第 29 卷 第 1 期
2003 年 1 月

自 动 化 学 报
ACTA AUTOMATICA SINICA

Vol. 29, No. 1
Jan., 2003

A Rate-Based PD Congestion Controller for High-Speed Computer Communication Networks[1)]

TAN Lian-Sheng YIN Min

(*Department of Computer Science, Central China Normal University, Wuhan* 430079)

(E-mail: L. Tan@ccnu. edu. cn; yinmin78@sohu. com)

Abstract With regard to the flow regulation of the best-effort traffic, i. e., the controllable traffic in high-speed computer communication networks, the paper proposes a novel control theoretic approach that designs a proportional-plus-derivative (PD) controller for congestion controlling. Based on the traffic model of a single node and on the system stability criterion, it is shown that the PD controller can regulate the source rate on the basis of the knowledge of buffer occupancy of the destination node in such a manner that the congestion-controlled network is asymptotically stable without oscillation in terms of the buffer occupancy of the destination node. Simulations show good performance of such controlled networks.

Key words Computer communication networks, congestion control, PD controller, buffer occupancy

1 Introduction

Congestion is the state of sustained network overloaded, in which the network reaches a situation where the demand for network resources is approximate to or even exceeds its capacity. It is unrealistic to sort this issue out simply by expanding network resources, i. e., link bandwidth and buffer space in the routers, for generally both of them are relatively limited and still expensive in many cases. Therefore, high-speed computer communication networks seem to suffer from congestion problem unavoidably due to uncoordinated resource sharing. Congestion control has subsequently become a more and more challenging problem in network engineering.

High-speed computer communication networks are expected to support multimedia traffic consisting of a variety of traffic classes with different quality of service (QoS) requirements. Two basic classes of service are under investigation: reserved traffic with guaranteed service, and best-effort traffic with no explicitly guaranteed service. Correspondingly, two classes of congestion control schemes have been discussed: open-loop control for the guaranteed service, and closed-loop control for the best-effort service[1]. Most of them use end-to-end feedback-based flow control mechanisms for matching the source's rate to the receiver's rate and the bottleneck's capacity. Typical examples of available-bit-rate (ABR) traffic control are the single/binary-bit types which include the forward explicit congestion notification (FECN) approach and the backward explicit congestion notification (BECN) approach[1]. In these schemes, a periodic-sampling feedback control mechanism has been used. At certain intervals, the source rate is proportionally increased or proportionally decreased to the current cell rate according to network state (buffer occupancy) information stored in a congestion bit carried by the piggyback cell. These schemes are well known and very effective in conventional low-speed networks. However, they suffer serious problems of stability, exhibit oscillatory dynamics, and require large amount of buffer in order to avoid cell loss when applied to high-speed computer communication

1) Supported by National Natural Science Foundation of P. R. China (60174043) and by the Scientific Research for Returned Overseas Chinese Scholars, China Scholarship Council
Received December 10, 2001; in revised form May 8, 2002
收稿日期 2001-12-10; 收修改稿日期 2002-05-08

networks. The main reason lies in the fact that the propagation delay is long compared to the transmission time of a data unit in high-speed networks, the network buffer occupancy information received in the source end of a virtual connection may be outdated. Thus, the simple proportional increase and decrease scheme may cause the local controllers in source nodes and even the whole network to operate at an unstable point, which in turn leads to the notorious oscillation problem that greatly degrades the network performance. As a consequence, in order to address the oscillation problem in the FECN and BECN schemes, an explicit rate (ER) congestion control scheme was developed in [2]. It is demonstrated by simulation that properly designed ER scheme can significantly outperform FECN and BECN schemes in terms of much less buffer size and much less queuing oscillation. However, the dynamic oscillation problem remains unsolved satisfactorily in the ER scheme. Most of the existing congestion control approaches lack of fundamental analysis of the closed-loop network dynamics.

Stability of closed-loop system is critical in any congestion control scheme to ensure that the network has a good dynamic characteristic and then avoids data loss. Concerning this issue, some control-theoretic concepts were proposed in [3] for ATM networks, and were further applied in [4-5]. These approaches, however, usually require an online turning of control parameters to ensure stability and good performance under different network conditions, which definitely bring inconvenience to actual network implementation. It was proposed in [6] a hop-by-hop congestion controller designing method which alleviates the oscillations, reduces the control delay and hence the reaction time of a network to the congestion at a switching node. In [7], Smith's principle was applied to designing a control law both for ABR input rates in ATM networks and for TCP/IP congestion windows. In [8], two linear feedback control algorithms were proposed for the case of a single connection with a constant service rate, which were further extended to the case of multiple connections in [9]. A single-controlled traffic source was considered in [10] by sharing a bottleneck node with other sources, where H_∞ control approach was used for designing the controller.

In this paper, we address the issue of congestion control in a general packet switching network using classical control theory. Classical control theory provides an established set of tools that enables us to design algorithms whose performance can be predicted analytically, rather than by simulations alone. To analyze the performance of the proposed algorithm it is sufficient to use the standard z-transform technique. The important advantage of mathematical analysis is that it allows us to demonstrate the properties of the proposed control law in a general setting, whereas the validation via computer simulation is inevitably restricted to the simulated scenarios. Notice that the analysis of transient dynamics is extremely important in the context of communication networks because these systems never reach a steady-state condition due to continuous joining and leaving of connections.

