by user 1 and user 2 are $x_{01} = 0$ and $x_{02} = 0$, respectively. Assume the corresponding utilities are $U_1(x_{01}) = 0$ and $U_2(x_{02}) = 0$. Denote resources required to achieve Q_{th} are $(x_{1,\text{th}})$ and $(x_{2,\text{th}})$. We also assume the maximum utilities achievable satisfy $U_1(X) > U_2(X)$, and x_2 is resource required such that

$$\frac{U_1(X) - Q_{\text{th}}}{U_1(X)} = \frac{U_2(X) - U_2(x_2)}{U_2(X)}. \quad (8)$$

Then the resource can be allocated as follows. Case 1: if $X < (x_{1,\text{th}}) + x_2$, directly allocate the resource using the KSBS (competition). Case 2: if $(x_{1,\text{th}}) + x_2 \leq X \leq (x_{1,\text{th}}) + (x_{2,\text{th}})$, allocate $(x_{1,\text{th}})$ and $X - (x_{1,\text{th}})$ to user 1 and 2, respectively (*coopetition*). Case 3: if $X > (x_{1,\text{th}}) + (x_{2,\text{th}})$, first allocate $(x_{1,\text{th}})$ and $(x_{2,\text{th}})$ to user 1 and 2, respectively (coopetiton), and then allocate $X - (x_{1,\text{th}}) - (x_{2,\text{th}})$ using the KSBS (competition). These three cases are depicted in Fig. 2.

[1] If two or more users achieve the QoS threshold, they stop competing simultaneously. We assume only one user stops competing after each round.

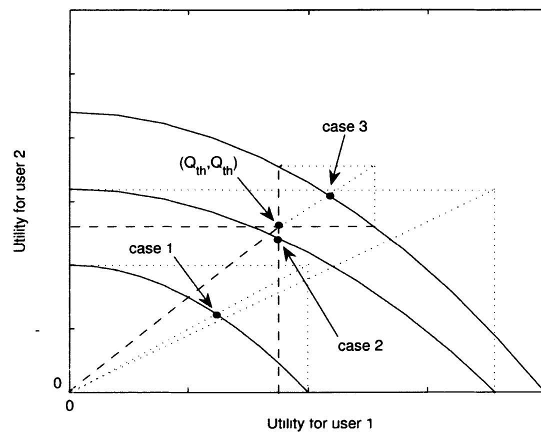

Fig. 2. Three cases of *coopetition* paradigm for two-user case.

C. Complexity Analysis

In this section, we approximately investigate the complexity of Algorithm 1 using the "flop" (floating-point operation) since it gives us a good estimate of the computation time of a numerical algorithm. For each repeat in algorithm 1, we denote the number of flops required by each user in step 4 and 5, with S_1 and S_2, respectively. Note that S_1, S_2 depend on the specifics of utility function. Let S_3 denote the number of flops required by step 6, 7 and 8. Since the maximum value of id is N, and in round id the maximum number of involved users is $N - id + 1$, the total number of flops required by all repeats can be computed as

$$\sum_{id=1}^{N} \left(S_1(N - id) + S_2(N - id + 1) + S_3\right) = \frac{N(N-1)}{2} S_1 + \frac{N(N+1)}{2} S_2 + N S_3. \quad (9)$$

The complexity of determining the KSBS is $O(N)$ [6]. Thus, we conclude that the complexity of the proposed *coopetition* paradigm based on the KSBS is $O(N^2)$.

IV. Numerical Results

A. System Setup

The same scenario as that in [6] is employed in this paper for the sake of performance comparison, and for reader's convenience, we review it briefly as follows. Total rate, R_{tot}, is allocated amongst multiple video users. User's utility function is defined as (see Section III-A in [6] for detailed derivation)

$$U(x) = \frac{255^2(x - R_0)}{D_0(x - R_0) + \mu}, x \geq R_0, \quad (10)$$

where x is the allocated rate, and R_0, D_0 and μ are sequence parameters, which are dependent on video sequence characteristics, such as spatial and temporal resolution, delay constraints as well as the percentage of INTRA coded macroblocks [6], [13]. Moreover, these parameters can be determined

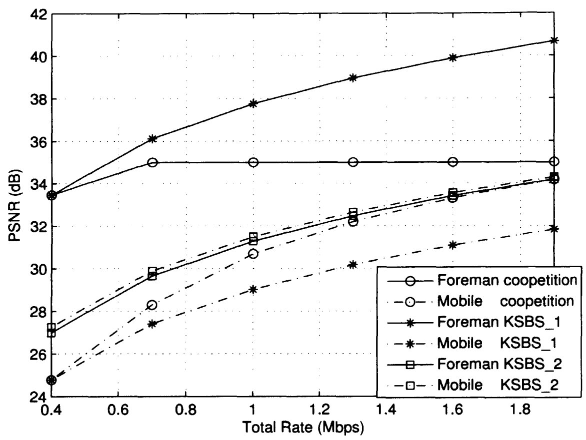

Fig. 3. Plot of individual PSNRs achieved by *coopetition*, KSBS_1, KSBS_2. User 1: Foreman (CIF, TL=4, 30Hz), user 2: Mobile (CIF, TL=4, 30Hz).

