A Microeconomics-Based Fuzzy QoS Unicast Routing Scheme in NGI*

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Abstract. Due to the difficulty on exact measurement and expression of NGI (Next-Generation Internet) network status, the necessary QoS routing information is fuzzy. With the gradual commercialization of network operation, paying for network usage calls for QoS pricing and accounting. In this paper, a microeconomics-based fuzzy QoS unicast routing scheme is proposed, consisting of three phases: edge evaluation, game analysis, and route selection. It attempts to make both network provider and user utilities maximized along the found route, with not only the user QoS requirements satisfied but also the Pareto-optimum under the Nash equilibrium on their utilities achieved.

1 Introduction

Recently, with the convergence of Internet, multimedia content, and mobile communication technology, the NGI (Next-Generation Internet) is becoming an integrated network, including terrestrial-based, space-based, sky-based, fixed and mobile sub-networks, supporting anywhere, anytime with any kind of information to communicate with anyone or even any object in fixed or mobile way [1]. In order to provide the user with the end-to-end QoS (Quality of Service) support, each part of NGI should support the QoS, with wired QoS and wireless QoS converged seamlessly. However, it is hard to describe the network status exactly and completely. With gradual commercialization of the network operation, paying for network usage become necessary, QoS pricing and accounting should be provided [2]. However, the network providers pursue profit as much as possible, while the users wish to get the best service with the smallest cost. There exist conflicts on profits between the network providers and their users, and thus “both-win” should be attained. Support from QoS routing should be provided to help the above problems solved.

Although a lot of researches have been done on the QoS routing, the simultaneous network provider and user utility optimization and network status fuzziness are not

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considered in depth [3-6]. In this paper, a microeconomics-based fuzzy QoS unicast routing scheme is proposed. It attempts to make both the network provider and the user utilities maximized along the found route, and no other routes can make the two utilities improved simultaneously any more unless one of them is sacrificed. Thus, the Pareto-optimum under the Nash equilibrium [7] on both the network provider and the user utilities is achieved or approached along the found route.

2 Problem Formulations

A network can be modeled as a graph $G(V,E)$, where V is the set of nodes representing routers and E is the set of edges representing links. For each node $v_j \in V(j=1,2,3,\mathbf{K},|V|)$, consider the following parameters: delay, delay jitter, and error rate; for each edge $e_{jk} \in E(j,k=1,2,3,\mathbf{K},|V|)$ between $\forall v_j, v_k \in V$, consider the following parameters: available bandwidth, delay and error rate. Just for the algorithm description simplicity, the parameters of node are merged into those of its upstream edge along the route. Thus, the parameters of the edge become as follows: available bandwidth bw_{jk}, delay del_{jk}, delay jitter jt_{jk}, and error rate ls_{jk}.

Suppose that the source node is $v_s \in V$ and the destination node is $v_t \in V$, look for the specific route p_{st} between v_s and v_t, trying to make the network provider utility TNU and the user utility TUU achieve or approach the Pareto-optimum under the Nash equilibrium as much as possible with the following constraints satisfied:

A1) The available bottleneck bandwidth along p_{st} is not smaller than the user bandwidth requirement bw_req.

A2) The delay along p_{st} is not bigger than the user delay requirement del_req.

A3) The delay jitter along p_{st} is not bigger than the user delay jitter requirement jt_req.

A4) The error rate along p_{st} is not bigger than the user error rate requirement ls_req.

The corresponding mathematical model is described as follows:

$$TNU + TUU \rightarrow \max\{TNU + TUU\} \tag{1}$$

$$TNU \rightarrow \max\{TNU\} \tag{2}$$

$$TUU \rightarrow \max\{TUU\} \tag{3}$$

$$\min\{bw_{jk} \mid e_{jk} \in p_{st}\} \geq bw\_req \tag{4}$$

$$\sum_{e_{jk} \in p_{st}} del_{jk} \leq del\_req \tag{5}$$

$$\sum_{e_{jk} \in p_{st}} jt_{jk} \leq jt\_req \tag{6}$$

$$1 - \prod_{e_{jk} \in p_{st}} (1 - ls_{jk}) \leq ls\_req \tag{7}$$

Among them, $TNU = \sum_{e_{jk} \in p_{st}} nu_{jk}$, $TUU = \sum_{e_{jk} \in p_{st}} uu_{jk}$, nu_{jk} and uu_{jk} represent the network provider utility and the user utility on the edge e_{jk} respectively.

The above problem is NPC [8], and is resolved by the proposed scheme.

3 QoS Routing Scheme Descriptions

The proposed QoS routing scheme in this paper consists of three parts: edge evaluation, game analysis and route selection.

