Fairness Strategies for Multi-user Multimedia Applications in Competitive Environments using the Kalai-Smorodinsky Bargaining Solution

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***Abstract*— With the emergence of shared overlay network infrastructures and the recent deregularization of spectrum policies, a new, more dynamic network resource "market" is emerging. To effectively operate this new market, resource management becomes of paramount importance. This is especially important for multimedia streaming applications that require a large amount of resources to guarantee an acceptable level of multimedia quality to the end users. However, providing the necessary resources to various networked multimedia users is challenging since they have different requirements in terms of multimedia characteristics, delay, or network constraints. To simplify this problem, we propose a novel utility-based resource management scheme for multi-user multimedia transmission over networks. To manage the available resources, the resource manager deploys bargaining solutions from economics in order to explicitly consider the utility impact for different resource allocation schemes. We focus on the Kalai-Smorodinsky bargaining solution (KSBS) because it can successfully model relevant non-collaborative utility-aware fairness policies for multimedia users. The KSBS explicitly considers the application-specific utility domain (i.e., resulting multimedia quality) when performing the resource allocation. The proposed KSBS allocates the resources in such a way that the achieved utility of every participating station incurs the same quality penalty, i.e., the same decrease in video quality as opposed to their maximum achievable qualities. Our simulations show that the proposed game-theoretic resource management provides a fairer and more efficient allocation of resources in terms of derived multimedia quality.**

***Index Terms*—** Multimedia resource management, multi-user fairness for multimedia, Kalai-Smorodinsky bargaining solution, bargaining power

I. Introduction

Numerous multimedia applications are recently emerging and these applications are increasingly serviced over various resource constrained network infrastructures (e.g., wireless networks). However, developing efficient resource management strategies for multimedia users sharing the same network infrastructure is a challenging task, because multimedia users are assumed to be selfish and care only about the utility benefits that they can derive from the network. Each user will try to acquire as much of the network resources as possible, unless a regulatory mechanism exists in the network [1]. Thus, a regulatory central system is needed that can ensure fair and efficient allocation of resources. To develop such resource management mechanisms for competing users streaming delay-sensitive multimedia, optimal utilities in terms of video quality resulting from the various strategies for allocating the network resources (e.g., rate) among users need to be explicitly considered. Moreover, users can be modeled as autonomous entities that separately determine and optimize their compression and transmission strategies based on their source, application, network, and system characteristics.

Game theory has been proposed to resolve resource allocation issues for various networks in a distributed and scalable manner [2], [3]. However, prior research has not considered the resulting impact on the multimedia quality for various content-aware and delay-sensitive streaming applications. However, video users can especially benefit from an efficient resource allocation as they require a high amount of resources (e.g., bandwidth) in a timely manner (given a delay constraint). Moreover, since multimedia is loss-tolerant (i.e., graceful degradation can be obtained), different resource-quality trade-offs can be performed during this resource allocation, depending on the content characteristics. Fair resource allocation needs also to consider the non-collaborative behavior of the users. Unlike conventional resource management policies that manage the resources without considering the actual benefit in terms of utility derived by the users, we propose a distributed allocation approach based on the well-suited game-theoretic concept from economics: the notion of bargaining [4], [5]. Even though several bargaining solutions exist in the literature, we consider in this paper the Kalai-Smorodinsky Bargaining Solution (KSBS) since its axioms can distribute the resources optimally (in a Pareto optimal sense) and fairly among autonomous WSTAs, by ensuring an equal quality penalty from each WSTAs maximum achievable quality given its current channel conditions, content characteristics, and cross-layer strategies. Therefore, the KSBS can be successfully used for autonomous WSTAs.

The main contribution of our paper is the use of bargaining solutions for multimedia streaming applications. We define an application-specific utility function and fairness criterion that enables an optimal allocation of resources among multimedia users. We consider an application-specific utility which *explicitly* considers the content characteristics, resolutions, and delay constraints. We introduce the bargaining powers to fairly distribute the resources among users. We consider the KSBS that can be used in resource management problems. We show that this solution exhibits important properties that can be used for effective resource allocation.

