Optimal Packet Price for Differentiated Internet Services

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ABSTRACT

As the Internet service evolves from the best effort data service to a multimedia service such as a mix of voice, data and video, a need for the guarantee of the quality of service to network services became one of the hot issues for the network operators. On the other hand, the introduction of the multimedia services over the IP network requires a managed differentiated service that adopts a prioritized treatment of packets. This incurs a need for a differentiated pricing scheme for the packets that receive different level of quality of service. This work proposes an analytic framework about packet pricing scheme for these services, and investigate the effect of service differentiation to the packet price for each class. Via numerical experiment, we validate our argument and illustrate the implication of the work

Key Words : DiffServ Internet, Quality of Service, Revenue Maximization, Optimal Price

Ⅰ. Introduction

Recently, real-time services such as VoIP(Voice over IP), VoD(Video on demand) and video telephony are introduced to an IP network where the conventional data-oriented BE(Best effort) Internet services have been served. In order to keep the current customers loyal to their network, ISPs have to offer better than today's offering by preparing QoS(Quality of service) mechanisms to the users. In order to guarantee strict QoS requirements such as packet delay and loss, packet service schemes such as the IntServ(Integrated services) or DiffServ(Differentiated services) are needed in the IP network[1].

IntServ aims at the guarantee of a deterministic QoS to a flow, where flow is defined as a sequence of packets belonging to one application. However, IntServ has drawbacks such as the limited scalability and low network utilization, so that it is not widely used in the whole scale of the IP network.

On the other hand, DiffServ exploits the advantage of the multiplexing and differentiation of QoS at the packet level, via which network can realize high scalability as well as guarantee of differentiated QoS[1].

It is usual that backbone of the network adopts the DiffServ scheme as a means to guarantee QoS to multimedia services. However, when it comes to the edge of the network, no DiffServ scheme is recommended. As such, the edge of the network is deprived of QoS.

Let us assume a DiffServ architecture in the IP networks, where a prioritized packet service scheme at the edge as well as the backbone of the network is introduced, via which QoS can be ensured to the real-time services.

It is usual that web access and VoIP account for the most of the traffic in the current IP network. Therefore, for the purpose of simplicity, let us assume that there exist two types of traffic class: class 1 for real-time service such as VoIP and class 2 for best effort Internet service such

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as the web browsing. Extension to multiple numbers of classes greater than two is trivial.

When class 1 packets are served with strict high priority over the class 2 packets, class 1 packets can be served with low delay as well as low packet loss if the offered load of class 1 packet itself is kept to a certain level[2]. On the other hand, class 2 packets can use a portion of bandwidth that is not used by class 1 packets, so that class 2 packets can meet unexpected packet delay.

From this discussion we can find that good quality of class 1 packet is obtained at the cost of quality degradation of class 2 packet. As such, there must be some way to reflect this incentive to a class 1 packet. That is, price for serving class 1 packet has to be higher than that of class 2 packet. Here, we have a problem: How much per-packet price has to be imposed upon the class 1 packets as compared to the class 2 packets? To the best of authors' knowledge, we could find no result about this problem. This is the primary purpose that we want to investigate in this work.

In this work we propose an analytic framework for the packet price in the DiffServ network with the following basic philosophy: We propose a method to present closed-form expressions for optimal packet price about the DiffServ Internet service that incorporates prioritized QoS service. To be more specific, let us describe the focus of our model from two points of view: service model and the pricing model.

As to the service model, let us assume a black-box model for the IP network with DiffServ architecture inside it. Also we use an M/G/1 queue with non-preemptive SP(Strict priority) service scheme that accommodates both premium traffic and BE traffic in a shared link, via which differentiation of QoS can be provided to each class.

As to the pricing model, our aim lies in two points: One is the differentiation of the perceived QoS to a differentiated per-packet price. The other is the maximization of the revenue for the ISP(Internet service provider).

Via mathematical optimization method we obtain an explicit and closed-form solution for the optimum price for the packets under the given constraint. This is the main contribution of this work.

This paper is composed as follows: In Section II, the state of the research for the pricing scheme about DiffServ network is reviewed. In Section III, a typical Internet service model is presented. In Section IV, a pricing model is described under the constraint of revenue maximization. In Section V, numerical results and implication of the work is presented. Finally, in Section VI, we summarize the work.

