CONGESTION CONTROL OF HIGH SPEED COMPUTER NETWORKS: A PID METHOD

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Keywords: ABR service, ATM networks, congestion control, PID controller, performance evaluation.

Abstract

In this paper, we present a novel method to the design of closed-loop rate-based flow controller for high-speed networks. In this method, a proportional-integral-plus-derivative (PID) controller is adopted, where the control parameters are designed to ensure the stability of the control loop in a control theoretic sense. Based on a general traffic model of computer network and on system stability criterion, it is shown that under PID controller the source rates are regulated, the congestion-controlled network is asymptotically stable in terms of both the buffer occupancy of the destination node and the user transmission rates, and the bandwidth fairness is achieved. The basic control theory approach for the algorithm is firstly presented, and steady state analysis is subsequently given to show how the max/min fairness is achieved in a natural way without additional computation. We then use simulations to show the good dynamic performance of the PID congestion control scheme under a variety of networking configurations and traffics.

1 Introduction

The ATM Forum has adopted the rate-based closed-loop control approach for the flow control of ABR service [1, 4]. In this approach, the ABR traffic sources will receive feedback information to decrease their data rate in order to avoid any buffer overflow in the network. The ATM Forum has specified the source and destination behaviors, and has defined special control cells called resource management (RM) cells, which are used to carry the feedback information to the connection endpoints. The specification in [1] requires each switch to control congestion by implementing at least one of the following three methods: EFCI marking, Relative rate (RR) marking and Explicit rate (ER) marking. The ATM Forum has not, however, specified any standard algorithm to be implemented in the switches to perform the above functions so far. Though a large amount of research, see for instance [1-5, 8, 9, 13], has been devoted to congestion control algorithms, it seems still to be a challenging task to design a comprehensive ABR control algorithm to achieve the buffer occupancy stability, the rate convergence, the fair share of each connection and excellent performance for a variety of network scenarios. The major difficulty arises from the long and heterogeneous round-trip delays involved in the closed-loop control. Especially when only a binary feedback mechanism (either EFCI or RR marking, or both) is applied, ABR queues in the network inevitably exhibit a persistent oscillation in the steady state due to the fact that the magnitude and period of the state feedback information are an increasing function of the delay-bandwidth product [5, 8, 13]. It is obvious that such an oscillatory behavior of ABR queues will increase the likelihood of cell loss and lead to link underutilization as buffer repeated overflowing and under-flowing. This would be especially notable nowadays as the speed and size of networks become higher and larger. Since the propagation delay (the time it takes for a bit to travel from sender to receiver) is relatively long in high-speed networks compared with the transmission time of one unit of data, the controller for each connection may receive out-of-date information. Thus the simple proportional scheme may cause the whole network to operate at an unstable point. This yields the notorious oscillation problem that greatly degrades the network performance. For rate-based congestion control schemes, the stability of the systems is thus especially important to guarantee good dynamic characteristic of the network.

In [2], a formal method was provided for stabilizing congestion controllers of ABR traffic, a relatively general method to analyze stability of congestion controller is still called for when considering enhancing the performance of networks. To this end, a general stability analyzing method, namely Schur-Cohn stability test is suggested to deal with the stability issue of ABR queue in this paper and the relevant algorithm is given. Based on this, the control parameters can be chosen such that the transmission rates and the buffer occupancy of the switch are asymptotically stabilized and the target buffer occupancy is achieved. Steady state analysis is subsequently given to show how the max/min fairness is achieved in a natural way without additional computation.

The main objective of this paper is to design a *proportional-integral-plus-derivative* **(PID)** congestion controller that not only has good behaviors under various networking conditions and loads, but also has a simple structure for implementation. We consider the bottleneck switching node that accumulates two classes of traffic, namely the best effort traffic stream including ABR traffic and the guaranteed traffic stream including VBR and CBR traffic. Our aim is to control the transmitting rate of ABR traffic. As simulation results will show, this kind of PID controller has good stability property and enhances the network performance.

2 The Network Model

A data communication network generally consists of a number of source/destination nodes that are geographically distributed. Cells generated at a source node are delivered to their destination through a series of intermediate nodes.