This paper is organized as follows. In Section II, we define the distortion-rate based utility function. In Section III, several basic concepts for the KSBS are reviewed, and we interpret the properties of the KSBS for our multimedia streaming problem. Simulation results to investigate the effect of the bargaining powers are presented are presented in Section IV. Conclusions are drawn in Section V.

II. Distortion-Rate based Utility and Convexity

In this section, we define the utility function based on the distortion-rate (DR) model. Since the general requirement of the KSBS is a feasible utility set that is closed, convex, and bounded, we need to show that the feasible utility set of our problem is indeed convex.

A. Definition of Utility Function

Several distortion-rate (DR) models for wavelet video coders have been proposed. Since the DR model proposed in [6] is well-suited for the average rate-distortion behavior of the state-of-the-art video coders [7], we choose it as our DR model. The DR model in [6] is given by

$$D = \frac{\mu}{R - R_0} + D_0,\ R \geq R_0,\ D_0 \geq 0,\ \mu > 0, \qquad (1)$$

where D is the distortion of the sequence, measured as the mean square error (MSE), and R is the rate for the video sequence. μ, R_0, and D_0 are the parameters for this DR model, which are dependent on video sequence characteristics, spatial and temporal resolutions, and delay. Note that the parameters μ is positive and D_0 is nonnegative. The corresponding Peak Signal to Noise Ratio (PSNR) is given by $PSNR = 10\log_{10} 255^2/D$. Correspondingly, we define the utility function that is from the definition of PSNR without considering the logarithm and constant multiplication as

$$U_i(x_i) \triangleq \frac{c}{D_i} = \frac{c \cdot (x_i - R_{0i})}{D_{0i}(x_i - R_{0i}) + \mu_i}, \qquad (2)$$

where c is a nonnegative constant and subscript i represents user i (i.e., $U_i(x_i)$ represents the utility function for allocated rate x_i to user i). Note that $U_i(R_{0i}) = 0$ by the above definition of the utility function, thus the disagreement point $\mathbf{d}$ is the origin in our problem. Moreover, since each user expects a higher utility than the disagreement point, we assume that more than R_{0i} of resource is allocated to user i (i.e., $x_i > R_{0i}$). Thus, the utilities are positive (i.e., $U_i(x_i) > 0$). Note that the total available resource R_{MAX} is the constraint of this resource allocation problem.

Based on the definition of the utility function, it is shown that the feasible utility set is convex [8], which is a generally required condition for the KSBS.

III. Kalai-Smorodinsky Bargaining Solution

In this section, we will briefly review several basic definitions and concepts related to the KSBS. In [8], the Nash bargaining solution (NBS) can be interpreted as the sum of video qualities, and the proportional fairness [9] is a special case of the NBS. These fairness policies are not desirable for selfish users in competitive networks, where a common goal is not desired. Instead, we argue that a possible desired fairness policy should ensure that every user should incur the same quality penalty. This feature can be implemented by the KSBS.

A. The Definition of the KSBS

In this resource allocation game, players (in our case, multimedia transmitters) are assumed to try maximizing their utilities. Our resource management can be formulated as follows. There are n (video) users. Each user i has its own utility function ($U_i(x_i)$) for the allocated resource (rate x_i) and it has also a minimum desired utility ($U_i(R_{0i})$), called the disagreement point. The disagreement point is the minimum utility that each user expects by joining the game without cooperation. Hence, we assume that the initial desired resource is at least guaranteed for each user in the cooperative game. Assume $\mathbf{S} = \{(U_1(x_1), \ldots, U_n(x_n))\} \subset \mathbb{R}^n$ is a joint utility set (or a feasible utility set) that is nonempty, convex, closed, and bounded and let $\mathbf{d} = (d_1, \ldots, d_n) = (U_1(R_{01}), \ldots, U_n(R_{0n})) \in \mathbb{R}^n$ be the disagreement point. The pair $(\mathbf{S}, \mathbf{d})$ defines the bargaining problem. We define the Pareto optimal points/surface for a game among multiple users such that it is impossible to find another point that leads to a strictly superior advantage for all the users simultaneously [10]. The bargaining set $\mathbf{B}$ is the set of all individually rational, Pareto optimal payoff pairs in the cooperative payoff region $\mathbf{S}$. The KSBS gives a unique and fair Pareto optimal solution that fulfills the following axioms [11]. Let F be a function $F : (\mathbf{S}, \mathbf{d}) \rightarrow \mathbb{R}^n$.