With regard to the flow regulation of the best-effort traffic, i. e. , the controllable traffic in high-speed computer communication networks, the present paper proposes a novel control theoretic approach that designs a proportional-plus-derivative (PD) controller for congestion controlling. Based on the traffic model of a single node and on the system stability criterion, it is shown that the PD controller can regulate the source rate on the basis of the knowledge of buffer occupancy of the destination node in such a manner that the congestion-controlled network is asymptotically stable without oscillation in terms of the buffer occupancy of the destination node. Simulations show good performance of such controlled networks.

2 Network modeling and basic analyses

A data communication network generally consists of a number of source/destination nodes that are geographically distributed. Packets generated at a source node are delivered to their destinations through a series of intermediate nodes. To model the traffic flowing through these intermediate nodes, one has to know the number of source-destination pairs routed through each node, the rates at which these sources introduce packets into the network, and the service rate of each intermediate node. In order to simplify the analysis, only a single switching node (see Fig. 1) is considered that accumulates two virtual connections (VCs). One is uncontrolled traffic (e. g., guaranteed traffic) which is not congested at the source node as long as it confirms to the specifications. The other is controlled traffic (e. g. best-effort traffic) that can only be transmitted when there is no congestion in the network. To the latter, there are two kinds of delays: τ_1' is the input delay from the source to the switch and τ_2' is the feedback delay from the switch to the source.

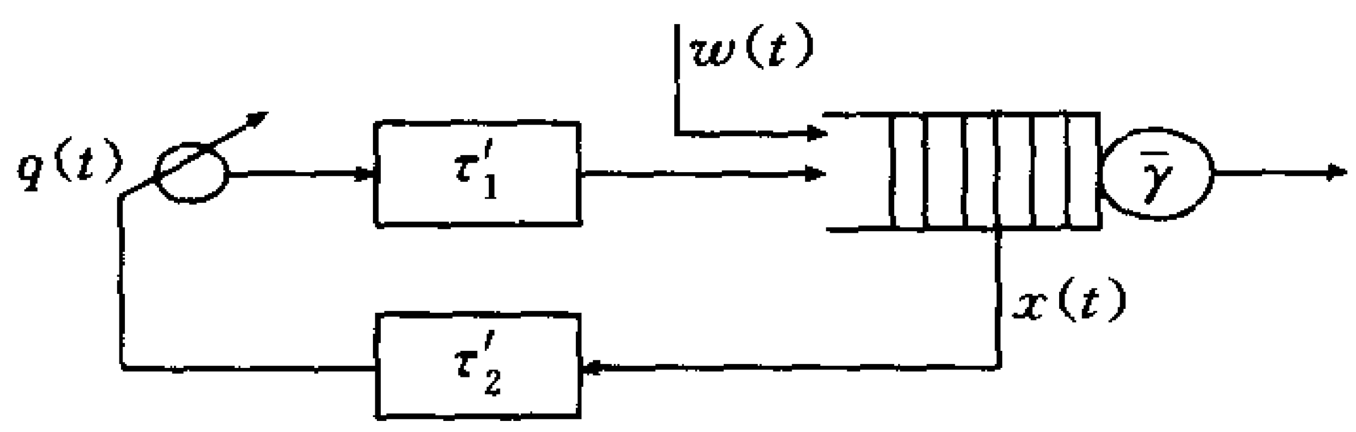

Fig. 1 A switching network model

Let $w(t)$ be the rate of the uncontrolled traffic, and let $q(t)$ be the rate of controlled traffic of the source node. The component $q(t)$ is adjusted by the buffer occupancy $x(t)$ which is sent to the controlled source node every T seconds. It can be assumed that the service is based on the rule of first-in-first-out (FIFO) and the packet length is constant. According to the above modeling assumptions, the dynamics of the controlled source node can be described by the following non-linear, time-invariant and delay-input differential equation[3]

$$\dot{x}(t) = Sat_K\{q(t-\tau_1') + w(t) - \bar{\gamma}\} \tag{1}$$

where K is the buffer size, $x(t)$ is the buffer occupancy and the saturation function is described by

$$Sat_K\{y\} = \begin{cases} K, & y > K \\ y, & 0 \leqslant y \leqslant K \\ 0, & y < 0 \end{cases}$$

If a feedback control is employed, the input function of system (1) can generate a round trip delay $\tau' = \tau_1' + \tau_2'$. Assume the source node transmits packets every T seconds, and the input delay $\tau_1' = \tau_1 T + \gamma$, where τ_1 is an integer and $0 \leqslant \gamma < T$. Then equation (1) can be discredited as

$$x(n+1) = Sat_K\{x(n) + \lambda\left(n - \tau_1 - \frac{\gamma}{T}\right) + d(n) - \mu\} \tag{2}$$

where the components $x(n)$ and $x(n+1)$ denote the buffer occupancy of the switch at time $t=nT$ and $t=(n+1)T$, respectively, the component $\lambda(n) = Tq(nT)$ denotes the number of controlled traffic packets transmitted from the source node to the switch in the nth interval of T, the component $d(n) = Tw(nT)$ denotes the number of packets transmitted from the uncontrolled traffic flow in the nth interval of T, and $\mu = T\bar{\gamma}$ denotes the number of packets sent from the switching node during the nth interval of T.