Ⅱ. Related Works on DiffServ Pricing

Let us investigate the state of the research for differentiated packet pricing and discuss possibility of improvement from the current results, which is the main contribution of this work.

Nguyen et al. presented a comprehensive review of the pricing schemes of the current and future Internet[3]. They summarized the history of the Internet pricing, where they discussed the pros and cons of various schemes for the current and future Internet by scanning the related works done for the last decade. From Nguyen's work we found that differentiated packet pricing is favorable as a pricing scheme for a DiffServ network where packets from different traffic class pay different price. However, we could find no specific method for the computation of packet price that incorporates the generic attributes of the DiffServ architecture from their work.

When it comes to the research for the pricing with QoS, we can find the work from Zhang, Mendelson, and Simon, etc. Zhang et al. proposed a pricing scheme for the data network with delay guarantee[4], where a pricing scheme for the data services with delay QoS guarantee is discussed. They assumed an M/G/1 queue with no priority, and investigated the impact of the pricing scheme on the social welfare as well as the consumer/provider surplus. The limit on this work lies in the ignorance of the differentiated packet scheduling scheme in the DiffServ architecture.

Mendelson et al. considered a pricing scheme for a multi-class M/M/1 queue with non-posted priority pricing scheme, where they presented an optimal price upon which the expected net value of the jobs is maximized[5]. They argued that their model can be easily extended to an M/G/1 queue. However, no practical discussion about the attributes of the DiffServ services is done.

Simon et al. extended the model of Mendelson et al., and proposed a framework for the packet price for a service differentiation scheme in IP network with revenue maximization[6]. They extended the traditional bandwidth model for the BE traffic by assuming a two-class bandwidth model.

However, Simon's model has a few drawbacks. First, they assumed a redemption scheme with respect to the backlog of non-real-time packets by assuming that the delay for the real-time packets is guaranteed by SLA(Service level agreement). However, this is not realistic in the following two points. First, the delay of real-time packets can be affected by the offered load of non-real-time traffic, which will be shown later. Second, the standard for the current Internet does not mendate the guarantee of delay for the best effort service. Therefore, we argue that Simon's pricing model is not realistic to the Internet model.

Next, the Simon et al.'s model assumes a separate bandwidth for the high and low class traffic, which is not only unrealistic in implementing their scheme at the router but also inaccurate in the estimation of the expected delay for BE traffic. The realistic IP router serves packets from high and low class based on the implemented packet scheduling scheme, which is complicated than the Simon's simplified model.

Finally, the Simon et al.'s model assumes measurement-based bandwidth estimation for the high and low-class traffic. However, it is not easy to compute the packet price in real-time by measuring the available bandwidth for each class. Packet price should be determined before the service is introduced.

In addition, Simon et al.'s work used a simulation method to obtain the price of packets. Note that a closed-form solution will give us information about the incentive-compatibility in more explicit way.

Elovici et al. proposed a per-packet pricing scheme in the DiffServ network, which computes per-packet price based on the actual service received by the network[7]. Their scheme charges the users based on the actual service level or the state of the queue. However, their work does not show a discussion on the problem of revenue maximization and explanation on the relationship between the perceived QoS and price in an explicit manner.

Ⅲ. DiffServ Service Model

In this section, we describe a typical DiffServ Internet service model where class 1 users generate real-time services such as the voice or video and the class 2 users generate non-real-time services such as file transfer and e-mail.

As to the QoS, basic building blocks such as packet classification and scheduling are provided to each class where packets from class 1 users receive service with high priority than those from the class 2 users. In this work let us argue that we can decompose the delay budget defined for the end-to-end path of the source-destination pair into the nodal budget, which can be seen in[8],[9].

It is usual that the delay budget at the edge network is tight when a very high-speed backbone network with reliable QoS scheme is provided. From this argument, we can simplify that the delay budget for the edge network is the only performance measure of concern, and the remaining budget is ignorable. This is in line with the basic concept of the edge pricing, where contraction of SLA and pricing is carried out. From now on let us focus only at the edge node of the network.

There exist lots of packet service models that utilize prioritized packet services in IP network.

The typical two schemes are SP and WFQ(Weighted fair queuing). SP gives an absolute priority to higher classes of packets, whereas WFQ gives relative priorities between competing classes. For a detailed description for the service scheme, refer to [2]. This work assumes the SP scheme.