Definition 1: Kalai-Smorodinsky Bargaining Solution. $\mathbf{X}^* = F(\mathbf{S}, \mathbf{d})$ is said to be an KSBS in $\mathbf{S}$ for the disagreement point $\mathbf{d}$, if the following axioms are satisfied.

1. *Individual Rationality*: $\mathbf{X}^* \geq \mathbf{d}$.
2. *Feasibility*: $\mathbf{X}^* \in \mathbf{S}$.
3. *Pareto Optimality*: $\mathbf{X}^*$ is Pareto optimal.
4. *Individual Monotonicity*: Given another feasible utility set $\mathbf{S}'$, if $\mathbf{S}' \supset \mathbf{S}$, $\mathbf{d} = \mathbf{d}'$, and $\max_{\mathbf{X} \in \mathbf{S}, \mathbf{X} \geq \mathbf{d}} X_k = \max_{\mathbf{X}' \in \mathbf{S}', \mathbf{X}' \geq \mathbf{d}'} X'_k$ for all $k \in \{1, \ldots, M\} \backslash \{i\}$, then $[F(\mathbf{S}', \mathbf{d}')]_i \geq [F(\mathbf{S}, \mathbf{d})]_i$.
5. *Independence of Linear Transformations*: For any linear scale transformation φ, $\varphi(F(\mathbf{S}, \mathbf{d})) = F(\varphi(\mathbf{S}), \varphi(\mathbf{d}))$.
6. *Symmetry*: If $\mathbf{S}$ is invariant under all exchanges of users, $F_i(\mathbf{S}, \mathbf{d}) = F_j(\mathbf{S}, \mathbf{d})$ for all possible user i, j.

The axioms 1, 2, and 3 define the *bargaining set*, which is the set of all individually rational and Pareto optimal utility pairs [5]. Thus, the KSBS is located in the bargaining set.

The axioms 4, 5, and 6 are called ”axioms of fairness”. Axiom 4 states that increasing the bargaining set size in a direction favorable to user i always benefits user i. For example, let $(\mathbf{S}, \mathbf{d})$ and $(\mathbf{S}', \mathbf{d})$ be two bargaining problems, where $\mathbf{S} \subset \mathbf{S}'$ and the maximum achievable utilities of all users are the same except user i. Individual monotonicity states that the user i gains more utility in $(\mathbf{S}', \mathbf{d})$ than in $(\mathbf{S}, \mathbf{d})$. A simple example for this axiom is shown in Fig. 1. This axiom can be used to solve application specific problems. For instance, it might be necessary to improve the quality of some selected users (e.g. users transmitting more important content) by allocating them additional resources. In this example, the

KSBS guarantees that this requirement keeps the optimality for all users.

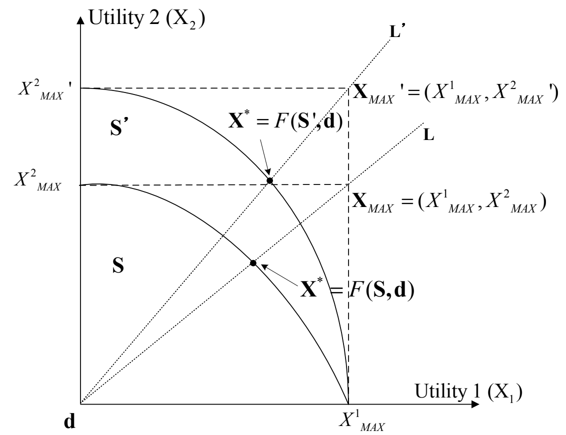

Fig. 1. A simple example to illustrate the axiom of *individual monotonicity* of the KSBS. In this example, there are two bargaining sets $\mathbf{S}$ and $\mathbf{S}'$ such that $\mathbf{S}' \supset \mathbf{S}$ and the maximum achievable utility of user 1 is fixed in both bargaining problems while the maximum achievable utility of user 2 is increased (i.e., ${X_{MAX}^2}' > X_{MAX}^2$). In this case, the KSBS always allocates more utility to user 2 due to the axiom of individual monotonicity of the KSBS.