Now we assume the input delay is the multiple of T, that is $\gamma = 0$. This is a sound assumption because one can add a small delay to the path delay and make it be a multiple of T otherwise. Then we have

$$x(n+1) = Sat_K\{x(n) + \lambda(n - \tau_1) + d(n) - \mu\} \tag{3}$$

3 Idea of PD feedback congestion control and algorithm

One of the main aims in congestion control is that the congestion controller can adjust the rate of the source node in order for the destination's buffer occupancy not to overflow and in the meantime to be stable. For the sake of simplicity and without loss of generality[3], we remove the non-linearity saturation imposed on the network dynamic description (3) and only study the following equation

$$x(n+1) = x(n) + \lambda(n-\tau_1) + d(n) - \mu \tag{4}$$

whose z-transform is

$$(z-1)X(z) = z^{-\tau_1}\lambda(z) + D(z) - \frac{\mu z}{z-1} \tag{5}$$

where $X(z)=\sum_{n=0}^{\infty}x(n)z^{-n}$, $\lambda(z)=\sum_{n=0}^{\infty}\lambda(n)z^{-n}$, $D(z)=\sum_{n=0}^{\infty}d(n)z^{-n}$.

We propose the following PD (proportional-plus-derivative) congestion controller

$$\lambda(n) = \mu_1 - [\alpha(x(n-\tau_2)-x_0) + \beta(x(n-\tau_2)-x(n-\tau_2-1))] \tag{6}$$

where $\tau=\tau_1+\tau_2$, τ_2 is the standardized feedback delay, that is, for some positive integer τ_2, $\tau_2'=\tau_2 T$. The component x_0 denotes the pre-specified threshold of the buffer occupancy which is essentially an indication of the congestion level, μ_1 is the maximum rate allowed for the source node to transmit packets into the network in interval T, α is the proportional coefficient, β is the derivative coefficient, which will be specified on the basis of the analyses to the stability of closed-loop system. Taking the z-transform of (6), one yields

$$\lambda(z) = \frac{\mu_1 z}{z-1} - \left[\alpha\left(z^{-\tau_2}X(z) - \frac{x_0 z}{z-1}\right) + \beta(z^{-\tau_2} - z^{-\tau_2-1})X(z)\right] =$$

$$\frac{\mu_1 z}{z-1} + \frac{\alpha x_0 z}{z-1} - (\alpha+\beta)z^{-\tau_2}X(z) + \beta z^{-\tau_2-1}X(z) \tag{7}$$

By substituting (7) into (5), one has

$$(z-1)X(z) = z^{-\tau_1}\left[\frac{\mu_1 z}{z-1} + \frac{\alpha x_0 z}{z-1} - (\alpha+\beta)z^{-\tau_2}X(z) + \beta z^{-\tau_2-1}X(z)\right] + \left[D(z) - \frac{\mu z}{z-1}\right]$$

After certain manipulation, the above equation takes the form

$$\Delta(z)X(z) = \frac{z^{\tau_2+2}}{z-1}(\mu_1 + \alpha x_0) + z^{\tau+1}\left[D(z) - \frac{\mu z}{z-1}\right] \tag{8}$$

where we have denoted

$$\Delta(z) = z^{\tau+1}(z-1) + (\alpha+\beta)z - \beta \tag{9}$$

The form $\Delta(z)$ is the characteristic polynomial (CP) of the closed-loop system (4) and (6), which determines stability of the system. For the sake of simplicity, we only consider a special case where $\alpha=-\beta$ in the sequel. For this case the CP (9) is turned out to be

$$\Delta(z) = z^{\tau+1}(z-1) - \beta$$

From the control-theoretic point of view, when all the zeros of the above CP lie within the unit disc, the closed-loop system (4) and (6) is asymptotically stable in terms of the buffer occupancy (the state). This is a prerequisite to guarantee that the buffer occupancy of switching node has no steady state oscillation and thus the network has the least packet loss rate when designing a congestion controller. With regard to the location of zeros of the above CP, the following theorem establishes an interesting observation.

Theorem 1. Consider the polynomial $\Delta_\xi(z)=z^\tau(1-z)+\xi$, where τ is an integer. There exists a positive number ε such that for any $\xi\in(-\varepsilon, 0)$, all the roots of $\Delta_\xi(z)=0$ lie within the unit disc. In this situation the original system is stable.

