DYNAMIC SERVICE DISCRIMINATION STRATEGY DEVELOPMENT USING GAME THEORY

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Abstract: This research proposes a dynamic service discrimination strategy for wireless multimedia services. In particular, bargaining solutions in the game theory are applied to allocate the limited resources to users for the purpose of proportional fairness. We assume that users can choose one of discriminated media services and multimedia resources are then allocated to users according to their service selections. In the mechanism, an efficiency function for the network manager and a utility function for users are devised to reflect quality of service and cost. The optimized service discrimination and resource allocation policy have been developed not only from user's standpoint, but also from network manager's. We illustrated experimental results with synthesis multimedia data and analyzed the effect of the proposed service differentiation and resource allocation algorithms.

1 INTRODUCTION

As the real-time wireless multimedia service requires pretty much resource, it has been the major issues to utilize the limited resources in the wireless network. There are lots of researches how to utilize the limited resources, especially using the game theoretic approaches. Game theory has been already applied and shown the advances to improve the performance of resource allocation in the various research areas including wireless multimedia networks.

The most intuitive way to allocate resources is to equally allocate resources to the participating users. But an important disadvantage of this policy is that it does not consider characteristics of users and systems. Alternatively, the notion of proportional fairness was introduced to allocate resources based on the user's requirements (Kelly, Maulloo, & Tan, 1998). In the point of proportional fairness, KSBS (Kalai-Smorodinsky Bargaining Solution) was compared with the NBS. Park and Schaar (2007) analyzed the optimality conditions of both solutions and differences between the quantitative proportional fairness of NBS and the qualitative one of KSBS. Although this proportional fairness policy was successfully implemented in several works (Kelly, Maulloo & Tan, 1998), it is not suitable for content aware multimedia applications since it does not consider explicitly the resulting impact on the quality of the service (Park & Schaar, 2007).

In this research, the concept of cost, to model the efforts which users invest to achieve their own goals, is additionally considered to express user's satisfaction. Although there are a lot of researches related to the costing or pricing (Courcoubetis, Siris & Stamoulis, 1996; Shenker, 1995), it is general to charge according to the amount of allocated resources (Avriel, 1976). And the most important thing is that pricing mechanism and resource allocation policy should be able to maximize the

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profit or revenue of each participants of the game (Ya¨ıche, Mazumdar,& Rosenberg, 2003).

2 BASIC ASSUMPTIONS

The salient concepts and the basic assumptions for service discrimination and the resource allocation game are presented. Parameters and descriptions are summarized in Table 1.

Table 1: Parameters and descriptions.

Parameters	Descriptions
R^{MAX}	total available resource
R_i^{MAX}	maximum requirement of user i
R_i^0	minimum requirement user i
R_i	amount of resource allocated to user i
C_j	unit price for resource of jth service type
x_{ij}	decision variable of user i
α_i	bargaining power of user i
β_j	bargaining power of j th service type
$\pi_i(\cdot)$	utility function of user i
X_i	utility of user i
EF_j	resource usage efficiency of jth service type
ζ	weight value for the linear combination of service discrimination strategies

In this research, following wireless communication network is assumed. There are n users who compete for the available network resources. A user i has its own utility function $(\pi_i(R_i))$ which can be derived from the allocated resource (R_i) and it has also a minimum desired utility $(\pi_i(R_i^0))$, called a disagreement point. The disagreement point is the minimum requirement that each user expects by joining the game. There are m different service types. Users who want to stay in this network should select one of the service types and pay for allocated resource according to the selected service type. The network manager can discriminate service levels by adjusting the bargaining power of each service type $(\beta = (\beta_1, \cdots, \beta_m))$. However, the network manager does not announce the adjusted bargaining power because it is internal decision of the network manager. The bargaining power of user i (α_i) is determined when the user selects a service type.

3 SERVICE DISCRIMINATION STRATEGIES

In this section, the procedure network manager to discriminate services with bargaining power. Adjusting the bargaining power is conducted based on the result of service selection of users.

3.1 Efficiency based Strategy

Based on the result of service type selection, the network manager adjusts its service discrimination policy. The bargaining power is the only one that the network manager can change. The efficiency, the performance measure of the system, can be calculated with the ratio between actual profit and service selection and expected profit. The expected profit can be derived from the bargaining power of each service type because it can be said that the network manager already planned to allocate a certain amount of resources, $\beta_j R^{MAX}$, to the j th service type. Therefore, considering the system performance with the resource allocation results, utility function of network manager can be defined as following equation (1):

$$EF_j(\beta) = \min\left(1, \frac{\sum_{i=1}^{n} R_i^* C_j x_{ij}}{\beta_j R^{MAX} C_j}\right) = \min\left(1, \frac{\sum_{i=1}^{n} R_i^* x_{ij}}{\beta_j R^{MAX}}\right) \quad (1)$$