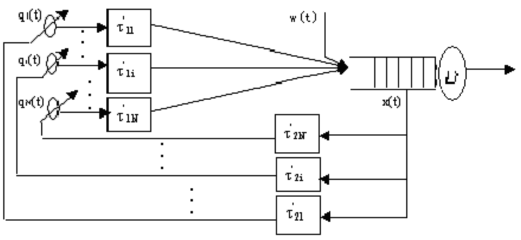

Figure 1: A congestion control model for an ATM switching network

In modeling the traffic through these nodes, one has to know the number of source/destination pairs and the rates at which these sources introduce cells into the network. Figure 1 represents a congestion control model for an ATM switching network that we are going to consider in the sequel. For the sake of simplicity, only one single switching node is considered, which is connected by multiple virtual connections (VCs). The number of VCs that are to be controlled is equal to the number of virtual connections which are incorporated in at the node and is assumed to be N though the number of active sources denoted by M may vary with time t. The switching node has a limited buffer size K to store the incoming cells and a service data rate v.

For the VCs, one needs to consider two kinds of delays, namely τ'_{1i} the path delay from the i^{th} source node to the switching node and τ'_{2i} the feedback delay from the switching node back to the i^{th} source node. There are also two kinds of traffic in the source nodes: uncontrolled traffic (e.g., guaranteed service traffic such as CBR, VBR and UBR traffic), which will not be congested at the source node, and controlled traffic (e.g., best-effort service traffic including ABR traffic), which can only be transmitted when there is no congestion appearing in the network. The component $w(t)$ denotes the total uncontrolled traffic rate, while $q_i(t)$ denotes the controlled traffic rate from the i^{th} source. Based on the buffer occupancy $x(t)$ that is measured and sent back to the controlled source nodes every T seconds, $q_i(t)$ will be adjusted.

Under the above notations and assumptions, the dynamics of a switching node in a network can be described by the following non-linear time-variant and time-delayed equation (Filipiak [7]; Benmohamed and Meekov [2])

$$\dot{x}(t) = Sat_K\{\sum_{i=1}^{N} e_i q_i(t-\tau'_{1i}) + w(t) - \upsilon\} \tag{1}$$

where $x(t)$ is the buffer occupancy at time t, and

$$Sat_K\{x\} = \begin{cases} K\ , & \mathrm{x > K;} \\ \mathrm{x}\ , & \mathrm{0 \le x \le K;} \\ 0\ , & \mathrm{x < 0,} \end{cases}$$

$$e_i = \begin{cases} 1\ , \text{the ith source node is active;} \\ 0\ , \text{otherwise.} \end{cases}$$

If a feedback control is applied to the above system, then the input to the closed-loop system has a round-trip delay $\tau'_i = \tau'_{1i} + \tau'_{2i}$, $i = 1, 2, \cdots, N$. This round-trip delay includes propagation, queuing, and transmission and processing times. We assume it is constant. Now assume that the switching node sends information to a source node every T seconds, i.e., the signals get sampled every T seconds, and τ'_{1i}, τ'_{2i} are exactly integral multiples of T, i.e., $\tau'_{1i} = \tau_{1i}T$, $\tau'_{2i} = \tau_{2i}T$, τ_{1i} and τ_{2i} are integers. We further denote $\tau_i = \tau_{1i} + \tau_{2i}$. Let $\lambda_i(n) = Tq_i(nT)$ and $d(n) = Tw(nT)$ denote respectively the number of cells flowing into the network from the i^{th} VC and from the uncontrolled traffic during the n^{th} interval of T, and let $\eta = T\nu$ denote the number of cells emitted from the switching node during the n^{th} interval. The equation (1) can be written into

$$x(n+1) = Sat_K\{x(n) + \sum_{i=1}^{N} e_i \lambda_i(n - \tau_{1i}) + d(n) - \eta\}. \tag{2}$$

It is seen that, generally the non-linearity imposed on the equation (2) will not be activated for small deviations around the network's operating point. We therefore remove the saturation non-linearity imposed on the equation (2) and focus on the following description

$$x(n+1) = x(n) + \sum_{i=1}^{N} e_i \lambda_i(n - \tau_{1i}) + d(n) - \eta \tag{3}$$