Proof. Assume that $z_i(\xi)$ $(i=1, 2, \cdots, \tau+1)$ are the roots of $\Delta_\xi(z)=0$. Obviously,

$$z_i(0) = 0,\ i = 1, 2, \cdots, \tau,\ z_{\tau+1}(0) = 1$$

Since $z_i(\xi)$ is a continuous function of ξ, there exists a positive integer ε_1 such that $\forall\xi\in(-\varepsilon_1, 0)$, $|z_i(\xi)|<\frac{1}{2}$, $i=1, 2, \cdots, \tau$. Whereas $|z_{\tau+1}(\xi)|>\frac{1}{2}$. Because the roots should be conjugated, for any $\xi\in(-\varepsilon_1, 0)$, $z_{\tau+1}(\xi)$ should have positive real part. Further assume there is $\xi_0\in(-\varepsilon_1, 0)$ such that $z_{\tau+1}(\xi_0)\geqslant 1$. Therefore,

$$\Delta_{\xi_0}(z_{\tau+1}(\xi_0)) = (z_{\tau+1}(\xi_0))^{\tau}(1 - z_{\tau+1}(\xi_0)) + \xi_0 \leqslant \xi_0 < 0$$

The above statement contradicts the fact that $z_{\tau+1}(\xi_0)$ is the root of $\Delta_{\xi_0}(z)=0$. One thus draws the conclusion that all the roots of $\Delta_{\xi}(z)=0$ lie within the unit disc. □

Remark 1. The main significance of Theorem 1 is that one can choose any value of β near the origin to achieve the stability of the control system. Apparently, such choices of α and β exist in great numbers, a class of controllers can subsequently be devised. Under all these control schemes, the network is asymptotically stable in terms of the buffer occupancy. Based on this class of controllers, one can further specify one such that other performances of the congestion-controlled network are also good. This mechanism will be presented in the following simulation analyses.

4 Simulation studies and performance evaluation

Because the congestion controller is designed to adjust the rate of the source node, we are mostly interested in analyzing the transient behaviors of the network. In the performance analysis, the duration of response time and steady state of buffer occupancy are the main concerns.

In simulations, we assume the transmitting rate of switch node $\bar{\gamma}=200$Mbps, which is also the maximum transmission rate of the source node, and the sampling time $T=1$msec. Also it is assumed that the threshold parameter $x_0=100$cells, the uncontrolled source generates the traffic data at a constant transmission rate of 15 Mbps and 55 Mbps. Assume the input delay $\tau_1=3$msec and the feedback delay $\tau_2=2$msec. Thus the total round-trip delay $\tau=\tau_1+\tau_2=5$msec. Figures 2~5 show the dynamic behaviors of a single controlled source node based on the system model (4) implemented with the PD congestion control algorithms described in (6) under different chosen values of α and β. The values of α and β in Figures 2 and 3 are chosen such that the network system is stable whereas those in Figures 4 and 5 are chosen such that the network is not stable. There are four sub-figures in Figures 2-5, they are (a) the assumed input rate of uncontrolled traffic, (b) the simulated input rate of controlled traffic, (c) the simulated total rate of the input rates, i. e. , the sum of controlled and uncontrolled traffic rates, and (d) the simulated buffer occupancy.