Hence the network manager should adjust the resource allocation policy to maximize the system efficiency. The optimization problem of the network manager can be expressed as follows:

$$\begin{aligned} \max \quad & EF(\beta) = \prod_{j=1}^{m} EF_j(\beta_j) \\ s.t \quad & \sum_{j=1}^{m} \beta_j = 1,\ 0<\beta_j, \forall j \in \{1,...,m\} \end{aligned} \quad (2)$$

3.2 Stepwise Service Discrimination

The optimal solution of problem (2) can be found by using Algorithm 1. Algorithm 1 guarantees the optimal solution of problem (2) and it can be proved as follows. First, as $\sum_{i=1}^{n} R_i^* x_{ij}$ and R^{MAX} have nothing to do with the decision variable β_j, the optimization problem (2) can be simplified to (3). At this time, it is assumed that $\sum_{j=1}^{m} a_j \le R^{MAX}$ and $a_j \le a_{j+1}$.

$$\begin{aligned} \max \quad & \prod_{j=1}^{m} \frac{a_j}{b_j} \\ s.t \quad & \sum_{j=1}^{m} b_j = R^{MAX}, 0<b_j, \forall j \in \{1,...,m\} \end{aligned} \quad (3)$$

Algorithm 1. Stepwise Service Discrimination.

1) Calculate amount of the allocated resources for the each service type $\left(\sum_{i=1}^{n} R_i^* x_{ij}\right), \forall j = \{1,...,m\}$
2) Set the order vector of service types (SEQ) based on the amount of allocated resources
3) if $SEQ[1] \le j \le SEQ[m-1]$, $\beta_j^{t'} = \frac{\sum_{i=1}^{n} R_i x_{ij}}{R^{MAX}}$,
4) else $\beta_m^{t'} = \frac{R^{MAX} - \sum_{j=1}^{m-1} \beta_j^{t'} R^{MAX}}{R^{MAX}}$

The optimal solution of the problem is that $b_j^* = a_j, 1 \le j \le m-1$ and $b_m^* = R^{MAX} - \sum_{j=1}^{m-1} b_j$.

Let $b = (b_1,...,b_m)$ be a feasible solution. If $z(b) \le z(b^*)$ is established, then it can be said that b^* always becomes the optimal solution. First of all, it can be assumed that $b_j \ge a_j, j \in \{1,...,m-1\}$ and there exists at least one b_j meet $b_j > a_j, j \in \{1,...,m-1\}$ from the Lemma 1.

Lemma 1. If $a_i < b_i$ and $a_j < b_j$ are established, $b_i \le b_j$ can be assumed without loss of generality. Let $a_j \to b_j$ and $b_i + b_j - a_j \to b_i$, the following equation becomes true.

$$\begin{aligned} & b_i b_j - \left(b_i + b_j - a_j\right) a_j \\ & = b_j \left(b_i + b_j - a_i\right) - a_j \left(b_i + b_j - a_j\right) > 0 \end{aligned} \tag{4}$$

In order to make the proof simple and readers easily understood, let the number of service types be two. Then it can be said that $R^{MAX} = b_1 + b_2$, $a_1 < a_2$, and $a_1 + a_2 < R^{MAX}$. If $a_1 < b_1$, following inequality (5) should be true.

$$\min\left\{\frac{a_1}{b_1},1\right\} \times \min\left\{\frac{a_2}{b_2},1\right\} < \frac{a_1}{a_1} \frac{a_2}{\left(R^{MAX} - a_1\right)} \tag{5}$$

And assuming $a_2 \ge b_2$ makes the following inequality true.

$$\begin{aligned} & \min\left\{\frac{a_1}{b_1},1\right\} \times \min\left\{\frac{a_2}{b_2},1\right\} \\ & = \frac{a_1}{b_1} \times 1 = \frac{a_1}{\left(R^{MAX} - a_2\right)} \frac{a_2}{a_2} < \frac{a_1}{\left(R^{MAX} - a_1\right)} \frac{a_2}{a_1} \end{aligned} \tag{6}$$

It is the reason that Lemma 1 makes the following equation (7) established.

$$\begin{aligned} & \left(R^{MAX} - a_2\right) a_2 - \left(R^{MAX} - a_1\right) a_1 \\ & = \left(R^{MAX} - a_1 - a_2\right)\left(a_2 - a_1\right) > 0 \end{aligned} \tag{7}$$

And then, assuming $a_2 < b_2$ and $a_1 < b_2$ become established from the condition, $a_1 < a_2$. As with the case of $a_2 \ge b_2$, the following equation is established from Lemma 1.

$$\begin{aligned} & \min\left\{\frac{a_1}{b_1},1\right\} \times \min\left\{\frac{a_2}{b_2},1\right\} \\ & = \frac{a_1}{b_1} \times \frac{a_2}{b_2} = \frac{a_1}{b_1} \times \frac{a_2}{R^{MAX} - b_1} < \frac{a_1}{a_1} \frac{a_2}{\left(R^{MAX} - a_1\right)} \end{aligned} \tag{8}$$

Therefore, it is proved that the following solution is the optimal solution of problem (3).

$$b_j^* = \begin{cases} a_j & 1 \le j \le m-1 \\ R^{MAX} - \sum_{k=1}^{m-1} b_k^* & j = m \end{cases} \tag{9}$$

3.3 Profitability based Strategy

Along with the efficiency of resource allocation policy, the network manager should also consider the unit price of each service type. Generally it is more beneficial to adjust bargaining power in order to induce users to get together in the more expensive service type. Therefore, the price ratio of each service type $\left(RC_j = C_j \big/ \sum_{j=1}^{m} C_j\right)$ should be considered to adjust the bargaining power.