3 Congestion Control Method

We propose here a new PID congestion control algorithm that can achieve good dynamic performance of networks. The following algorithm regulate the controllable source rate:

$$\begin{aligned} \lambda_i(n) = \mu_i + \alpha(x(n-\tau_{2i}) - x_0) + \beta \sum_{j=1}^{\tau_i} \lambda_i(n-j) \\ + \gamma_1(x(n-\tau_{2i}) - x(n-\tau_{2i}-1)) \\ + \gamma_2(x(n-\tau_{2i}-1) - x(n-\tau_{2i}-2)) \end{aligned} \tag{4}$$

where $\lambda_i(n)$, $x(n)$ and x_0 are the ER of the i^{th} source node computed by the switch at discrete time n, the buffer occupancy at time n, and the target buffer occupancy respectively. τ is the largest round-trip delay of ABR VCs on this link. τ_{2i} is the feedback delay from the switch to the i^{th}

source node. μ_i is the maximum number of packets allowed for the i^{th} source node to transmit into the network in one interval T . The coefficients α, β , γ_1 and γ_2 are proportional, integral, the first and second derivative gains respectively, which are to be determined on the basis of stability criteria.

The ATM Forum Technical Committee has specified [1] that rate-based congestion control algorithm be carried out with the aid of RM (resource management) cell. A source generates forward RM cells that are turned around by the destination and sent back to the source. These backward RM cells carry some information like the buffer occupancy in a switching node, a time stamp and the number of active controlled VCs in the switch. After the sources receive the feed-backed RM cells, they will take appropriate action to adjust their transmitting rates of ABR traffic. It is thus seen that, the buffer occupancy is measured at the instances $n-\tau_{2i}$ at the switch, after a feedback delay τ_{2i} the RM cell reaches the i^{th} source and the controlled source then takes those values at time $t=n$, $t=n-1$ and $t=n-2$. By doing so, the designed controller can be expected to have more flexibility than that in [7] to cope with the sharp oscillation in buffer occupancy which will lead the network to packet loss. As simulation results will show, this kind of PID controller not only has good stability property but also enhances the network performance. The coefficients α, β , γ_1 and γ_2 in (4) are used to locate all the poles of the closed-loop system of (3) and (4) within the unit circle to ensure the stability. The main analysis about this issue will be given in the next section.

4 Network Dynamic Performance Analyses

Due to the fact that the system stability is closely related to the dynamic of buffer occupancy, a stable dynamic of buffer occupancy eventually convergent to equilibrium after a disturbance thus ensures a low packet loss rate. We will pay much attention to this issue.

If z-transformation is applied to the equation (3), one easily arrives at

$$(z-1)X(z)=\sum_{i=1}^{N} e_i z^{-\tau_{1i}}\lambda_i(z)+D(z)-\eta R(z) \tag{5}$$

where the z-transformation of $x(n)$, $\lambda(n)$, and $d(n)$ are described by $X(z)=\sum_{n=0}^{\infty}x(n)z^{-n}$, $\lambda_i(z)=\sum_{n=0}^{\infty}\lambda_i(n)z^{-n}$, $D(z)=\sum_{n=0}^{\infty}d(n)z^{-n}$ and $R(z)=\dfrac{z}{1-z}$.

We propose the PID congestion controller described by (4). In (4) the coefficients α, β , γ_1 and γ_2 are proportional, integral, the first and second derivative gains to be determined on the basis of stability of the closed-loop system. Taking the z-transform of equation (4), one yields

$$\begin{aligned}\lambda_i(z)&=\mu_i R(z)+\alpha(z^{-\tau_{2i}}X(Z)-x_0R(z))+\beta\sum_{j=1}^{\tau_i}z^{-j}\lambda_i(z)\\&+\gamma_1(z^{-\tau_{2i}}X(z)-z^{-\tau_{2i}-1}X(z))+\gamma_2(z^{-\tau_{2i}-1}X(z)-z^{-\tau_{2i}-2}X(z))\end{aligned} \tag{6}$$

Taking into account $z^{-1}+\cdots+z^{-\tau_i}=\dfrac{1-z^{\tau_i}}{z^{\tau_i}(1-z)}$ the equation (6) can be further written into

$$\begin{aligned}&(1-\frac{\beta(1-z^{\tau_i})}{z^{\tau_i}(1-z)})\lambda_i(z)=\\&((\alpha+\gamma_1)z^{-\tau_{2i}}+(\gamma_2-\gamma_1)z^{-\tau_{2i}-1}-\gamma_2 z^{-\tau_{2i}-2})X(z)\\&+(\mu_i-\alpha x_0)R(z)\end{aligned} \tag{7}$$