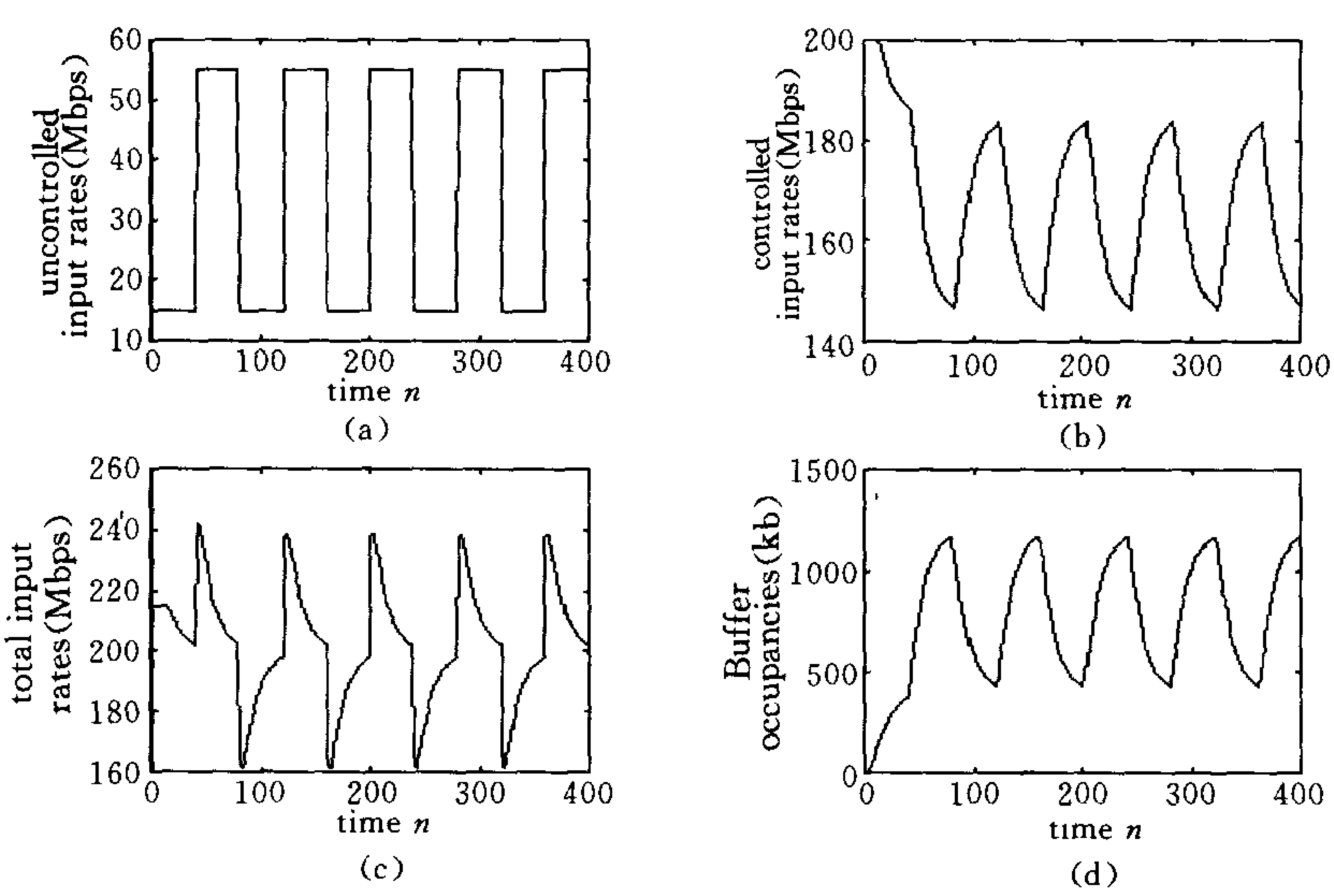

Fig. 2 Performance of a network implemented with a PD congestion control scheme with $\alpha=-\beta=0.05$