3.1 Edge Evaluation

The adaptability membership degree function is used to describe the adaptability of the candidate edge conditions to the user QoS requirements and is defined as follows:

$$g_1(bw, bw\_req) = \begin{cases} 0 & bw < bw\_req \\ \left(\dfrac{bw - bw\_req}{b - bw\_req}\right)^q + f_1(bw, bw\_req) & bw\_req \leq bw < b \\ 1 & bw \geq b \end{cases} \tag{8}$$

Among it, $f_1(bw, bw\_req) = \begin{cases} 0 & otherwise \\ \varepsilon & bw = bw\_req \end{cases}$.

The edge delay adaptability membership degree function is defined as follows:

$$g_2(Jp, del, del\_req) = \begin{cases} 0 & del > del\_req \\ 1 - e^{-\left(\frac{del\_req - del}{\sigma_1}\right)^2} + f_2(Jp, del, del\_req) & del \leq del\_req \end{cases} \tag{9}$$

Among it, $f_2(Jp, del, del\_req) = \begin{cases} 0 & otherwise \\ \varepsilon & Jp = 1 \wedge del = del\_req \end{cases}$.

The edge delay jitter adaptability membership degree function is defined as follows:

$$g_3(Jp, jt, jt\_req) = \begin{cases} 0 & jt > jt\_req \\ 1 - e^{-\left(\frac{jt\_req - jt}{\sigma_2}\right)^2} + f_3(Jp, jt, jt\_req) & jt \le jt\_req \end{cases} \tag{10}$$

Among it, $f_3(Jp, jt, jt\_req) = \begin{cases} 0 & otherwise \\ \varepsilon & Jp = 1 \wedge jt = jt\_req \end{cases}$.

The edge error rate adaptability membership degree function is defined as follows:

$$g_4(Jp, ls, ls\_req) = \begin{cases} 0 & ls > ls\_req \\ 1 - e^{-\left(\frac{ls\_req - ls}{\sigma_3}\right)^2} + f_4(Jp, ls, ls\_req) & ls \le ls\_req \end{cases} \tag{11}$$

Among it, $f_4(Jp, ls, ls\_req) = \begin{cases} 0 & otherwise \\ \varepsilon & Jp = 1 \wedge ls = ls\_req \end{cases}$.

(9)-(11) all are Gaussian alike with smooth transition feature. $f_h(h = 1,2,3,4)$ is used to deal with the special one hop route case. Jp is a positive integer, representing the hop count of end-to-end route. e is a positive pure decimal fraction and much smaller than 1. bw, del, jt and ls are the available bandwidth, delay, delay jitter and error rate of the candidate edge respectively. q, b, s_1, s_2 and s_3 all are positive constants, $q > 1$. An evaluation matrix $R = [g_1, g_2, g_3, g_4]^T$ of the candidate edge can be gotten from (8)-(11). According to the application nature, a weight matrix $W = [w_1, w_2, w_3, w_4]$ $(0 < w_1, w_2, w_3, w_4 < 1)$ is given. Here, w_1, w_2, w_3 and w_4 are the significance weights of bandwidth, delay, delay jitter and error rate on the application QoS respectively. The comprehensive evaluation value w on the candidate edge conditions with regard to the user QoS requirements is computed as follows:

$$\omega = W \times R \tag{12}$$

The bigger the value of w is, the higher the adaptability of the candidate edge conditions to the user QoS requirements is.

Whether the available bandwidth of the candidate edge is abundant can be derived from the result of (8), and thus the bandwidth supply and demand relation of the candidate edge can be deduced. If $g_1 < h_1$ (h_1 is a constant and $0 < h_1 < 1$), the available bandwidth of the candidate edge is considered to be scarce; if $h_1 \le g_1 < h_2$ (h_2 is a constant and $0 < h_1 < h_2 < 1$), the available bandwidth of the candidate edge is considered to be moderate; if $g_1 \ge h_2$, the available bandwidth of the candidate edge is considered to be abundant. Thus, a tuning coefficient for the amount of bandwidth to be actually allocated to the user is introduced, and its definition is as follows:

$$r = \begin{cases} r_1 & g_1 < h_1 \\ r_2 & h_1 \le g_1 < h_2 \\ r_3 & g_1 \ge h_2 \end{cases} \tag{13}$$

Among it, $0 < r_1 < 1$, $r_2 = 1$, $r_3 > 1$, the values of r_1 and r_3 are preset according to the actual experience. The actually allocated amount of bandwidth nbw to the user on the candidate edge is calculated as follows:

$$nbw = r * bw\_req \tag{14}$$

3.2 Game Analysis

In this paper, there are two players in the game, that is, the network provider and the user. The network provider has two game strategies: s_1 and s_2, denoting whether it is willing to provide the bandwidth of the candidate edge to the user or not respectively; the user also has two game strategies: t_1 and t_2, denoting whether he is willing to accept the provided bandwidth of the candidate edge respectively.

