JACET Journal of Advances in Computer Engineering and Technology, 1(1) 2015

A Differentiated Pricing Framework for Improving the Performance of the Elastic Traffics in Data Networks

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Received (21-8-2011)
Accepted (17-10-2011)

***Abstract* - Rate allocation has become a demanding task in data networks as diversity in users and traffics proliferate. Most commonly used algorithm in end hosts is TCP. This is a loss based scheme therefore it exhibits oscillatory behavior which reduces network performance. Moreover, since the price for all sessions is based on the aggregate throughput, losses that are caused by TCP affect other sessions as well and aggressively reduce their throughput and also have a drastic effect on the overall goodput of the system. In this paper a new differentiated pricing method is proposed that not only reduces the loss phenomenon in the network, it improves the overall performance of the network and allows other sessions such as Proportional or Minimum Potential Delay schemes achieve more fair rates. Stability property of the algorithm is investigated and some numerical analysis is presented to verify the claims .**

***Index Terms* - AQM, Congestion control, Rate allocation, TCP, Fairness.**

I. INTRODUCTION

RATE control is one of the important tasks of end hosts in avoiding congestion in data networks. The most prevalent algorithms implemented in operating systems nowadays are variations of TCP. Improvement to this algorithm has long been of major consideration by research groups and as a result new improved substitutions are proposed, as those we will discuss in the paper.

But the compatibility of new algorithms with the conventional ones should be studied. It is shown that in the conventional environments in which the usual Active Queue Management (AQM) used in intermediate nodes, the interaction between TCP and other methods would decrease the overall performance. Other variants of TCP algorithm are XCP [1], Fast TCP [2] and MulTCP [3].

Two different methods exist for accomplishing congestion control in the data networks. One is window-based method in which the number of outstanding packets in the network is regulated by adjusting the size of the congestion window to a reference value [4]. In the rate-based methods, we look at the network traffics as fluid flows and algorithms such as the Kelly's method are used in order to achieve some fairness criteria in rate allocation [5].

There are different fairness criteria such as max-min, proportional and minimum potential delay fairness [6]. Selecting a fairness criterion depends on the network's designer strategy.

For example in the max-min criterion, the focus is on the users with lowest rates whereas in proportional criterion the objective is to maximize the sum of the logarithms of the user rates and penalize more the users who use long routes in the network. In minimum potential delay criterion,

L. Massoulié et al. define a delay measure in terms of the user rates and try to minimize that.

In this paper we assume that the network traffic can adapt itself to the network conditions. In another word, we use the term 'elastic' for the traffic as it was introduced by

S. Shenker in [7] and used in the Kelly's paper [5]. Examples of such traffic type are TCP traffic in the current Internet and ABR traffic in the ATM networks.

1- This work was supported in part by the Iran Telecom Research Center (ITRC) under Grant 8732353.
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As it is known, large networks such as the Internet have been designed to be decentralized and depend on the well-defined behavior from end-hosts. The increasing complexity and size of these networks make centralized rate allocation impractical. Without a centralized control, the network users have a great deal of freedom in sharing the available bandwidth in the network.

To achieve the flow control, congestion avoidance and bandwidth allocation, the researchers have proposed different rate allocation algorithms to be implemented at the end-hosts in a decentralized manner as discussed in [8], [9], [10] and [11].

The most widely used flow control/congestion avoidance mechanism in the current Internet is TCP, which is a window-based mechanism. TCP, however, does not necessarily lead to a fair or efficient rate allocation of the available bandwidth [4].

Recently, Kelly et al. have proposed an algorithm that results in proportional fairness criterion and they used a Lyapunov function approach for stability analysis of their rate allocation method [5].

Mo and Walrand [4] have proposed and studied another fair window-based end-to-end congestion control mechanism, which is similar to TCP Vegas [12] but has a more sophisticated window-updating rule. They have shown that the proportional fairness can be achieved by their $(\Omega,1)$- proportionally fair algorithm and max-min fairness can be achieved as a limit of (Ω,α)- proportionally fair algorithm as α goes to infinity.