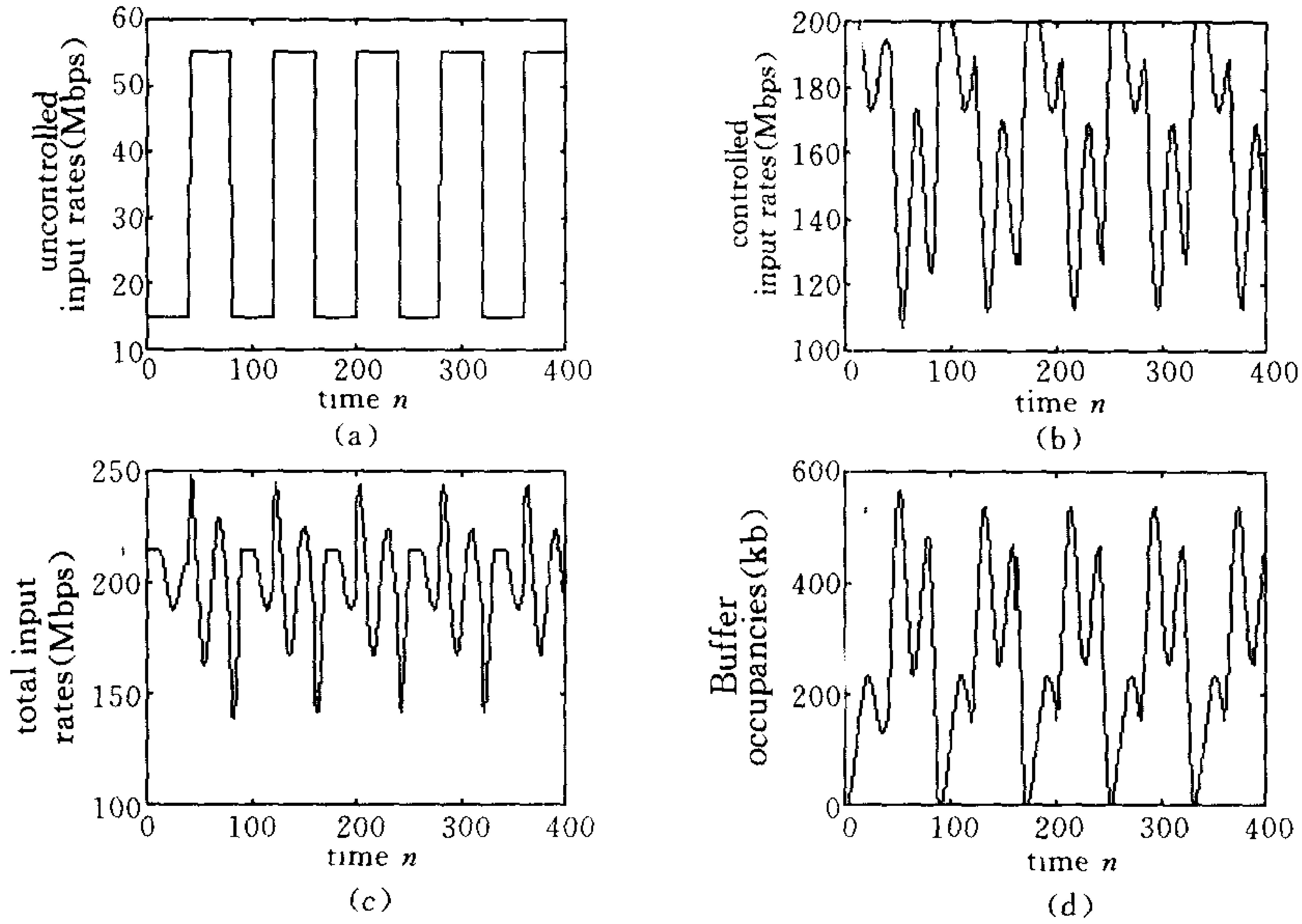

Fig. 3 Performance of a network implemented with a PD congestion control scheme with $\alpha=-\beta=0.2$

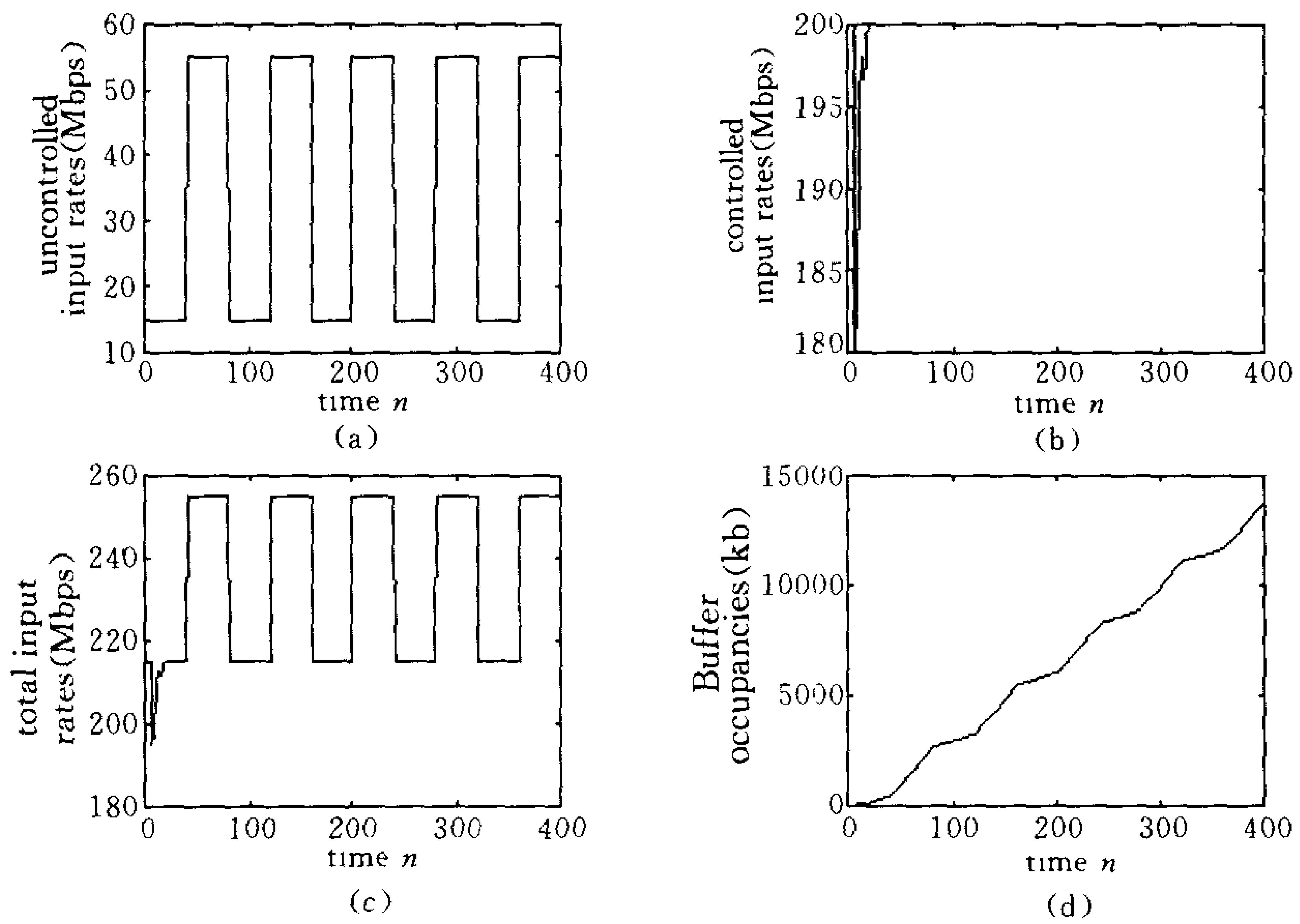

Fig. 4 Performance of a network implementec with a PD congestion control scheme with $\alpha=-\beta=-0.2$

Figures 2 and 3 indicate that in the time interval $[0, \tau_1]$, the switch node only transmits the packets of uncontrolled traffic into the network because the packets of controlled traffic have still not arrived during this interval. But in the time interval $[\tau_1, \tau]$, packets begin to accumulate in the buffer because the feedback information from the switch node to the source node has not still reached the source and the source node still transmits packets at the maximum rate. After a round-trip delay the source node adjusts its transmission rate and then after a relatively short period the buffer occupancy becomes steady.