The network provider and the user game matrixes, NM and UM, are defined as follows:

$$NM = \begin{bmatrix} pn_{11} & pn_{12} \\ pn_{21} & pn_{22} \end{bmatrix} \tag{15}$$

$$UM = \begin{bmatrix} pu_{11} & pu_{12} \\ pu_{21} & pu_{22} \end{bmatrix} \tag{16}$$

Here, the rows in NM and UM correspond to the game strategies s_1 and s_2 of the network provider, and the columns correspond to the game strategies t_1 and t_2 of the user. The element $pn_{mn}(m,n=1,2)$ in NM represents the relative utility of the network provider on the candidate edge for s_m and t_n; the element $pu_{mn}(m,n=1,2)$ in NM represents the relative utility of the user on the candidate edge for s_m and t_n.

After the edge evaluation described in section 3.1, the comprehensive evaluation value of w on the candidate edge has been gotten. According to the actual experience, a threshold value w_0 is set. If $w > w_0$, the actual status of the candidate edge is considered better than that the user expected; if $w = w_0$, the actual status of the candidate edge is considered to be just what the user expected; if $w < w_0$, the actual status of the candidate edge is considered worse than that the user expected. Therefore, the matrix element values of NM and UM are given as follows:

$$NM=\begin{bmatrix}\dfrac{\left(uct\dfrac{w}{w_0}-uct\right)}{nbw} & \dfrac{\left(uct\dfrac{w}{w_0}-uct\right)}{nbw}\\ -m\dfrac{\left(uct\dfrac{w}{w_0}-uct\right)}{nbw} & -\dfrac{\left(uct\dfrac{w}{w_0}-uct\right)}{nbw}\end{bmatrix} \tag{17}$$

$$UM=\begin{bmatrix}\dfrac{nbw\dfrac{w}{w_0}}{uct}-\dfrac{nbw}{uct} & -m\left(\dfrac{nbw\dfrac{w}{w_0}}{uct}-\dfrac{nbw}{uct}\right)\\ \dfrac{nbw\dfrac{w}{w_0}}{uct}-\dfrac{nbw}{uct} & -\left(\dfrac{nbw\dfrac{w}{w_0}}{uct}-\dfrac{nbw}{uct}\right)\end{bmatrix} \tag{18}$$

Among (17) and (18), uct denotes the amount of money that the user should pay for his usage of the candidate edge. In NM, $uct\dfrac{w}{w_0}/nbw$ represents the virtual utility of the network provider on the candidate edge, and uct/nbw represents its actual utility, the difference between which represents the relative utility of the network provider on the candidate edge. The minus sign in pn_{21} and pn_{22} mean that, if the network provider rejectes the user, its utility will be lost. m is a penalty factor and its value is set bigger than 1 [9], meaning that rejecting one willing user would bring the negative effect on this and other users' willingness to use the services provided by the network provider in the future considerably. Similarly, in UM, $nbw/uct\dfrac{w}{w_0}$ represents the virtual utility of the user on the candidate edge, and nbw/uct represents his actual utility, the difference between which represents the relative utility of the user on the candidate edge. The negative values of elements and m in UM have the similar meanings as those in NM. In NM or UM, if the values of pn_{mn} and pu_{mn} are negative, it does mean that the network provider and/or the user are/is not satisfied on the current game strategy combinations. If the following inequations [10] are satisfied:

$$\begin{cases} pn_{m^*n^*} \geq pn_{mn^*} \\ pu_{m^*n^*} \geq pu_{m^*n} \end{cases} \qquad m,n=1,\ 2 \tag{19}$$

The corresponding strategy pair $\{s_{m^*}, t_{n^*}\}$ represents a pair of non-cooperative pure strategies, namely the specific solution under Nash equilibrium [11], here, m^* and n^* stand for some *m* and *n*.