It is clear that fairness is a desirable feature of a rate allocation algorithm. Users' preferences can be captured by appropriate utility functions. Due to the various requirements of different applications, it is likely that the users will have different utility functions [7]. For example, suppose that a user is transferring a file. The per-transfer delay is inversely proportional to the rate it receives. Hence, the delay might be modeled as the utility function of the user which is a function of its rate. This reveals this fact that although fairness is a desirable property, fairness by itself may not be sufficient. A good rate allocation mechanism should not only be fair, but also should allocate the available bandwidth in such a way that the overall utility of the end-users is maximized [13].

In this paper, using a new differentiated pricing scheme as an AQM algorithm implemented in the intermediate nodes we would see how the overall performance of the system would be improved.

In the second section we will review the background in rate allocation literature and formulize the discrete time versions suitable for the proposed simulations. Then we depict the improvements brought about by the proposed algorithm in the performance analysis section where we would have a comparison between the different methods. The last section is devoted to the concluding remarks.

In the sequel, we will review the model and the rate allocation algorithm which are used by Kelly and then, we will describe the proposed algorithm in detail.

II. PROBLEM FORMULATION

In the following parts, two popular (Ω,α)- Fair and MulTCP models have been introduced.

1. (Ω,α)- *Fair model*

Consider a network with a set J of resources or links and a set $\Re$ of users and let C_j denotes the finite capacity of link $j\in J$. Each user r has a fixed route R_r, which is a nonempty subset of J. Also, define a zero-one matrix A, where $A_{r,j}$=1 if link j is in user r's traffic-route R_r and $A_{r,j}$=0 otherwise. When the allocated rate to the user r is x_r, user r receives utility $U_r(x_r)$. The utility $U_r(x_r)$ is an increasing, strictly concave and continuously differentiable function of x_r over the range $x_r \geq 0$.

Furthermore, assume that the utilities are additive so that the aggregate utility of rate allocation $X=(x_r, r\in\Re)$ is: $\Sigma_{r\in\Re} U_r(x_r)$ ·

This is a reasonable assumption since these utilities are those of independent network users. Finally, let the utility and capacity vectors to be $U=(U_r(.), r\in\Re)$ and $C=(C_j, j\in J)$ respectively.

The Kelly's formulation of the problem is as follows:

SYSTEM (U; A, C):

$$\text{Max} \quad \sum_{r\in\Re} U_r(x_r)$$
$$\text{Subject to} \quad A^T X \le C \tag{1}$$
$$\text{Over} \quad X \ge 0$$

The first constraint says that the total rate through a link cannot be larger than the capacity of the link. Given that the system knows the utility functions U of the users, this optimization problem might be mathematically tractable. However, in practice, the network is not likely to know U_r of each user; additionally it is impractical for a centralized system to compute and allocate the users' rates due to the scale of the network. Hence, Kelly in [5] has proposed to consider the following two simpler problems. Suppose that each user r is given the price per unit rate λ_r [14].

Given λ_r, user r selects an amount that he/she is willing to pay per unit time, ω_r , and receives a rate $x_r = \omega_r / \lambda_r$. Then, the user r optimization problem becomes selecting ω_r such that:

USER$_r$ (U_r ; λ_r):

$$\text{Max} \quad U_r(\omega_r / \lambda_r) - \omega_r \tag{2}$$
$$\text{Over} \quad \omega_r \ge 0$$

The network, on the other hand, given the amounts that users are willing to pay, Ω=(ω_r,$r\in\Re$), attempts to maximize the sum of weighted log functions $\Sigma_{r\in\Re}\, \omega_r \log(x_r)$. Then the network's optimization problem can be written as follows:

NETWORK (A,C; Ω):

$$\text{Max} \quad \sum_{r\in\Re} \omega_r \log(x_r)$$
$$\text{Subject to} \quad A^T X \le C \tag{3}$$
$$\text{Over} \quad X \ge 0$$