Assume that there are M ($M\le N$) source nodes are active, $\mu_1=\mu_2=...=\mu_M=\mu$, $\tau_{11}=\tau_{21}=...=\tau_{M1}=\tau_1$, $\tau_{12}=\tau_{22}=...=\tau_{M2}=\tau_2$, i.e., $\tau_1=\tau_2=...=\tau_M=\tau$, from (6) and (7) one has

$$\begin{aligned}&(z-1)(1-\frac{\beta(1-z^{\tau})}{z^{\tau}(1-z)})X(z)=\\&Mz^{-\tau_1}(((\alpha+\gamma_1)z^{-\tau_2}+(\gamma_2-\gamma_1)z^{-\tau_2-1}-\gamma_2 z^{-\tau_2-2})X(z)\\&+(\mu-\alpha x_0)R(z))+(D(z)-\eta R(z))(1-\frac{\beta(1-z^{\tau})}{z^{\tau}(1-z)}),\end{aligned}$$

i.e.,

$$\begin{aligned}\Delta(z)X(z)&=M(\mu-\alpha x_0)z^{\tau_2+2}R(z)\\&+z^{\tau+2}(D(z)-\eta R(z))(1-\frac{\beta(1-z^{\tau})}{z^{\tau}(1-z)})\end{aligned}$$

where we have denoted

$$\begin{aligned}\Delta(z)&=z^{\tau+3}-(\beta+1)z^{\tau+2}\\&+(\beta-M\alpha-M\gamma_1)z^2-M(\gamma_2-\gamma_1)z-M\gamma_2\end{aligned} \tag{8}$$

The component $\Delta(z)$ is the *characteristic polynomial* (**CP**) of the closed-loop system given by (3) and (4). The CP (8) is closely related to the stability of the congestion-controllable network system. From a control-theoretic point of view when all the zeros of (8) lie within the unit disc, the original network system (3) with the controller (4) is stable in terms of the buffer occupancy.

4.1 Algorithm for stability analysis of buffer occupancy

There are several computation procedures that aid us in determining if all the roots of a characteristic polynomial lie within a unit disc. These procedures are called *stability criteria.* For them one can refer to [14]. For our purpose, we use Schur-Cohn stability test here.

Generally, for a polynomial $A_N(z)=1+\sum_{n=1}^{N}a_n^{(N)}z^{-n}$ we need to know if all its zeros lie in the unit disc. The following algorithm is proposed for this purpose.

Algorithm 1: ***Schur-Cohn stability test***

Step 1: Starting with the original polynomial of degree N (N coefficients);

Step 2: Generate a sequence of polynomials recursively. $A_i(z), i=N:-1:0$ according to

$$A_{i-1}(z)=\frac{1}{1-q_i^2}(A_i(z)-q_i z^{-i}A_i(z^{-1})),$$

where $q_i = a_i^{(i)}$. Note that $z^{-i}A_i(z^{-1})$ is a flipped version of $A_i(z)$.

Step 3: The zeros of the polynomial $A_N(z)$ are inside the unit circle iff

$$|q_i| < 1, \quad i = N:-1:1.$$

With regard to CP (9), some manipulations are needed for it to satisfy the form of the polynomial $A_N(z)$. This is done in the following manner

$$\begin{aligned}\Delta(z) &= z^{\tau+3} - (\beta+1)z^{\tau+2} \\ &\quad + (\beta - M\alpha - M\gamma_1)z^2 + M(\gamma_2 - \gamma_1)z - \gamma_2 \\ &= z^{\tau+3}(1 - (\beta+1)z^{-1} + (\beta - M\alpha - M\gamma_1)z^{-\tau-1} \\ &\quad - M(\gamma_2 - \gamma_1)z^{-\tau-1} - M\gamma_2 z^{-\tau-1}) \\ &= z^{\tau+3}\Delta_1(z)\end{aligned}$$

By letting

$$\begin{aligned}\Delta_1(z) &= 1 - (\beta+1)z^{-1} + (\beta - M\alpha - M\gamma_1)z^{-\tau-1} \\ &\quad - M(\gamma_2 - \gamma_1)z^{-\tau-1} - M\gamma_2 z^{-\tau-1}\end{aligned}$$

it is sufficient to ensure the stability if all the roots of $\Delta(z)$ lie inside the unit circle for $\Delta(z)$ has all roots of $\Delta_1(z)$ together with a root $z = 0$, which is obvious inside the unit circle. Thus, Schur-Cohn criterion can be applied to $\Delta_1(z)$ directly with $N = \tau + 3$.