3.3 Route Selection

Heuristic cost. After the game result of the candidate edge e_{jk} is gotten, it is transformed into one kind of weight, denoted by Ω_{jk}, which is defined as follows:

$$\Omega_{jk} = \begin{cases} 1 & Nash\ \ Equilibrium \\ >1 & non\text{-}Nash\ \ Equilibrium \end{cases} \tag{20}$$

The heuristic cost $T_{f_{jk}}(\Omega_{jk}, nu_{jk}, uu_{jk})$ of e_{jk} is defined as follows:

$$T_{f_{jk}}(\Omega_{jk}, nu_{jk}, uu_{jk}) = \Omega_{jk}\left(q_1 \frac{1}{nu_{jk}} + q_2 \frac{1}{uu_{jk}}\right) \tag{21}$$

In formula (21), Ω_{jk} represents the influence of Nash equilibrium on the route selection. q_1 and q_2 are the preference weights, representing whether and how much the network provider/user utility should be considered with priority when routing. nu_{jk} and uu_{jk} use the actual utility of the network and the user respectively.

The objective of the proposed scheme in this paper is to minimize the heuristic cost sum along the route, that is,

$$minimize\left\{\sum_{e_{jk}\in p_{st}} T_{f_{jk}}(\Omega_{jk}, nu_{jk}, uu_{jk})\right\} \tag{22}$$

Routing Algorithm. v_s and v_t are source and destination node respectively. Let pc and Tc denote pc label and Tc label of node v. $pc(v)$ is the minimum heuristic cost from v_s to v with the specific constraints satisfied. $Tc(v)$ is the upper bound of $pc(v)$. S_i is the set of those nodes with pc label at Step i. Each node is given a l. When the proposed algorithm ended, if $l(v) = m$, the precedent node of v along the route with the minimum heuristic cost is v_m; if $l(v) = m'$, there does not exist the satisfied route from v_s to v; if $l(v) = 0$, $v = v_s$. How to assign certain value to l is described in (6) of $2nd$ labeling at Step1, that is, when the $1st$ and $2nd$ labeling conditions are met with, the l value of the considered node is marked as the number of the specific node leading to it along the route with the minimum heuristic cost. In addition, $minbw(v_j)$ is the available bottleneck bandwidth; $del(v_j)$ is the delay; $jt(v_j)$ is the delay jitter; and $ls(v_j)$ is the error rate along the path from v_j to v_s. $T_{f_{kj}}$, bw_{kj}, del_{kj}, jt_{kj}, and ls_{kj} are the heuristic cost, the available bandwidth, the delay, the delay jitter, and the error rate of the edge e_{kj} respectively. Based on the algorithm proposed in [8], the following routing algorithm is designed:

Step0. Initialization: $i = 0$, $S_o = \{v_s\}$, $l(v_s) = 0$. $\forall v \neq v_s$, $Tc(v) = +\infty$, $l(v) = m'$, $k = s$.

(1) $pc(v_k) = 0$;

(2) $minbw(v_k) = +\infty$;

(3) $del(v_k) = 0$, $jt(v_k) = 0$, $ls(v_k) = 0$;

Step1. Labeling procedure

For each node v_j with $e_{kj} \in E$ and $v_j \notin S_i$, compute $T_{f_{kj}}$ according to (8)-(21).

1*st* labeling condition: in order to meet with the objective of (22), if $Tc(v_j) > pc(v_k) + T_{f_{kj}}$, compute as follows:

(1) $pc'(v_j) = pc(v_j) + T_{f_{kj}}$;

(2) $minbw'(v_j) = min\{minbw(v_k), bw_{kj}\}$;

(3) $del'(v_j) = del(v_k) + del_{kj}$, $jt'(v_j) = jt(v_k) + jt_{kj}$, $ls'(v_j) = 1 - (1 - ls(v_k))(1 - ls_{kj})$;

2*nd* labeling condition: according to (4)- (7), if

(1) $minbw'(v_j) \geq bw\_req$;

(2) $del'(v_j) \leq del\_req$, $jt'(v_j) \leq jt\_req$, $ls'(v_j) \leq ls\_req$;

then

(1) $Tc(v_j) = pc'(v_j)$;

(2) $minbw(v_j) = minbw'(v_j)$;

(3) $del(v_j) = del'(v_j)$, $jt(v_j) = jt'(v_j)$, $ls(v_j) = ls'(v_j)$;

(4) $l(v_j) = k$;

go to Step2; otherwise, negotiate with user: if succeeded, go to Step2, otherwise the algorithm ends.

Step2. Modification procedure

In order to meet with the objective of (22), let $H_1 = \left\{ v_{j_i} \mid \min_{v_{j_i} \notin S_i} \{Tc(v_{j_i})\} \right\}$. For any $v_{j_i} \in H_1$, if $Tc(v_{j_i}) < +\infty$, go to Step2.1; otherwise, there does not exist any feasible solution, and then negotiate with the user: if succeeded, go to Step2.6, otherwise the algorithm ends.

Step2.1. If $|H_1| = 1$, get $v_{j_i} \in H_1$, and go to Step2.6; otherwise go to Step2.2.