Note that the network does not require the true utility functions (U_r(.), $r\in\Re$), and to carry out its computations pretends that user r utility function is ω_r log(x_r). It is shown in [5] that one can always find vectors λ^*= (λ_r^*, $r\in\Re$), Ω^* = (ω_r^* , $r\in\Re$) and X^* = (x_r^* , $r\in\Re$) such that X* solves NETWORK (A, C; Ω), ω_r^* solves USER$_r$ (U_r ; λ_r) and $\omega_r^* = x_r^* . \lambda_r^*$ for all $r\in\Re$. Furthermore, the rate allocation X* is also the unique solution to SYSTEM (U; A, C). As we have mentioned earlier, the format of users' utility functions are in close relationship to the fairness criterion that exists in rate allocation [4].

From now on, to implement proportional fairness [5] it is assumed that the users' utility functions are in logarithmic forms.

It must be mentioned that in the special case of logarithmic utility functions, USER problem has a unique solution equal to the user's ω and does not need to be solved by the users periodically. Thus, we only focus on the NETWORK problem.

Definition [5,15]:

A vector of rates X=(x_r,$r\in\Re$) is per unit charge proportionally fair if it is feasible, that is $X \ge 0$ and $A^T X \le C$, and if for any other feasible vector X* the aggregate of proportional changes is zero or negative[5]:

$$\sum_{r\in\Re} \omega_r \frac{x_r^* - x_r}{x_r} \le 0 \tag{4}$$

If we assume that $\omega_r = 1$, $\forall r \in \Re$ then we reach to the proportional fairness criterion. From now on, for notational brevity, we drop the prefix per unit charge for the general case and refer to the general definitions as proportionally fair.

The Kelly's discrete time algorithm for

solving NETWORK $(A, C; \Omega)$ is as follows:

$$x_r[n+1] = \left\{ x_r[n] + k_r \cdot \left(\omega_r - x_r[n] \cdot \sum_{j \in R_r} \mu_j[n] \right) \right\}^+ \quad (5)$$

Where $\{x\}^+ \triangleq \max(0,x)$ and:

$$\mu_j[n] = p_j\left(\sum_{s:j \in R_s} x_s[n] \right) \quad (6)$$

Parameter k_r controls the speed of convergence in equation(5). $p_j(y)$ is the amount that link j penalizes its aggregate traffic y and is a non-negative, continuous increasing function (see Fig.1).

One of the interpretations is that using (5), the system tries to equalize ω_r with $x_r[n]. \sum_{j \in R_r} \mu_j[n]$ by adjusting $x_r[n]$.

In [5] it is shown that the unique, optimal and proportionally-fair equilibrium point of the equations (5)-(6) is:

$$\omega_r = x_r^* \cdot \sum_{j \in R_r} p_j\left(\sum_{s:j \in R_s} x^*_s \right) \quad , r \in \Re \quad (7)$$

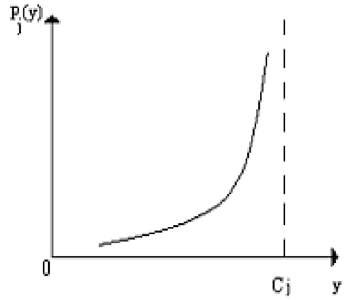

Fig.1- A sample penalty function

It is necessary to mention that as Kelly et al. have discussed in [5], for satisfying the constraints of relations (1) to (3), we may use the following form of the link penalty function:

$$p_j(y) = (y - c_j + \varepsilon)^+ / \varepsilon^2 \quad , \varepsilon \to 0 \quad , j \in J \quad (8)$$

Where, c_j is the capacity of j-th link and $\varepsilon > 0$ is a small positive constant.

Considering the more general (Ω, α)- fair rate allocation algorithms (the Kelly's algorithm or proportional fairness is the special case with α =1 and the minimum potential delay fair algorithms is another special case with α = 2) the discrete time rate allocation algorithm would be [7]:

$$x_r[n+1] = \left\{ x_r[n] + k_r \cdot \left(\omega_r - (x_r[n])^\alpha \cdot \lambda_r[n] \right) \right\}^+ \quad (9)$$

Where:

$$\lambda_r[n] = \sum_{j \in R_r} p_j \left(\sum_{s \in j} x_s[n] \right) \quad (10)$$

is the aggregate price for user r.