Let us assume an approximate model about delay performance for the SP scheme in a node by using M/G/1 queuing model, where a link is modeled as a single server, the arrival process is Poisson, the service time is generally distributed, and the buffer capacity is sufficiently large. Furthermore, let us assume the server is non-preemptive.

Let us describe the model briefly. Packet arrival process from each class is mutually independent, and it follows a Poisson process with mean arrival rate λ_1 and λ_2, for class 1 and class 2 packets, respectively. The service time of packets from each traffic class follows a general distribution with mean service time $1/\mu_1$ and $1/\mu_2$ for class 1 and class 2 packets, respectively. The variance of the service time of packets from each traffic class is assumed to be σ_1^2 and σ_2^2, respectively. The mean offered load of the class 1 and class 2 packets into corresponding buffer is $\rho_1 = \lambda_1/\mu_1$ and $\rho_2 = \lambda_2/\mu_2$, respectively. The total offered load ρ to the system is given by $\rho = \rho_1 + \rho_2$.

There exist a well-known result for the mean waiting time of class 1 and class 2 packets for the SP scheme, and one can find comprehensive results for the delay performance for each class of packets in the SP scheme, which is given in [2]. The mean waiting time of class 1 packet is given in (1).

$$W_1 = \frac{\sum_{i=1}^{2} \lambda_i \tau_i}{2(1-\rho_1)} \tag{1}$$

where $\tau_i = \sigma_i^2 + \frac{1}{\mu_i^2}$, for i=1 or 2

In (1), it is assumed that $\rho_1 < 1$ as a stability condition for the system. The mean waiting time of a class 2 packet in the system is given in (2).

$$W_2 = \frac{\sum_{i=1}^{2} \lambda_i \tau_i}{2(1-\rho_1)(1-\rho_1-\rho_2)} \tag{2}$$

Note that there exists the following relationship between W_1 and W_2:

$$W_2 = W_1 \frac{1}{(1-\rho)} \tag{3}$$

Therefore, we can find that W_2 is always greater than W_1, which is inversely proportional to the marginal load of the system. This implies that class 1 packet receives high incentive as compared to class 2 packet. Therefore, it is natural that the price of serving class 1 packet has to be higher than that of class 2 packet, which is incentive-compatible.

Note, however, that one can not use eq.(3) as an index of incentive-compatibility, because user's satisfaction about the delay performance does not map with eq.(3) in a linear manner, so that one has to develop a means to represent the incentive-compatibility, which is elaborated in Section IV.

Ⅳ. Pricing Differentiated Service

Let us present a basic rule for pricing the packet in the DiffServ Internet service. First, the price of the network usage is based on the sender-pay-the-price principle. Second, per-packet pricing is based on the incentive-compatibility of the service provided by the network. That is, the price for the high-priority service is higher than that for the low-priority service.

When a prioritized packet treatment is introduced to the DiffServ architecture with two-class users, charge is levied to each class such that the total revenue of the network service is maximized.

Let us denote the price of successful transmission of a class 1 and class 2 packet to be p_1 and p_2 respectively. Since the mean arrival rate of the class 1 and class 2 packet is λ_1 and λ_2, respectively, the price for each type of packet is given as follows:

$$V_1 = p_1\lambda_1, \quad V_2 = p_2\lambda_2 \tag{4}$$

On the other hand, the ISP has to redeem some amount of money to the user when the delay performance of the network is not satisfactory to the user, which is proportional to the incurred delay. As we have described before, class 2 packets do not claim redemption due to delay because they belong to a BE service.

However, when it comes to the class 1 packets, there exists possibility of delay at the network due to the random nature of the offered load and bursty property of class 2 traffic. Therefore, it is highly probable that users who transmit class 1 packets get intolerant about unexpected delay.

Therefore, we argue that the user inconvenience can be quantified as a minus-utility of a service, and a certain amount of money has to be redeemed to a user for the minus-utility, which is a function of the mean delay[10].

There exist various types of functions that illustrate the minus-utility due to delay[11,12]. Yamori et al. proposed a power-law function of the mean waiting time for the utility function in [11], whereas Shenker et al. assumed different types of utility functions for the different types of applications in[12].

In this work let us assume that the minus-utility is proportional to the mean packet delay, based upon which let us define the redemption fee as follows: ξ per backlogged packet is assigned to the mean experienced delay in the class 1 queue. Then, from the Little's law, the amount of packet waiting in the queue of class 1 service is $\lambda_1 W_1$, and the redemption fee to a flow is equal to $\xi\lambda_1 W_1$.