Axiom 5 states that the bargaining solution is invariant if the utility function and disagreement point are scaled by a linear transformation. Axiom 6 implies that if users have the same disagreement points and the same achievable utility range, they will have the same utility allocation.

B. The Interpretation of the KSBS

In this section, we analyze the KSBS. The n-user KSBS satisfies

$$\mathbf{X}^* = F(\mathbf{S}, \mathbf{d}) = \mathbf{d} + \lambda_{MAX}(\mathbf{X}_{MAX} - \mathbf{d}), \quad (3)$$

where $\mathbf{S}$ is the feasible utility set, $\mathbf{X}^* = (X_1^*, \ldots, X_n^*)$ is the KSBS, and $\mathbf{d} = (d_1, \ldots, d_n)$ is the disagreement point, which is the origin in our problem. $\mathbf{X}_{MAX} = (X_{MAX}^1, \ldots, X_{MAX}^n) \geq \mathbf{d}$ is the ideal point for n users and λ_{MAX} is the maximum value of λ such that $\mathbf{d} + \lambda(\mathbf{X}_{MAX} - \mathbf{d}) \in \mathbf{S}$. As we stated in Section III, the bargaining set is defined as

$$\mathbf{B} = \{\mathbf{X} | \sum_{i=1}^{n} \frac{\mu_i X_i}{c - D_{0i} X_i} = R_{MAX} - \sum_{i=1}^{n} R_{0i}, X_i > 0 \, \forall i\}. \quad (4)$$

The KSBS is the intersection between the bargaining set $\mathbf{B}$ and the line $\mathbf{L}$ defined by

$$\mathbf{L} = \{\, \mathbf{X} \,|\, \frac{X_1}{\alpha_1 X_{MAX}^1} = \ldots = \frac{X_n}{\alpha_n X_{MAX}^n}, \; X_i > 0 \, \forall i\}, \quad (5)$$

where $\sum_{i=1}^{n} \alpha_i = 1, \alpha_i > 0$, and $X_{MAX}^i = U_i(R_{MAX})$ since the disagreement point is the origin. A simple example of the KSBS for the two-user case is depicted in Fig. 2.

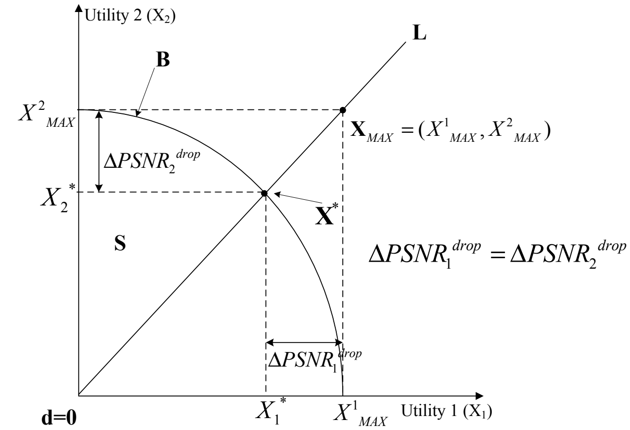

Fig. 2. A simple example of KSBS for the two-user case. The quality drop is the same for all users.