Combining these two service discrimination strategies can be the overall strategy as following equation (3). And weight factor, (ζ), means the weight of profitability compared to the efficiency.

$$\beta_j^{t+1} \leftarrow \zeta \cdot RC_j + (1-\zeta)\beta_j^{t'}, 0 \le \zeta \le 1 \tag{10}$$

4 RESOURCE ALLOCATION

In this section utility function of users and resource allocation algorithm will be explained.

4.1 Utility Function for Users

The utility function of each user, π_i , can be defined by summing noise ratio and the cost factor.

$$\begin{aligned} X_i &= \pi_i\left(x_i\right) = NoiseRatio_i(R_i(x_i)) + \tau_i COST(R_i(x_i)) \\ &= \frac{k_i\left(R_i\left(x_i\right) - R_i^0\right)}{D_{0i}\left(R_i\left(x_i\right) - R_i^0\right) + \mu_{0i}} + \tau_i R_i\left(x_i\right) \sum_{j=1}^{m} C_j x_{ij} \end{aligned} \tag{11}$$

The parameter τ_i is a term to adjust the scale of cost factor to distortion rate factor. Since it means the degree of cost-sensitivity, it has negative value. The first part of the function, *NoiseRatio*, is designed based on the distortion rate model (Stuhlmüller *et al.*, 2000), which is well suited for the multimedia network (Andreopoulos *et al.*, 2004). In addition, the cost factor added to the noise ratio part.

4.2 Resource Allocation: KSBS

The criteria for bargaining solution to allocate resources to users are needed. Multiple bargaining solutions which have different properties can be found in prior researches dealing with resource management problems. And they provide consideration of optimality and fairness (Monderer & Shapley, 1996; Andreopoulos *et al.*, 2004). Specifically KSBS guarantees the same quality drop from each user's maximum achievable utility (Kalai & Smorodinsky, 1975). The generalized KSBS can be obtained by the following equation (12).

$$\delta = \frac{X_1}{\alpha_1 X_1^{MAX}} = \cdots = \frac{X_n}{\alpha_n X_n^{MAX}} \qquad (12)$$

However, this equation is generally an n th degree polynomial of δ . Hence, efficient and simple numerical methods like the bisection method is required (Boyd & Vandenberghe, 2004). Because the upper and lower bounds are already known, the bisection method can be applied. After finding the optimal utility of the first user, it is easy to calculate the others' optimal utilities.

It can be said that finding the optimal resource allocation plan using KSBS means finding the maximum value of δ . It is possible to obtain the optimal resource allocation plan with the reverse function of the utility function.

$$R_i^* = \pi_i^{-1}\left(X_i^*\right)\pi_i^{-1}\left(\delta^* \cdot X_i^{MAX}\sum_{j=1}^{m}\beta_j x_{ij}\right) \qquad (13)$$

As described earlier, the optimal solution should meet three different constraints $\sum_{i=1}^{n} R_i \le R_{MAX}$, $R_i \sum_{j=1}^{m} C_j x_{ij} \le b_i$ and $\left(R_i^0 \le R_i \le R_i^{MAX}\right)$.

4.3 Utility based Service Selection

Decision problems of users, which service type should be selected, is absolutely based on the utility. If all users try to change service type at the same time, the resource allocation plan cannot be ensured. Therefore it should be assumed that only one user can change the service type at time and implement the *Elementary Stepwise System (ESS)*, where each user decides their service type sequentially. It has already proved that the ESS converges to Nash Equilibrium in polynomial time (Park & Schaar, 2007-2). The order to change the service type is determined based on the utility status, the difference between maximum required utility and current derived utility.

5 CONCLUSIONS

Different from current related researches, this paper assumed multiple service types and presented service discrimination algorithm which can be actively determined by the network manager. Moreover, users' utility function includes both concepts of quality and cost of service. Also, this paper suggested an efficient resource allocation algorithm which considers both the network manger and users.

Considering the concept of "traffic classes", it seems that discriminated services can be released over the short haul when the number of users rapidly increases, although a flat sum system is the most general way in the multi-media services such as Wibro, DMB, and IPTV. Likewise, the proposed approach can be applied when there are multiple multimedia servers and cost factor of utility function can be substituted with channel status according to the distance.

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