5 Max/Min Fairness and Steady State Analyses

Among the requirements for an ideal congestion control mechanism, the most critical component of fair rate allocation is to design a fair rate-allocation policy. In this paper, we adopt the max/min fairness definition [15]. We show that the PID control schemes achieve max/min fairness in a natural way without additional computation or information about bottleneck rates of individual connections, and in the meantime they guarantee minimum cell rate (MCR)>0 without any additional computation.

Let x^s, λ^s, d be the steady state values corresponding to $x(n), \lambda_i(n), d(n)$. Under the assumption that the input traffic is constant, then the original state equation (3) and the controller equation (4) take their steady state forms

$$x^s = x^s + \sum_{i=1}^{N} e_i \lambda^s + d - \eta \tag{9}$$

$$\lambda^s = \mu_i + \alpha(x^s - x_0) + \beta \sum_{j=1}^{\tau} \lambda^s + \gamma(x^s - x^s) \tag{10}$$

From (10), one has

$$\lambda^s = \frac{\eta - d}{M}, \tag{11}$$

where the component M is the total active ABR source nodes, the component η is the emitting rate of the switch, and the component d is the transmitting rate of uncontrollable traffic. It is noted that the component $\eta - d$ is the available bandwidth for all ABR sources, which is distributed equally amongst the activate VCs. Thus the requirement of Max/Min fairness is achieved in this approach.

We further find that the PID controller guarantees minimum cell rate (MCR)>0 without any additional computation. This exposition is very similar to that discussed in [9], it has thus been omitted.

From (11), we have

$$\lambda^s = \mu_i + \alpha(x^s - x_0) + \beta\tau\lambda^s,$$

i.e.,

$$x^s - x_0 = \frac{(1-\beta\tau)\lambda^s - \mu_i}{\alpha}.$$

It is seen that if the equation

$$(1-\beta\tau)\lambda^s - \mu_i = 0 \tag{12}$$

holds, then the steady state value of the buffer occupancy is equal to the specified threshold, i.e.,

$$x^s - x_0 = 0.$$

Considering in (11) and (12), we need to choose the admissible parameters μ_i and β such that

$$\mu_i = (1-\beta\tau)\frac{\eta - d}{M}. \tag{13}$$

6 Simulation Results

To evaluate the performance of the studied PID congestion control method, we focused upon the following three aspects:

(i) Stability of the system in terms of the buffer occupancy. Of particular interest is the setting time that it takes for the system to reach an equilibrium state.

(ii) Transient response of the source rates.

(iii) Utilization of the link.

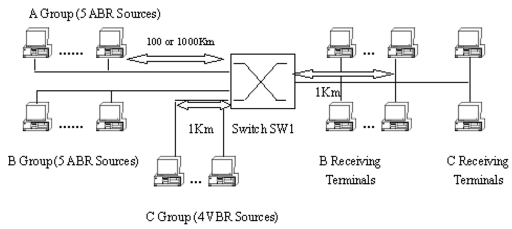

Figure 2: Single-node network model [9].

Simulations are carried out over a wide range patterns and propagation delays both in the **LAN** (Local Area Network) case and the **WAN** (Wide Area Network) case.

The model we adopt is depicted in Figure 2, shows a single node network configuration with a generic input/output switch (SW1). There are two groups of ABR sources, with each group consisting of five persistent sources. It is assumed that the output port of SW1 is the bottleneck link. The distance from the sources A and B to the switch SW1 varies from $100\,\text{km}$ (**LAN**) to $1000\,\text{km}$ (**WAN**). The distance from the receiving terminals to the switch SW1 is $1\,\text{km}$. All links have a capacity of $\mu = 155\,\text{Mbps}$. The ABR source parameter chosen is that: $PCR = 365\,\text{cells/ms}\,(155\,\text{Mbps})$.