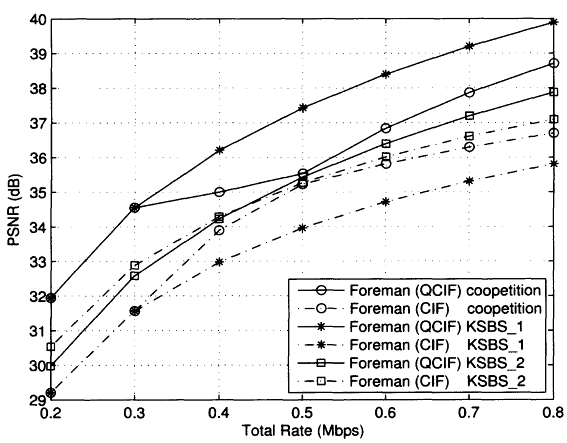

Fig. 4. Plot of individual PSNRs achieved by *coopetition*, KSBS_1, KSBS_2. User 1: Foreman (QCIF, TL=4, 30Hz), user 2: Foreman (CIF, TL=2, 30Hz).

offline, and same test sequences are employed as those in [6]. Corresponding PSNR is given by

$$\text{PSNR} = 10\log_{10} U(x). \tag{11}$$

B. Performance Analysis

We compare our *coopetition* paradigm (*coopetition*) to other two schemes proposed in [6], KSBS with same bargaining power (KSBS_1) and KSBS with different bargaining power for similar PSNR (KSBS_2).

Fig. 3 shows the individual PSNRs achieved by above three schemes, for the two users that transmit different video sequences at CIF resolution 30Hz[2]. User 1 and user 2 transmit *Foreman* and *Mobile* sequences, respectively. In this case, user 1 can achieve higher PSNR than user 2 if same bargaining powers are used (KSBS_1). In other words, it is very hard for user 2 to achieve satisfying video quality (PSNR $\geq$ 35dB in our experiments). KSBS_2 adapts the bargaining powers (see [6] for algorithm) such that similar level of video quality is achieved for two users. However, importantly, the disadvantage of KSBS_2 is that, it might lead to bad video quality for all users if resource available is insufficient. For instance, for these sequences the resources required to achieve the quality level of PSNR=35 dB are 255 Kbps and 1998 Kbps, respectively. Hence, none of them is satisfied using KSBS_2 in this experiment since the maximum resource available is 1.9 Mbps. The proposed *coopetition* paradigm eliminates this disadvantage. As shown in the figure, the *coopetition* coincides with KSBS_1 if total resource is quite limited, e.g., in the case of total rate equalling 0.4 Mbps. In other cases, the *coopetition* decreases user 1's PSNR to 35 dB. Consequently user 2 achieves a video quality which is obviously improved as opposed to KSBS_1 and comparable to KSBS_2, while at least user 1 is guaranteed satisfying QoS. Thus, the *coopetition* not only avoids penalizing the same user (user 2 here) too much, but also avoids leading to system wide bad performance (i.e., no user is satisfied). This argument is further verified in other simulation results.

Fig. 4 shows individual PSNRs for three schemes for *Foreman* sequence at 30 Hz with different spatial resolutions. User 1 and user 2 transmit the sequence at QCIF and CIF resolutions, respectively. With low total rate (e.g., below 0.4 Mbps), the situation here is similar to that in Fig. 3. However, with moderate total rate (e.g., between 0.5 and 0.6 Mbps), both *coopetiton* and KSBS_2 could satisfy all users, while KSBS_1 keeps penalizing user 2. In the case of sufficient total rate (e.g., above 0.7 Mbps), two users can be satisfied by all three schemes. We also note that, like KSBS_1, the *coopetition* also takes into account the sequence characteristics in resource allocation, i.e., lower resolution (QCIF) should lead to higher video quality (in PSNR).