2. MulTCP model

Another algorithm which we implement in the simulations is the general MulTCP model (which usual TCP is the special case with m=1). The fluid-flow representation for MulTCP is [6]:

$$\frac{d}{dt} x_r(t) = \frac{m_r}{T_r^2} - \left(\frac{m_r}{T_r^2} + \frac{x_r^2}{2m_r} \right) \lambda_r(t) \quad (11)$$

Where the T_r is the round trip time (RTT) of the flow r. The discrete time version which we used in simulation is:

$$x_r[n+1] = x_r[n] + \frac{m_r}{T_r^2} - \left(\frac{m_r}{T_r^2} + \frac{x_r^2[n]}{2m_r} \right) \lambda_r[n] \quad (12)$$

III. DIFFERENTIATED PRICING FRAMEWORK

1. Differentiated pricing

In flat pricing scheme, a form of penalty function such as that used in Eq. (8) can be used but in differentiated pricing, a form of tangential biased pricing function such as the following equation will be used [16]:

$$p_{jr}(y) = \varepsilon_{jr} . \tan(\pi . y / (2c_j)) \quad , j \in J \text{ and } r \in \Re \quad (13)$$

The incurred price is completely link and flow dependent and the amount of link price can be controlled by parameter $\varepsilon_{jr} > 0$. The greater parameter ε_{jr} will result in more penalized user traffic and more starvation in the dedicated network resources.

2. Stability Analysis

The stability properties of the discrete (Ω, α)-Fair model in Eq. (9) are investigated in [5]. Also, in [17] it is shown that by exploiting the following Lyapunov function, the stability property of Eq. (11) can be derived.

$$V(x) = \sum_r \frac{\sqrt{2m_r}}{T_r} \arctan\left(\frac{x_r T_r}{\sqrt{2m_r}}\right) \sum_{j\in J} \int_0^{\sum_{s:j\in s} x_s} p_j(y)dy \tag{14}$$

In another words, based on a similar approach as in [5], these stability properties can be extended to discrete-time system in Eq. (12).

IV. PERFORMANCE ANALYSIS

We have assumed that a simple network topology with one bottleneck common link exists (Fig. 2) that its resources are shared by n different elastic flows.

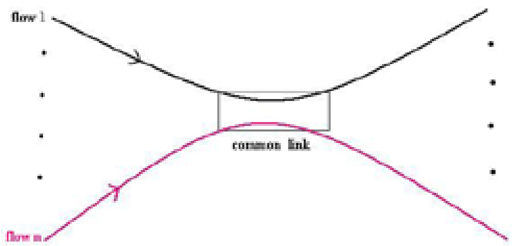

Fig. 2 Simulated network scenario

Assume that n=5 and the bottleneck link with capacity of 20 is shared by a TCP, two MulTCP with parameters m=2 and m=3, a proportionally fair scheme (α = 1) and a minimum potential delay fair (α = 2) sessions.

First we just simulate these algorithms in a simple usual environment without discriminating between these flows i.e. we have used the flat pricing as in Eq. (8) with ε =0.0001. The allocated rates to these sessions and the overall throughput are derived based on Eqs. (9) and (12) and are depicted in the Fig.3.

In this figure, the acronyms (P) and (MPD) stand for (Proportional) and (Minimum Potential Delay) fairness criteria, respectively.

The oscillatory behavior is inevitable since it is intrinsic to TCP. But the overall throughput and goodput can be improved as we will see in the next figure.

We have compared the overall throughput with link capacity, and if it be more than link capacity we would have a loss. As is clear from the Fig. 4, we have 8 losses. Using the area under the graph as an indication to throughput we had the results shown in Table I.