Step2.2. Let $H_2 = \left\{ v_{j_i} \mid \max_{v_{j_i} \in H_1} \{\min bw(v_{j_i}) - bw\_req\} \right\}$. If $|H_2| = 1$, get $v_{j_i} \in H_2$, and go to Step2.6; otherwise go to Step2.3.

Step2.3. Let $H_3 = \left\{ v_{j_i} \mid \max_{v_{j_i} \in H_2} \{del\_req - del(v_{j_i})\} \right\}$. If $|H_3| = 1$, get $v_{j_i} \in H_3$, and go to Step2.6; otherwise go to Step2.4.

Step2.4. Let $H4 = \left\{ v_{j_i} \mid \max_{v_{j_i} \in H_3} \left\{ jt\_req - jt\left(v_{j_i}\right) \right\} \right\}$. If $\left|H_4\right| = 1$, get $v_{j_i} \in H_4$, and go to Step2.6; otherwise go to Step2.5.

Step2.5. Let $H_5 = \left\{ v_{j_i} \mid \min_{v_{j_i} \in H_4} \left\{ ls\left(v_{j_i}\right) \right\} \right\}$. If $\left|H_5\right| = 1$, get $v_{j_i} \in H_5$, and go to Step2.6; otherwise, get any $v_{j_i} \in H_5$, and go to Step2.6.

Step2.6. Modify the Tc label to pc label, that is, let $pc\left(v_{j_i}\right) = Tc\left(v_{j_i}\right)$ and $S_{i+1} = S_i \cup \left(v_{j_i}\right)$, $k = j_i$, $i = i + 1$, if $k = t$, output the results and the algorithm ends, otherwise go to Step1.

4 Performance Evaluations and Conclusions

Simulations have been done on NS (Network Simulator) 2 platforms [12]. SPF-based unicast routing scheme, fuzzy-tower-based QoS unicast routing scheme and the scheme proposed in this paper have been performed over some actual and virtual network topologies (Fig.1, Fig.2 and Fig.3 are three examples), and performance comparisons among them have been done. For simplicity, the above three schemes are denoted by SPF, FTQ, and MFQ respectively.

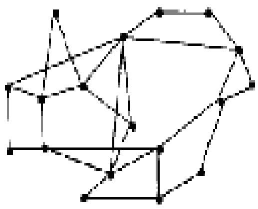

Fig.1 The 1*st* topology

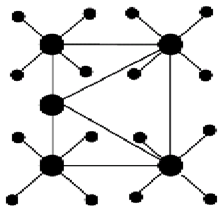

Fig. 2 The 2*nd* topology

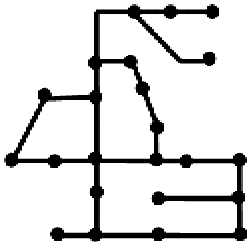

Fig.3 The 3*rd* topology

About the network provider utility, the user utility and the comprehensive utility (the network provider utility plus the user utility), SPF:MFQ:FTQ over 1*st*, 2*nd* and 3*rd* topologies are shown in Fig.4, Fig.5 and Fig.6 respectively. Simulation results have shown that the proposed scheme is effective and efficient.

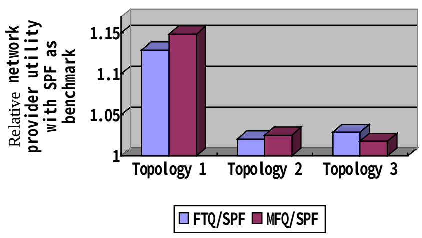

Fig.4 Comparison of network provider utility

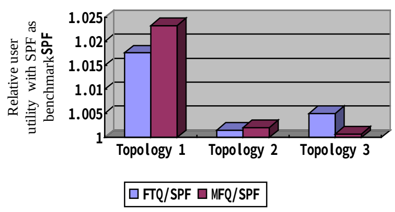

Fig.5 Comparison of user utility

In future, the proposed scheme will be improved on its practicability with its prototype systems developed and its extensions to multicast scenarios will also be done. In addition, taking the difficulty on exact and complete expression of the user QoS requirements into account, how to tackle the fuzziness of both the user QoS requirements and the network status in our proposed scheme is another emphasis of our future research.

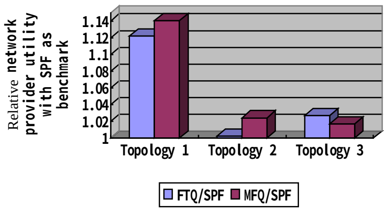

Fig.6 Comparison of comprehensiveutility

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