To investigate the performance of the PID controller over short distances (a LAN case), we set the distance from sources A and B to switch SW1 to be 100 km with the path delay and the feedback delay being $\tau_{1i} = 1m\sec$, $\tau_{2\mathrm{i}} = 1m\sec$, $(i = 1,2,\cdots,10)$ respectively. Therefore the sum of propagation delay in the forward and backward path that represents the round-trip delay (RTD) is $\tau_i = 2m\sec$. We assume that the propagation delay is dominant compared to other delays such as processing delays and queuing delays, etc.
For this LAN case, on the basis of the Schur-Cohn stability test, we choose the PID controller parameters $\alpha = -0.095, \beta = -1, \gamma_1 = -0.005, \gamma_2 = -0.003$. We then choose $x_0 = 100$ Kb and yield $\mu_\mathrm{i} = 46.5 Mbps$ from the steady state condition (13).

We also assume that sources in group A start transmission at time $t = 1$ ms, while sources in group B start at time $t = 300$ ms. Figure 3 shows the rates of each source under the PID control scheme. Figure 4 shows the buffer occupancy transient responses at the switch SW1. And finally Figure 5 shows the link utilization. It is seen from Figure 3 that, the transient performance of PID controller is good in the sense that it achieves stability very quickly with very little steady-state oscillations and achieve the fairly shared rate 15.5 Mb/s (155/10) very quickly. There are some transient oscillations appearing in the source rate dynamics in the PID control, however this is still acceptable and does not cause too much degradation of the network performance due to the fact that the switch is still underutilized before the equilibrium point. In Figure 4, we could see that control results in small setting time (about 310 ms) as well as small buffer occupancy that converge exactly to the specified threshold ($x_0 = 100$ Kb).

Generally a less setting time means the quicker action of the network to congestion and load change in the router. This will then avoid the cell lose more efficiently. From Figure 4, there is almost no cell loss during the transient periods. A less buffer occupancy and a less steady state value of buffer occupancy generally suggests better link utilizing situation. Figure 5 suggests that the link utilization is almost kept at 100% persistently except at the glitches.

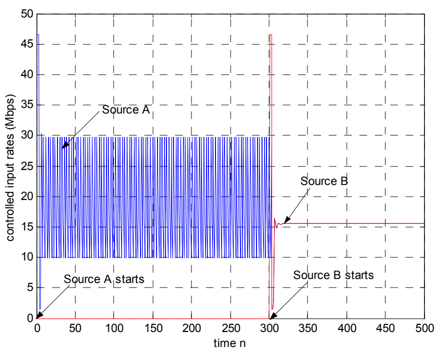

Figure 3: Source-rate transient response (a LAN case)

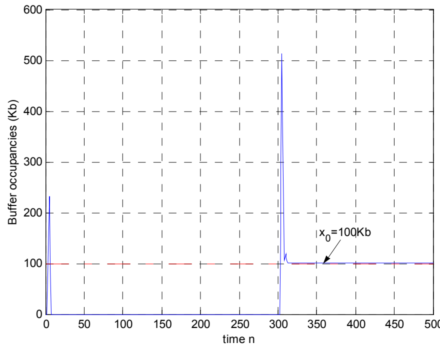

Figure 4: Buffer occupancy transient response (a LAN case)

Now, we study the performance of PID control in a WAN environment when the available rate for ABR service continuously changes with time. At this time, we put the sources 1000 km apart from the switch SW1, and assume that the path delay and the feedback delay being $\tau_{1i} = 6m\sec$, $\tau_{2\mathrm{i}} = 4m\sec$, $(i = 1,2,\cdots,10)$ respectively. Therefore the sum of propagation delay, i.e., RTD is $\tau_i = 10m\sec$. We add four video MPEG sources at the input ports of the switch SW1. It should be noted that the MPEG source represents the standard MOBI sequence with a peak rate of 17 Mb/s and average rate of 10 Mb/s. The MPEG sources have service priority over ABR sources at the output port and start transmission at time $t = 1$ ms.

For the above WAN case, on the basis of the Schur-Cohn stability test, we choose the PID controller parameters $\alpha = -0.099, \beta = -1, \gamma_1 = -0.001, \gamma_2 = -0.001$. We then choose $x_0 = 200$ Kb and yield $\mu_\mathrm{i} = 130.9 Mbps$ from the steady state condition (13).