Generally, a shot response time of buffer occupancy indicates that the controlled net-

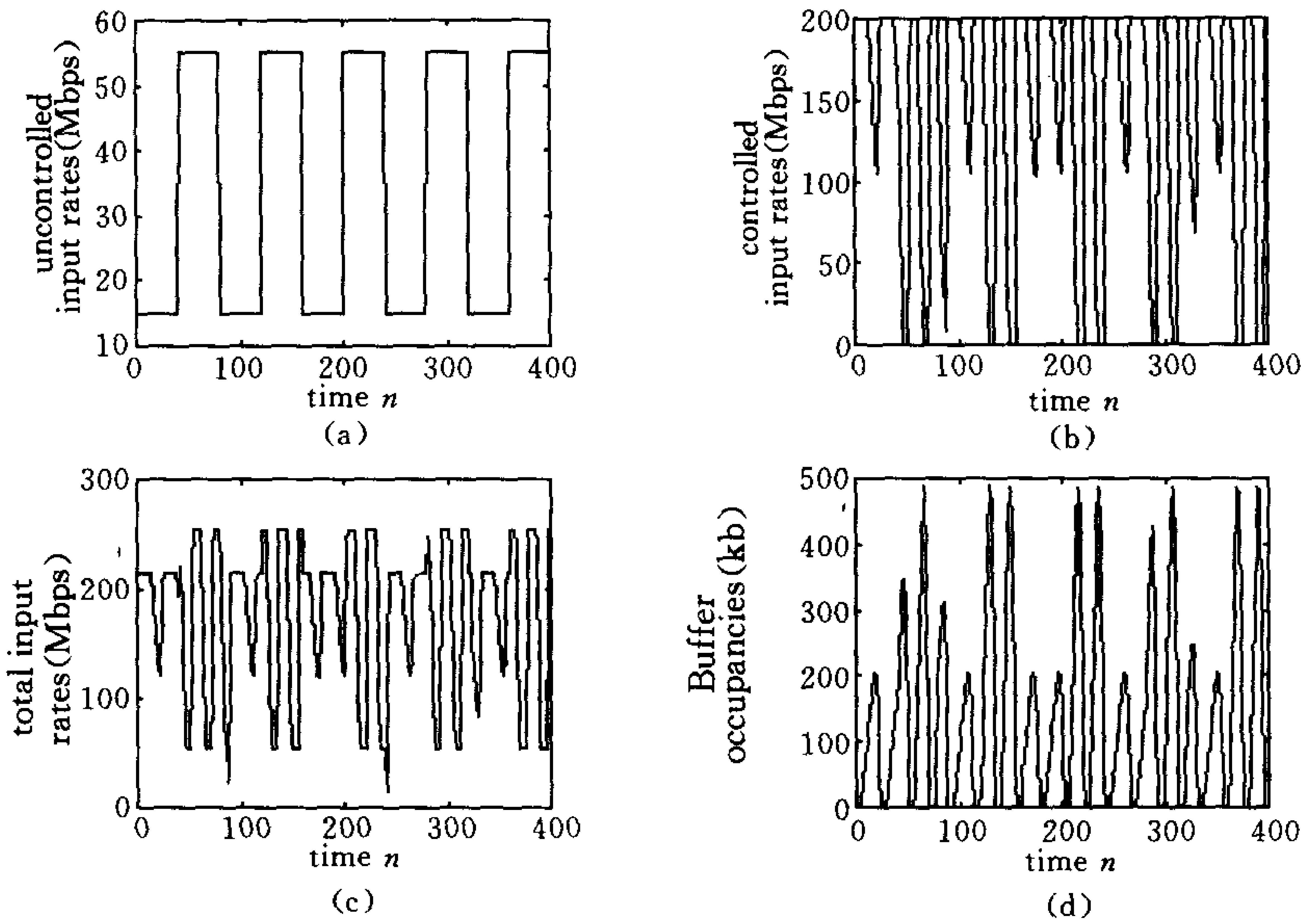

Fig. 5 Performance of a network implemented with a PD congestion control scheme with $\alpha=-\beta=0.9$

work achieves stability quickly. This is essential for the network to have a least packet loss rate. A small upper bound of buffer occupancy usually leads to a larger throughput, the performance of the network is subsequently promising. Comparing Figure 2 with Figure 3, one finds that both cases have short response time but the upper bound of buffer occupancy in Figure 3 is less. This then suggests the control schemes with the parameters $\alpha=-\beta=0.2$ corresponding to Figure 3 is better in terms of performance. From Figure 4 (b), it is seen that though at the beginning period of time the controlled traffic rate is adjusted, after this period it is not adjusted any more, i. e. , this rate is fixed at 200 Mbps. Further observation in Figure 4(d) finds that, in this situation no stability of the buffer occupancy is guaranteed, the buffer occupancy diverges and goes to unbounded, and consequently the buffer will overflow. The network will consequently lose packets in this situation. By observing Figure 5, one can see that there is a dramatic change in the dynamic of controlled rate, very heavy oscillations have appeared in the dynamic of buffer occupancy. The controlled network will also lose packets in this situation. In summary, among all the four control schemes corresponding to the four different kinds of control parameters, namely, $\alpha=-\beta=0.05$, $\alpha=-\beta=0.2$, $\alpha=-\beta=-0.2$, and $\alpha=-\beta=0.9$, respectively, the one corresponding to $\alpha=-\beta=0.2$ is the best, the one corresponding to $\alpha=-\beta=0.05$ is acceptable, while the last two are not acceptable.