Let us now investigate the physical meaning of the KSBS. Since the KSBS is located in the bargaining set as well as in the line in (5), the bargaining solution must satisfy

$$\frac{X_1^*}{\alpha_1 X_{MAX}^1} = \ldots = \frac{X_n^*}{\alpha_n X_{MAX}^n}, \quad (6)$$

where $(X_1^* \ldots, X_n^*) \in \mathbf{B}$. Taking the logarithm in (6) with $c = 255^2$, we have

$$(PSNR_{MAX}^1 - PSNR_1^*) + 10\log_{10}\alpha_1 = \ldots$$
$$= (PSNR_{MAX}^n - PSNR_n^*) + 10\log_{10}\alpha_n, \quad (7)$$

and equivalently,

$$\triangle PSNR_1^{drop} + 10\log_{10}\alpha_1 = \ldots = \triangle PSNR_n^{drop} + 10\log_{10}\alpha_n, \quad (8)$$

where $PSNR_{MAX}^i = 10\log_{10} X_{MAX}^i$ is the maximum achievable PSNR for user i and $PSNR_i^*$ is achieved PSNR by the KSBS X_i^*. The PSNR drop denoted by $\triangle PSNR_i^{drop} \triangleq (PSNR_{MAX}^i - PSNR_i^*)$ represents the quality decrease (or drop) from user i's maximum achievable quality. If the same bargaining powers are used, the KSBS allocates resources such that the quality drop for all users are the same. Importantly, note that the KSBS can be thus interpreted as an utility-based fair resource allocation for selfish users. If different bargaining powers are used, the user with a higher bargaining power obtains a higher PSNR than the other users.

C. Complexity of the KSBS

The KSBS is analyzed in the previous section. By setting the equation in (6) equal to k^*, the KSBS can be expressed as

$$\mathbf{X}^* = (k^* \cdot \alpha_1 X_{MAX}^1, \ldots, k^* \cdot \alpha_n X_{MAX}^n). \quad (9)$$

To solve this equation, we can use the bisection method. The required flops for k^* are $\lceil \log_2((u - l)/\epsilon) \rceil \cdot (9n + s_2)$ and computation of each utility $X_i = k^* \cdot \alpha_i X_{MAX}^i$, $i = 1, \ldots, n$ requires $2n$ flops. Therefore, the total required flops is $\lceil \log_2((u - l)/\epsilon) \rceil \cdot (9n + s_2) + 2n$ and it also has a complexity of $O(n)$. Note that $l = \min(R_{01}, \ldots, R_{0n})$

KSBS	R_{MAX} (Mbps)	$PSNR_1$ (dB)	$PSNR_2$ (dB)	$PSNR_3$ (dB)	$\triangle PSNR^{drop}$	$\overline{PSNR}$ (dB)
same bargaining powers	0.5	33.3017	31.1786	24.2212	4.7348	29.5672
	1.0	36.6487	33.5285	27.7108	4.3981	32.6293
	2.0	39.9999	35.3868	31.0466	4.0571	35.4778
different bargaining powers	0.5	27.3190	27.8771	27.8568	-	27.6843
	1.0	30.4845	30.0456	31.1649	-	30.5650
	2.0	33.6509	31.7191	34.3159	-	33.2286

TABLE I

ALLOCATED QUALITY BY KSBS. USER 1: FOREMAN (CIF), USER 2: COASTGUARD (CIF), USER 3: MOBILE (CIF)

denotes the lower bound, $u = R_{MAX}$ represents the upper bound, and ϵ denotes the tolerance. Moreover s_1 and s_2 denote some constant flops required for square root and comparison operation, respectively.

IV. SYSTEM SETUP AND SIMULATION RESULTS

In this section, we define a mechanism or system to implement the previously analyzed bargaining solutions in a network infrastructure. Then we provide several simulation results, and compare the achieved quality (i.e., PSNR) using the various bargaining solutions and resource allocation scenarios. In our simulations, we assume that there are two or three users and assume "ideal" network conditions (i.e., no loss, the entire network resources (bandwidth) are allocated to the participating users). This scenario can be extended for wireless communications, congested networks, etc.

A. System Setup

A central resource manager allocates the available network resources to the multiple users. To enable the fair resource allocation, we assume that each user truthfully declares the following parameters to the resource manager every allocation interval: (μ, R_0, D_0). Based on this information, the resource manager determines the bargaining solution, computes the bargaining solutions and informs the users of the allocated rate which they can allocated for video transmission.