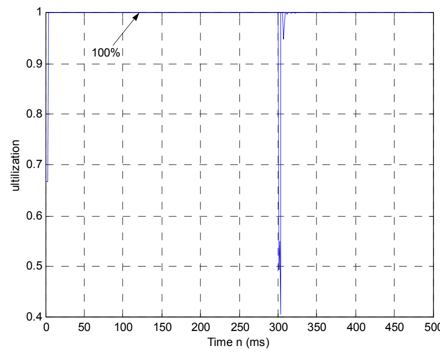

Figure 5: Link utilization (a LAN case)

From Figure 6, one observes the PID controller reacts quickly to changes in the available capacity for ABR service. This capacity is always equally shared among all ten ABR sources. It is seen that, the average aggregate rate of four MPEG sources is about 30 Mbps and the ABR source rate converges to about 12 Mbps. The total ABR source rate is then equal to 120 Mbps roughly. Therefore, the achieved utilization is close to, during most time slots, 100%, this is depicted in Figure 8. Looking closely into Figure 6, 7, and 8, we note that the PID control yields a short setting time of source rate (about 370 ms), small overshoot, low buffer occupancy, and therefore, achieves good link utilization.

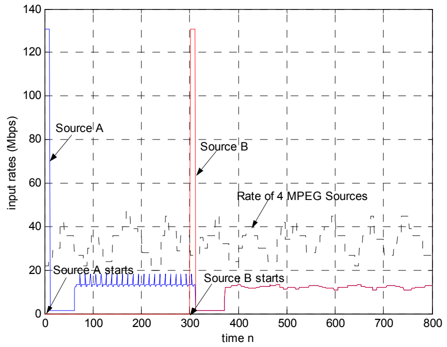

Figure 6: Source-rate transient response (a WAN case)

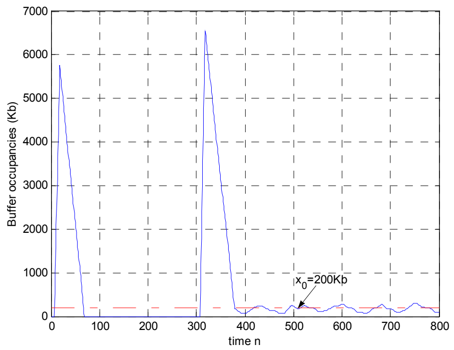

Figure 7: Buffer occupancy transient response (a WAN case)

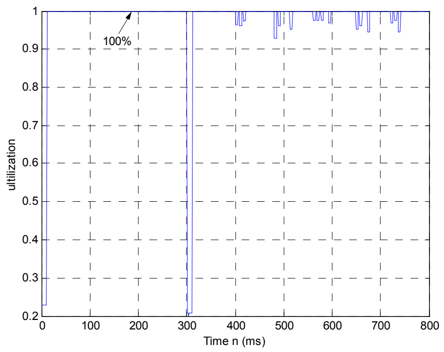

Figure 8: Link utilization (a WAN case)

7 Conclusions

This paper has presented a control-theoretic approach to design a PID controller for regulating the ABR source rates in high-speed computer communication networks. The control parameters are suggested to be designed on the basis of Schur-Cohn stability test to ensure the stability of the closed loop system (the buffer occupancy and the source rates). The control scheme is verified to be efficient over a wide range of traffic patterns and propagation delays, it is also attractive in the sense that it is simple to implement and has very low computation overhead. We have shown how the PID controller can be designed to adjust the rates of ABR service based on the feedback ER mechanism, to achieves a maximum throughput and the max/min fairness in a natural way. Simulations have been carried out in the LAN and WAN scenarios and under a variety of load conditions. Simulation results show that the proposed PID controller performs well in the sense that it leads to low buffer occupancy, fast response of the buffer occupancy as well as of the controlled ABR rates, small steady overshoots of ABR traffic and good utilization of network links. Future research should look into the issue of congestion control in a multicast network scenario along the control theoretic line.

Acknowledgements

This research has been supported by National Natural Science Foundation of China under Grant No. 60174043 and by the Key Project of Natural Science Foundation of Hubei Province under Grant No. 2002AB025.

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