Using the proposed differentiated pricing scheme, which uses a new tangential biased pricing scheme (Eq. 13) for TCP, and two MulTCP sessions, in the proposed scenario the loss reduced to zero and we observed improvement in the overall utilization of the network (Fig. 4). In this scenario, we have paid more attention to P and MPD flows in price of more penalizing other MulTCP and TCP flows. The simulation results are summarized in the Table II.

The main reason for the improved system performance in the differentiated pricing scheme is that in this case, the non-TCP traffics ((Ω, α)-fair ones) have been paid more attention and will be less penalized. So these non-TCP traffics can have a more share of the bottleneck link's capacity. On the other hand, as non-TCP traffics do not rely on the occurrence of the network loss for congestion notification, they have more controllable behavior and can present some forms of the inherent congestion avoidance properties before the onset of the congestion. Thus, paying more attention to these type of traffics can reduce the network loss and reduces the un-necessary loss-based retransmissions in TCP which improves the system throughput.

V. CONCLUSION

Using a new differentiated pricing scheme we showed that the overall throughput of the network could be increased without significant decrease in TCP sessions throughput. The reason can be the fact that we achieved this goal by decreasing the unnecessary drops caused by TCP using the proposed differentiated pricing scheme, therefore avoiding unnecessary reductions and oscillations in the allocated rates of the other sessions.

ACKNOWLEDGMENT

The author must thank the ITRC for its financial support during the research.

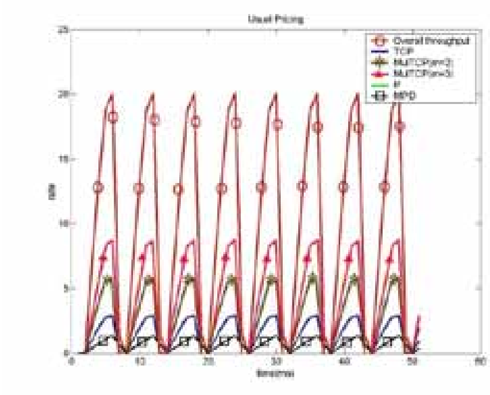

Fig.3 Rates achieved by sessions in flat pricing

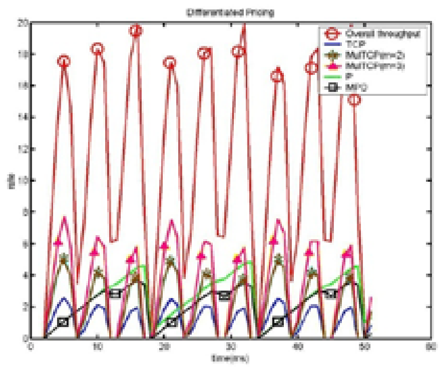

Fig.4 Rates achieved by sessions in differentiated pricing

TABLE I

RESULTS IN USUAL ENVIRONMENT

Symbol	Value
Overall throughput	479.5789
Loss numbers	8
TCP throughput	69.9173
MulTC P(m=2) throughput	139.8346
MulTCP(m=3) throughput	209.7519
Proportional throughput	33.1345
Minimum Potential Delay throughput	33.5129
Overall throughput	479.5789
Loss numbers	8
TCP throughput	69.9173
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MulTCP(m=3) throughput	209.7519
Proportional throughput	33.1345
Minimum Potential Delay throughput	33.5129
Overall throughput	479.5789

TABLE II

RESULTS IN PROPOSED ENVIRONMENT

Symbol	Value
Overall throughput	547.4754
Loss numbers	0
TCP throughput	54.2468
MulTC P(m=2) throughput	108.4935
MulTCP(m=3) throughput	162.7403
Proportional throughput	126.0447
Minimum Potential Delay throughput	102.5708
Overall throughput	547.4754
Loss numbers	0
TCP throughput	54.2468
MulTC P(m=2) throughput	108.4935
MulTCP(m=3) throughput	162.7403
Proportional throughput	126.0447
Minimum Potential Delay throughput	102.5708
Overall throughput	547.4754

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