B. Comparison of the KSBS with Different Bargaining Powers

In this section, we compare the KSBS with the same and different bargaining powers. In this simulation, we assume that there are three users that transmit three different video sequences. The achieved PSNRs for the same and different bargaining powers are listed in Table I.

The quality drop ($\triangle PSNR^{drop}$) when the same bargaining powers are used is the same for all the users as we shown in Section III. This is a unique interpretation of the KSBS, and is a desirable fairness policy for selfish multimedia users.

The different bargaining powers are determined to achieve a similar level of quality, and they are α_1=0.0832, α_2=0.1543, and α_3=0.7625. Compared with the same bargaining powers (i.e., α_1=α_2=α_3=1/3), only the user 3 has higher bargaining powers after adapting bargaining powers. Hence, we expect that the user 3 obtains higher PSNRs in different bargaining power case. In Table I, we observe that the user 3 achieves higher PSNR after adapting bargaining powers. Moreover, the achieved PSNR for each user is a similar level of quality after changing bargaining powers even though the average PSNRs ($\overline{PSNR}$) are lowered compared with the same bargaining case. Therefore, the KSBS has a tradeoff between fairness and performance.

V. CONCLUSION

In this paper we propose an alternative and novel solution to the problem of rate allocation for video users, based on the bargaining methodology from game theory. As shown in this paper, a solution is selected out of the set of possible choices that satisfies a set of rational and desirable axioms. Hence, the purpose is *not* to maximize a system utility, but rather select a solution from the Pareto optimal surface and satisfy several rational properties in making the choice. We provided interpretation for the KSBS, which ensures that all users incur the same utility penalty relative to the maximum achievable utility. In addition, the bargaining powers can be used to provide additional flexibility in choosing solution by taking into consideration the visual quality impact, the deployed spatio-temporal resolutions, etc. Summarizing, the proposed bargaining solutions can provide a good solution for fair and optimal resource allocation for multi-user multimedia transmission with reasonable complexity, robustness, and flexibility.

REFERENCES

[1] R. W. Lucky, "Tragedy of the commons," *IEEE Spectrum*, p. 43(1):88, Jan. 2006.

[2] C. Douligeris and R. Mazumdar, "A game theoretic perspective to flow control in telecommunication networks," *Journal Franklin Inst.*, vol. 329, no. 2, pp. 383–402, Mar. 1992.

[3] R. Mazumdar, L. G. Mason, and C. Douligeris, "Fairness in network optimal flow control: Optimality of product forms," *IEEE Trans. Commun.*, vol. 39, no. 5, pp. 775–782, May 1991.

[4] J. Nash, "The bargaining problem," *Econometrica*, vol. 18, pp. 155–162, 1950.

[5] K. Binmore, *Fun and Games: A Text on Game Theory*. Lexington, MA: D.C. Health, 1992.

[6] K. Stuhlmüller, N. Färber, M. Link, and B. Girod, "Analysis of video transmission over lossy channels," *IEEE J. Select. Areas Commun.*, vol. 18, no. 6, June 2000.

[7] Y. Andreopoulos, A. Munteanu, J. Barbarien, M. van der Schaar, J. Cornelis, and P. Schelkens, "In-band motion compensated temporal filtering," *Signal Processing: Image Communication(special issue on "Subband/Wavelet Interframe Video Coding")*, vol. 19, no. 7, pp. 653–673, Aug. 2004.

[8] H. Park and M. van der Schaar, "Bargaining strategies for networked multimedia resource management," *accepted IEEE Trans. Signal Processing*.

[9] F. Kelly, "Charging and rate control for elastic traffic," *Eur. Trans. Telecommun.-"Focus on Elastic Services Over ATM Networks"*, vol. 8, no. 1, pp. 33–37, 1997.

[10] H. Yaïche, R. R. Mazumdar, and C. Rosenberg, "A game theoretic framework for bandwidth allocation and pricing in broadband networks," *IEEE/ACM Trans. Networking*, vol. 8, no. 5, pp. 667–678, Oct. 2000.

[11] E. Kalai and M. Smorodinsky, "Other solutions to Nash's bargaining problem," *Econometrica*, vol. 43, no. 3, pp. 513–518, May 1975.