References

1 Yang C Q, Reddy A A S. A taxonomy for congestion control algorithms in packet switching networks. *IEEE Network*, 1995, **9**(5): 34~45

2 Jain R, Kalyanaraman S, Fahmy S, Goyal R. Source behavior for ATM ABR traffic management: An explanation. *IEEE Communication Magazine*, 1996, **34**(11): 50~57

3 Benmohamed L, Meekov S M. Feedback control of congestion in packet switching networks: The case of a single congested node. *IEEE/ACM Transactions on Networking*, 1993, **1**(6): 693~707

4 Benmohamed L, Meekov S M. Feedback control of congestion in packet switching networks: The case of multiple congested node. In: Proceedings of American Control Conference, Baltimore: MD, 1994

5 Kalarov A, Ramamurthy G. A control theoretic approach to the design of closed loop rate-based flow control for high speed ATM networks. In: Proceedings of IEEE Infocom'97, Japan: Kobe, 1997

6 Zhang H, Yang O W, Mouftah H. A hop-by-hop flow controller for a virtual path. *Computer Networks*, 2000, **32**

(1): 99～119

7 Mascolo S. Smith's principle for congestion control in high-speed data networks. *IEEE Transactions on Automatic Control*, 2000, **45**(2): 358～364

8 Izmailov R. Adaptive feedback control algorithms for large data transfer in high-speed networks. *IEEE Transactions on Automatic Control*, 1995, **40**(8): 1469～1471

9 Izmailov R. Analysis and optimization of feedback control algorithms for data transfer in high-speed networks. *SIAM Journal of Control and Optimization*, 1996, **34**(5): 1767～1780

10 Pan Z, Altman E, Basar T. Robust adaptive flow control in high speed telecommunication networks. In: Proceedings of the 35th Conference on Decision and Control, Japan: Kobe, 1996

11 Tan Lian-Sheng, Yang S H, Yin Min, Zhao Fu-Zhe. Analysis of rate-based congestion control in ATM switching networks. In: Proceedings of the 4th International ICSC Symposium Soft Computing and Intelligent Systems for Industry, Scotland: Paisley, 2001, CD-ROM, ISBN 3-906454-27-4

12 Tan Lian-Sheng, Pugh A C. A novel method to determine the finite and infinite frequency structure of a rational matrix. *IMA Journal of Mathematical Control and Information*, 2001, **18**(2): 129～151

13 Pugh A C, Tan Lian-Sheng Tan. A generalized chain-scattering representation and its algebraic system properties. *IEEE Transactions on Automatic Control*, 2000, **45**(5): 1002～1007

14 Tan Lian-Sheng, Pugh A C. A note on the solution of regular PMDs. *International Journal of Control*, 1999, **72**(14): 1235～1248

15 Tan Lian-Sheng. Structural and behavioral analyses to linear multivariable control systems[Ph. D. Thesis]. UK: Loughborough University, 1999

TAN Lian-Sheng Professor in Department of Computer Science, Central China Normal University since 2000. He received his Master's degree from the Chinese Academy of Sciences in 1991 and his Ph. D. degree from Loughborough University, in the UK in 1999. In 2001, as a postdoctoral research fellow he worked in School of Information Technology and Engineering, University of Ottawa, Canada. His current main research interests include intelligent control, H-infinity control and congestion control and performance evaluation of computer communication networks.

YIN Min Master's degree research student at Department of Computer Science, Central China Normal University. Her research interest includes congestion control in high-speed computer communication network.

计算机高速互联网中一类基于速率的PD拥塞控制方法

谭连生　　尹　敏

(华中师范大学计算机科学系　武汉　430079)

(E-mail: L. Tan@ccnu. edu. cn; yinmin78@sohu. com)

摘　要　运用现代控制理论和方法，针对计算机高速互联网中最大努力服务交通流即能控交通流的调节问题，提出了一种基于速率的具有比例加微分(PD)控制器结构的拥塞控制理论和方法. 在单个节点的交通流的模型基础上，运用控制理论中系统稳定性分析方法，讨论如何利用信终端节点缓冲占有量的比例加微分的反馈形式来调节信源节点的能控交通流的输入速率，从而使被控网络节点的缓冲占有量趋于稳定. 仿真结果显示，在所设计的PD控制方案下，网络的有关性能较好.

关键词　计算机通讯网络，拥塞控制，PD控制器，缓冲占有量

中图分类号　TP3