Finally, we obtain the total revenue R_T of an ISP by adding the price for class 1 and class 2 packets and subtracting the redemption fee due to delay penalty for class 1 packets, which is given in (5).

$$R_T = V_1 + V_2 - \xi\lambda_1 W_1 \tag{5}$$

Note here that R_T should be non-negative, otherwise there is no reason for the ISP to operate the network. Note also that R_T is concave with respect to λ_1. This can be easily observed if we arrange the formula R_T as a function of λ_1, which results in a function in the form given as follows:

$$R_T = \frac{-L\lambda_1^2 + M\lambda_1 + N}{2(1-a\lambda_1)} \tag{6}$$

where

$$\begin{aligned} &a = 1/\mu_1, \\ &L = 2p_1 a + \xi\tau_1, \\ &M = 2p_1 - 2p_2 a\lambda_2 - \xi\tau_2\lambda_2, \\ &N = 2p_2\lambda_2 \end{aligned}$$

Now let us fix λ_1 to a constant, and observe the function R_T when λ_2 increases. Note that R_T is not concave with respect to λ_2. Instead, it increases as λ_2 increases, which has the following formula.

$$R_T = A\lambda_2 + B \tag{7}$$

where

$$\begin{aligned} &A = p_2 - \frac{\tau_2\xi\lambda_1}{2(1-a\lambda_1)}, \\ &B = \left(p_1 - \frac{\tau_2\xi\lambda_1}{2(1-a\lambda_1)}\right)\lambda_1 \end{aligned}$$

Therefore, we may have a maximum for R_T at a certain point in the plane composed of two axes λ_1 and λ_2.

Since the delay performance of class 2 packets as well as the class 1 packets are closely dependent on the mixing ratio of the load of the class 1 and class 2 packets, the purpose of the network operators is to maximize R_T for all values of λ_1 and λ_2, which is stated as follows:

$$\begin{aligned} &Objective: \underset{\lambda_1,\lambda_2}{Max} R_T = V_1 + V_2 - \xi\lambda_1 W_1 \\ &Condition: R_T \geq 0, \rho_1 + \rho_2 < 1 \end{aligned} \tag{8}$$

Here let us assume that users of class 1 and class 2 service generate packets independently from each other, so that λ_1 and λ_2 are independent from each other.

On the other hand, note that the upper limit for the offered load of each class can be regulated by the network operator such that the mean delay to a class 1 packet is kept to a certain upper bound. Note also that the total offered load to a system is not greater than the operating limit, which is also determined by a network operator.

The necessary condition for the existence of maximum in the function given in (8) gives us the following result:

$$\frac{\partial R_T}{\partial \lambda_1} = 0 \tag{9}$$

Since λ_1 and λ_2 are independent from each other, we obtain eq. (10).

$$p_1 = \xi \frac{\partial}{\partial \lambda_1}(\lambda_1 W_1) \tag{10}$$

Similarly for λ_2, from $\frac{\partial R_T}{\partial \lambda_2} = 0$, we obtain eq.(11).

$$p_2 = \xi\lambda_1 \frac{\partial W_1}{\partial \lambda_2} \tag{11}$$

Let us present an explicit formula for p_1, which can be obtained from eq.(10) using eq.(1).

$$\begin{aligned} p_1 &= \xi \frac{\partial}{\partial \lambda_1} \left\{ \frac{\lambda_1(\lambda_1\tau_1 + \lambda_2\tau_2)}{2(1-\rho_1)} \right\} \\ &= \xi \left(\frac{2\tau_1\lambda_1 + \tau_2\lambda_2}{2(1-\rho_1)} + \frac{\tau_1\lambda_1^2 + \tau_2\lambda_1\lambda_2}{2\mu_1(1-\rho_1)^2} \right) \end{aligned} \tag{12}$$

In the same way, we have the following formula for p_2:

$$\begin{aligned} p_2 &= \xi\lambda_1 \frac{\partial}{\partial \lambda_2} \left\{ \frac{\lambda_1\tau_1 + \lambda_2\tau_2}{2(1-\rho_1)} \right\} \\ &= \frac{\xi\tau_2\lambda_1}{2(1-\rho_1)} \end{aligned} \tag{13}$$

From the result (12) and (13) we can find that the price of class 1 packet is always higher than that of class 2 packet.

