MULTI-USER MULTIMEDIA RESOURCE MANAGEMENT USING NASH BARGAINING SOLUTION

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ABSTRACT

Multi-user multimedia applications such as enterprise streaming, surveillance, and gaming are recently emerging, and they are often deployed over bandwidth-constrained network infrastructures. To ensure the Quality of Service required by the delay-sensitive and bandwidth intensive multimedia data for these applications, efficient resource (bandwidth) management becomes paramount. We propose to deploy the well-known game theoretic concept of bargaining to allocate the bandwidth fairly and optimally among multiple collaborative users. Specifically, we consider the Nash bargaining solution (NBS) for our resource management problem. We provide interpretations for the NBS for multi-user resource allocation: the NBS can be used to maximize the system quality. The bargaining strategies and solutions are implemented in the network using a resource manager, which explicitly considers the application-specific distortion for the bandwidth allocation.

***Index Terms*—** Nash bargaining solution, resource allocation, bargaining power, cooperative game

1. INTRODUCTION

A plethora of collaborative multimedia networking applications such as multi-camera surveillance and multi-user enterprise streaming are recently emerging. These applications are often deployed over time-varying and bandwidth-constrained infrastructures such as the Internet and wireless networks. These infrastructures do not provide support for the Quality of Service (QoS) required by the delay-sensitive and bandwidth-intensive multimedia data. To ensure the necessary QoS, recent research has focused on innovative solutions that provide efficient bandwidth allocation, rate-adaptation or joint source-channel coding to cope with the rapidly-varying resources [1]. However, these adaptation techniques have been performed in isolation, at each multimedia transmitter, and suffer from the important limitation of not considering their interactions (in terms of resource utilization) with other devices sharing the same network infrastructure. The disadvantage of static reservation-based solutions is that they do not scale to the number of users and time-varying network resources. Moreover, since the allocation is static and performed prior to transmission time, it does not consider the video sequence characteristics etc. Alternatively, the resource allocation can be determined dynamically based on the currently available resources, participating users and their video content characteristics. In this case, fairness policies are needed to allocate the available resources among the multiple multimedia users. Several resource allocation policies have been proposed in the literature (e.g., [2, 3]). However, these approaches are not suitable for content-aware multimedia applications since it does not consider explicitly the resulting impact on video quality.

To address the above limitations, we propose a distributed resource management approach for multi-user multimedia transmission based on the well-suited game-theoretic concept from economics: the notion of bargaining [4, 5]. The proposed solution attempts to solve this problem directly in the multimedia utility domain. To deploy bargaining solutions, we define an application-specific utility function and fairness criterion that enables an optimal allocation of resources among multimedia users. Unlike alternative resource allocation strategies that consider solely the network condition, we consider an application-specific utility which *explicitly* considers the content characteristics, resolutions, and delay constraints. Efficient resource allocation is especially important for multimedia applications as the necessary bandwidth for these applications is very huge and varies continuously based on the contents. We show that this solution exhibits important properties that can be used for effective resource allocation.

This paper is organized as follows. In Section 2, several basic concepts and definitions about cooperative game theory are reviewed. In Section 3, we define the distortion-rate based utility function. In Section 4, we analyze the NBS and interpret this solution for our collaborative multimedia networking problem. In Section 5, we define a mechanism to implement the resource management and simulation results are presented. Conclusions are drawn in Section 6.

2. BACKGROUND

In this section, we will briefly review several basic definitions and concepts related to bargaining solutions.

In cooperative games, players (in our case, multimedia transmitters or cameras) are assumed to try reaching an agreement that gives mutual advantage. 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. The Pareto optimal surface for a game among multiple users is defined such that it is impossible to find another point that leads to a strictly superior advantage for all the users simultaneously. The bargaining set $\mathbf{B}$ is the set of all individually rational, Pareto optimal payoff pairs in the cooperative payoff region $\mathbf{S}$. The NBS gives a unique and fair Pareto optimal solution that fulfills the following axioms [5]. Let F be a function $F:(\mathbf{S},\mathbf{d})\rightarrow\mathbb{R}^n$.

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

1. *Individual Rationality*: $X_i^*\geq d_i$ for all i.
2. *Feasibility*: $\mathbf{X}^*\in\mathbf{S}$.
3. *Pareto Optimality*: $\mathbf{X}^*$ is Pareto optimal.
4. *Independence of Irrelevant Alternatives*: If $\mathbf{X}^*\in\mathbf{S}'\subset\mathbf{S}$ and $\mathbf{X}^*=F(\mathbf{S},\mathbf{d})$, then $\mathbf{X}^*=F(\mathbf{S}',\mathbf{d})$.
5. *Independence of Linear Transformations*: For any linear scale transformation ψ, $\psi(F(\mathbf{S},\mathbf{d}))=F(\psi(\mathbf{S}),\psi(\mathbf{d}))$.
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 users i,j.