Fig. 5 and Fig. 6 show the number of satisfied users and minimum PSNR for 15 users each transmitting one sequence randomly selected. We observe from Fig. 5 that, the *coopetition* paradigm leads the other two KSBS-based strategies, especially when having total rate larger than 11 Mbps, with which all 15 users can be satisfied by *coopetition*, but only 7 and 8 users satisfied by KSBS_1 and KSBS_2, respectively. This better performance of *coopetition* results from the fact that it allocates resource explicitly taking into account users' satisfaction degree by making satisfied users stop competing for resources until all users are satisfied. Recall that *coopetition* implies a judicious mixture of competition and cooperation, while KSBS_1 and KSBS_2 are purely competition-based. We also observe that curves in Fig. 5 are stepwise. This stepwise nature comes from, first, there may exist several users transmitting the same sequences, and second, video quality of all unsatisfied users are improved simultaneously and gradually through the process of rate

[2]Hereafter, numerical results are obtained by mathematical calculation from applying the concepts in Section II and III, but not based on simulation. This is feasible, as the rate-distortion (R-D) model employed in utility function definition is simulation-based. See [13] for details.

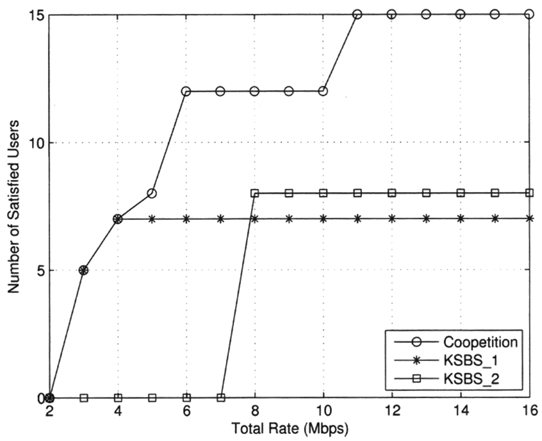

Fig. 5. Plot of the number of satisfied users with 15 users each transmitting one sequence randomly selected.

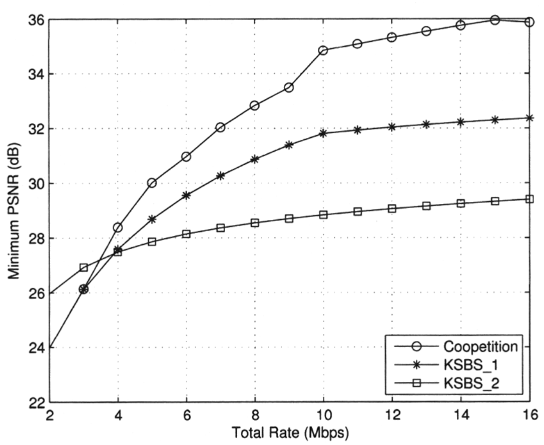

Fig. 6. Plot of achieved minimum PSNR with 15 users each transmitting one sequence randomly selected.

allocation.

Fig. 6 further illustrates the better performance of *coopetition* in terms of minimum PSNR. Compared to KSBS_1, *coopetition* can achieve an improvement around 3 dB when having total rate of 10 Mbps. This improvement comes from the fact *coopetition* limits the maximum of PSNR achievable at 35 dB, such that video quality of unsatisfied users can be improved. This is namely the essential of *coopetition*. We also observe that the KSBS_2 does not necessarily lead to similar video quality (PSNR)[3], e.g., in the case of high rate. Note, KSBS_2 determines bargaining power in resource domain, but using them to determine utilitiy achieved by each user in utility domain. Determining and using bargaining power like this, KSBS_2 might make very high PSNR for users who are hard to achieve good video quality, but low PSNR for the others. Therefore, more feasible algorithms are desired to determine bargaining power to make KSBS-based strategies more applicable. Also, it is worth mentioning that the crossing point of the curves produced by KSBS_2 and *coopetition* depends on many factors, at least including the number of participating users, transmitted sequences, total rate as well as the method employed to determine bargaining power.

From above examples, we conclude that *coopetition* is the most applicable for multimedia services, in which user number and resources are much varying. Moreover, importantly, *coopetition* can result in an improved number of satisfied users, and in the meanwhile avoid penalizing same users in the case of scarce resources.

[3]Similar PSNR should result in a maximum of the minimum PSNR.

V. Conclusion

A novel *coopetition* paradigm based on the KSBS is presented for wireless multimedia resource management. The paradigm suggests a judicious mixture of competition and cooperation in resource allocation. Numerical results indicate that our proposed paradigm can result in an improved number of satisfied users, and importantly, it considers explicitly the video characteristics while simultaneously avoids penalizing same users. Algorithm with low complexity is also presented.

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