One can also find that the packet prices depend on the following factors: the source traffic parameters such as the arrival rate and the size of class 1 and class 2 packets, the load condition, and the redemption fee.

On the other hand, the redemption fee ξ can not be determined by mathematical analysis. It can be determined by the policy of the network operator, which is determined by a market force and the charging policy of the network service provider.

Ⅴ. Numerical Experiments

In this section let us investigate the packet price of two typical services in the Internet. That is, let us compute p_1 and p_2 by assuming two scenarios: In the first scenario, let us assume that a link is shared by VoIP and HSI(High speed Internet) as a class 1 and class 2 traffic, respectively. In the second scenario, let us assume that a link is shared by VoD and HSI as class 1 traffic and class 2 traffic, respectively.

5.1 Packet price for the combination of VoIP and HSI

Let us assume the following parameters for the Internet services: the mean packet size for the VoIP and HSI is 200 and 500bytes, respectively. Let us assume that the packet size of the VoIP is constant, but that for the HSI is variable where the standard deviation for the packet size of class 2 packets to be 150bytes. Let us also assume that the link speed allocated to a user is 2Mbps, which can sufficiently accommodate simultaneous services of VoIP and HSI to a user. Finally, let us assume that the unit redemption fee ξ is assumed to be 1 cent per packet.

In order to investigate the per-packet price for each class, let us assume that the offered load of class 2 traffic is assumed to be 0.3, 0.5, and 0.7. Under each condition let us investigate the packet price of VoIP and HSI services as the offered load of the voice packet increases.

Fig.1 illustrates the packet price for the VoIP service. The curve with index rho_2 = K shows the result for $\rho_2 = K$. The x-axis is the mean offered load ρ_1 of VoIP traffic, whereas the y-axis is the packet price p_1(unit:10^{-3}cent).

As one can see from Fig. 1, the packet price of VoIP service increases as the offered load of VoIP service increases. This implies that the proposed packet pricing scheme can act as a means to oppress the users for their overuse of network bandwidth, via which the network can avoid network congestion.

Note also that the packet price for class 1 service with less available bandwidth has to be higher than that of more avaliable bandwidth. For example, under the same condition for the offered load of $\rho_1 = 0.3$, the packet price of class 1 service with ρ_2=0.7 is 1.84(unit:10^{-3}cent), whereas the packet price of class 1 service with ρ_2=0.3 is 1.03(unit:10^{-3}cent). This is very similar to the basic rule of economy where the price of commodity is expensive for the consumption of rare items.

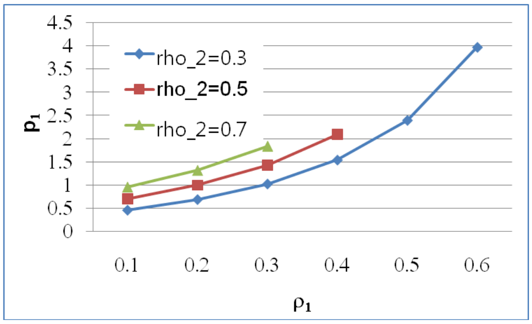

Fig. 1. Packet price for VoIP

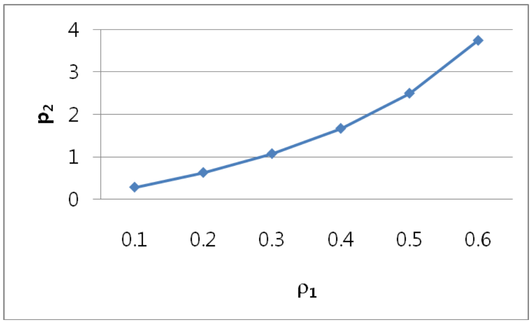

Fig. 2. Packet price for HSI

Fig. 2 illustrates the packet price for the HSI service. The x-axis is the mean offered load ρ_1 of VoIP traffic, whereas the y-axis is the packet price p_2(unit:10^{-3}cent). Note that the packet price for the HSI service is independent of the offered load of class 2 traffic, which is evident from eq.(13). Note also that the packet price of HSI service increases as the offered load of class 1 traffic increases. This implies that the proposed packet pricing scheme can also act as a means to oppress the users for their overuse of network bandwidth for BE service when more network resource is required for the class 1 service, via which the network can avoid the degradation of class 1 service.