The axioms 1, 2, and 3 define the bargaining set $\mathbf{B}$. Thus, the NBS is located in the bargaining set. The axioms 4, 5, and 6 are called axioms of fairness. The axiom 4 states that if the bargaining solution of the larger set is found on a smaller domain, then the solution is not affected by expanding the domain. This axiom provides a powerful property for our resource management problem when each user has its desire utility. The axiom 5 states that the bargaining solution is invariant if the utility function and disagreement point are scaled by a linear transformation. This is especially useful when the utility can be a linear function of the rate. The axiom 6 implies that if users have the same disagreement points and utility functions, they will have the same utility regardless of their indices. This represents an important fairness criteria for our problem that gives incentives to multimedia users to collaborate, as they can rely on the system to provide their equal treatment when their utility-resource tradeoffs vary over time.

3. DISTORTION-RATE BASED UTILITY

In this section, we define the utility function based on the distortion-rate (DR) model.

3.1. Definition of Utility Function

Several 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

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

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 sequences. The corresponding Peak Signal to Noise Ratio (PSNR) is given by $PSNR=10\log_{10}255^2/D$. Correspondingly, we define the utility function based on the definition of PSNR as

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

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 required for the NBS.

4. NASH BARGAINING SOLUTION

In this section, we analyze the NBS and provide a simple illustrative example of how the NBS-based resource allocation can be used in practice.

The function $F:\mathbf{S}\rightarrow\mathbb{R}^n$ is the generalized NBS for n user game [5] corresponding to the bargaining powers α_i for each user i if $F(\mathbf{S},\mathbf{d})=\{\mathbf{s}\in\mathbf{B}|\mathbf{s}=\sum_{i=1}^n\alpha_i\mathbf{r}_i\}$, where $\sum_{i=1}^n\alpha_i$=1, $\alpha_i\geq 0$ for all i. The set $\mathbf{S}$ is the feasible utility set and $\mathbf{d}$ is the disagreement point. $\mathbf{s}$ is a point in the bargaining set $\mathbf{B}$ of the set $\mathbf{S}$. A simple example of the NBS for two-user case is shown in Fig. 1 and several NBSs for different bargaining powers are shown in Fig. 2.

Note that the generalized NBS is the maximizer of the generalized Nash Product for the n user case, defined as $G(\mathbf{X})=\prod_{i=1}^n(X_i-d_i)^{\alpha_i}$, where the utility $X_i=U_i(x_i)$. Recall that the disagreement point $\mathbf{d}=\mathbf{0}$ in our paper. Hence, for the generalized NBS $\mathbf{X}^*=(X_1^*,\ldots,X_n^*)$ with $c=255^2$, we have

$$10\log_{10}G(\mathbf{X}^*)=\sum_{i=1}^n\alpha_i PSNR_i^*, \tag{3}$$

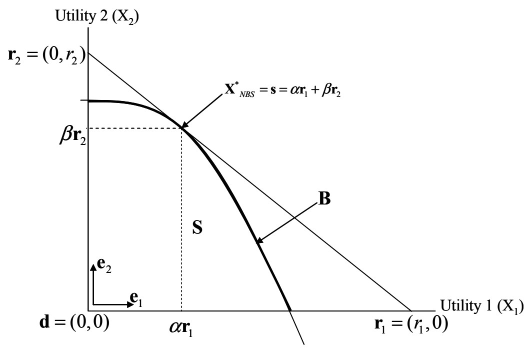

Fig. 1. A simple example of the NBS for two-user case with bargaining power α and β

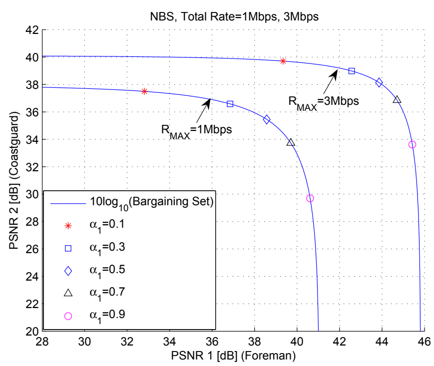

Fig. 2. Plots of Bargaining Set and the NBS with different bargaining powers for *Foreman* and *Coastguard* sequences

where $PSNR_i^* = 10\log_{10} X_i^*|_{c=255^2}$ is achieved PSNR by the resource allocation provided by the generalized NBS X_i^* for the ith user (i.e., video sequence of user i). We can interpret (3) as the *weighted sum of PSNR* according to the bargaining powers (i.e., importance) of users or video sequences. In other words, the total resource R_{MAX} is divided into small bandwidth segments that are allocated to the user that has the highest increase of utility by gaining this resource. This allocation also can be viewed as a fairness criterion, which maximizes the system utility represented by the weighted sum of PSNRs given the total rate R_{MAX} and the bargaining powers.

In [9], it was shown that NBS leads to the same allocation result as the proportional fairness (PF) [3] when the disagreement point is the origin. Thus, the PF is a special case of the NBS. However, for video applications, the disagreement point does not always need to be zero. For instance, the disagreement point needs to be defined as the utilities corresponding to the minimum video quality acceptable to the users (e.g. the base-layer quality). In this case, the disagreement point is not zero. Furthermore, as mentioned before, NBS provides additional important properties given by its axioms, which are not provided by the PF. An example is the axiom of independence of irrelevant alternatives. If the declared desire utilities by the users (e.g., 35dB) form a subset of the original feasible utility set, then the NBSs for both cases can be the same. A simple example for this axiom is shown in Fig. 3.

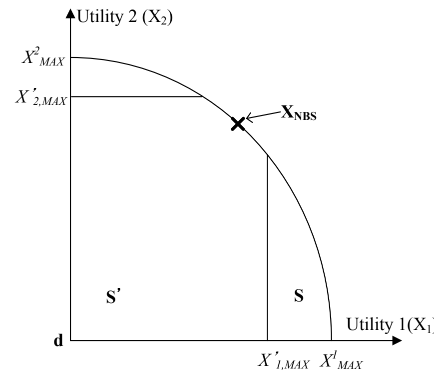

Fig. 3. The NBSs for $(\mathbf{S}, \mathbf{d})$ and $(\mathbf{S}', \mathbf{d})$, where $\mathbf{S} \supset \mathbf{S}'$, are the same by the axiom of Independence of Irrelevant Alternatives. $X'_{i,MAX}$ denotes the declared desire utility corresponding to the minimum video quality for user i

5. 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. 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 are allocated to the participating users). This scenario can be extended for wireless communications, congested networks, etc.

5.1. 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.

5.2. Comparison of the generalized NBS and Equal Rate Allocation Scenario

The generalized NBS allocates resources according to the video characteristics and bargaining powers. We compare this solution with the same bargaining powers to Equal Resource Allocation Scenario (ERAS) that allocates the same amount of resource to each user without considering the video characteristics or their importance. Assume that there are n users and set the same bargaining powers, i.e., $\alpha_i = 1/n$ for the generalized NBS and compare the system performance with ERAS. For this, we determined the average PSNR for the generalized

NBS and ERAS solutions as

$$\frac{1}{n}\sum_{i=1}^{n} PSNR_i^* \geq \frac{1}{n}\sum_{i=1}^{n} PSNR_i(\frac{R_{MAX}}{n}), \qquad (4)$$

where $PSNR_i(\cdot)$ denotes the achieved PSNR corresponding to the allocated rate for user i. Recall that the generalized NBS is the maximizer of the $\sum_{i=1}^{n} \alpha_i PSNR_i$. Hence, the average PSNR for the generalized NBS with the same bargaining powers is always higher than that of ERAS.

R_{MAX}	130Kbps	150Kbps	200Kbps	300Kbps
NBS [dB]	22.757	23.815	25.772	28.139
ERAS [dB]	18.645	22.593	25.399	28.027

Table 1. Average PSNR by the NBS and ERAS

Table 1 shows the average PSNR for the generalized NBS with the same bargaining powers and ERAS when three different video sequences are transmitted. We observe that the generalized NBS gives always a higher average PSNR value than that of ERAS. This is especially true at low rates (when the resources are scarce), where a judicious use of resource is essential.

5.3. Comparison of the NBS with Different Bargaining Powers

In this section, we compare the weighted PSNR for the generalized NBS with different bargaining powers to examine the effect of bargaining powers. The bargaining powers can be computed based on content characteristics, semantics, spatio-temporal resolutions etc. Different bargaining powers are essential when we consider *fairness* for the cooperative game theory. Fig. 4 shows the weighted sum of PSNR achieved by the generalized NBS for the same and different bargaining powers for sequences that are different *spatial resolution*. The bargaining powers are determined such that the each user's achieved PSNR is similar.

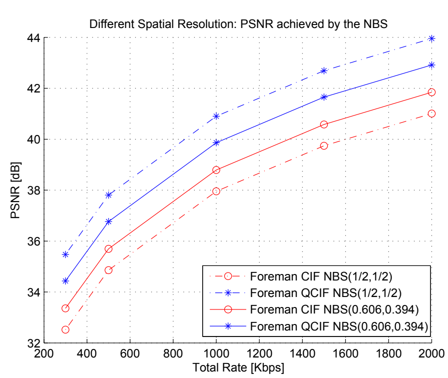

Fig. 4. Weighted sum of PSNRs for the same and different bargaining powers. *Foreman* (CIF) and *Foreman* (QCIF)

From above representative example, we conclude that bargaining powers of the generalized NBS play an important role for the tradeoff between *fairness* and *performance* and they need to be chosen appropriately depending on the application requirements.

6. CONCLUSION

In this paper we propose an alternative and novel solution to the problem of rate allocation for collaborative video users, based on the bargaining methodology from game theory. As shown in this paper, in axiomatic bargaining theory, a solution is selected out of the set of possible choices that satisfies a set of rational and desirable axioms. We provided an interpretations for the NBS, which can be used to maximize the system utility (i.e., weighted sum of PSNRs of the users). In addition, the bargaining powers can be used to provide additional flexibility in choosing solution by considering video characteristics. Summarizing, the proposed bargaining solutions can provide a good solution for fair and optimal resource allocation for multi-user multimedia transmission with robustness and flexibility.

7. REFERENCES

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