This is in line with the fundamental rule of thumb for the economy where the price of commodity is expensive when the resource is rare.

5.2 Packet price for the combination of Vod and HSI

Note that, even though VoIP and VoD services are all categorized into the real-time service in the DiffServ Internet, they have different attributes in the characteristics of source profile. We conjecture that this will affect the packet price. In order to investigate the effect of the attribute of the size of packet in the class 1 traffic to the packet price, let us assume a video source for the class 1 traffic. The video source is assumed to have a mean packet size of 500bytes and standard deviation of 150bytes. The other parameters for the network as well as the data traffic are assumed to be the same as that of the experiment shown in Fig. 1.

Fig. 3 illustrates the price of video packet when the offered load of VoD service increases. The x-axis is the mean offered load ρ_1 of VoD traffic, whereas the y-axis is the packet price p_1 (unit:10^{-3}cent) for VoD service. The curve with index rho_2=K shows the result for $\rho_2 = K$.

As one can see from Fig.3, the packet price of VoD service increases as the offered load of VoD service increases. This implies also that, as we have argued in Fig.1, the proposed packet pricing scheme can act as a means to oppress the users for their overuse of network bandwidth, via which the network can avoid network congestion. This is very similar to the basic rule of economy where the price of commodity is expensive for the consumption of rare items.

Fig.4 illustrates the packet price for the HSI service. The x-axis is the mean offered load ρ_1 of VoD traffic and the y-axis is the packet price p_2(unit:10^{-3}cent).

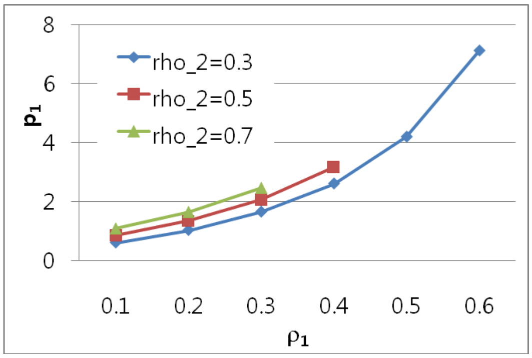

Fig. 3. Packet price for VoD

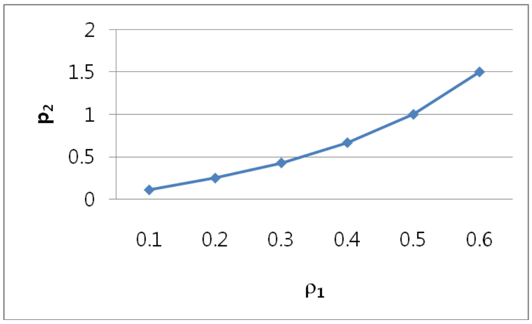

Fig. 4. Packet price for HSI

If we compare the packet price p_2 for the two scenarios, the packet price p_2 for the mix of VoD and HSI is cheaper than that of the mix of VoIP and HSI. On the other hand, the packet price p_1 for the mix of VoD and HSI is more expensive than that of the mix of VoIP and HSI. This implies that the more severe the required QoS is(VoD requires more bandwidth than VoIP), the more expensive the packet price is. This corresponds to the incentive-compatibility, too.

Therefore, the proposed pricing scheme is incentive-compatible in the wide-sense.

Ⅵ. Conclusions

In this work we have proposed an analytic framework to evaluate the packet price of the DiffServ Internet under the constraints of revenue maximization. Our proposal yields useful and intuitive means for the packet price of the real-time services as well as the BE services.

The main implication of this work is that the proposed scheme gives us analytic formulae that are explicitly represented by the system parameters concerning the source traffic profile and the network parameters, via which network operators can obtain useful insights about the effect of service differentiation to the packet price such that an individual customer chooses a premium service at the cost of paying high price.

Via numerical experiment we arrived at the following conclusions: First, there is a clear correlation between service differentiation and the packet price, which means that the packet price for the high-class service should be expensive as compared with low-class service. When it comes to the packet price of video service, this is more evident, which means that the packet price for the video service deserve to be expensive as compared to the current HSI service.

Second, the differentiated packet pricing scheme for the differentiated service can act as a means to congestion prevention to the Internet.

Therefore, we argue that the proposed differentiated packet pricing scheme can be used as a means to suppress the overuse of the network bandwidth by levying higher packet price to the users when the offered load of the network is high.

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