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Adaptive Sliding Mode Congestion Control for DiffServ Network

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Abstract: This paper is about the application of adaptive sliding mode control to solving congestion problem for DiffServ Network. A nonlinear fluid flow model which is transformed into a parametric strict feedback form is used to analyze and control. Backstepping design procedure is applied, which leads to a new adaptive sliding mode controller. And by using the adaptive sliding mode controller, we achieve buffer queue length regulation against model uncertainties and disturbances. The simulation results show that the proposed control system is robust to unknown nonlinearities and disturbances.

1. INTRODUCTION

The DiffServ Network that is under consideration by IETF can provide different services to users of the Internet (Chait *et al.,* 2005). It adheres to the basic Internet philosophy and can be seen as a kind of extending of the Internet. There are two impotant services of DiffServ Network, one is premium traffic service and the other is ordinary traffic service. Premium service is designed for applications with stringent delay and loss requirements on per packet basis that can specify upper bounds on their traffic needs and required quality of service (Ebrahimirad *et al.*, 2004), while ordinary traffic is intended for applications that have relaxed delay requirements and allow their rates into the network to be controlled (Pisillides *et al.*, 2005).

For DiffServ Network, the fluid flow model is extensively used for network performance evaluation and control, especially for congestion control problems. The model first introduced in (Agnew, 1976) captures the essential dynamic behaviour of Internet. Recently, in order to develop the network congestion controller, model-based schemes have been proposed to provide theoretic analysis for networking problems, but most of them are baesd on linear control theory (Imer *et al.*, 2001; Hollot *et al.,* 2001; Paganini, 2002; Quet *et al.*, 2004; Wen *et al.*, 2004). But due to the inaccurate and uncertain nature of network models, the design of congestion controllers whose performance can be analytically established and demonstrated in practice is still a challenging unresolved problem.

Sliding mode control (SMC), as a special class of nonlinear systems is widely accepted as a feasible robust control for dynamic systems. And the backstepping method is a breakthrough for adaptive nonlinear control. It provides a systematic procedure to construct a robust control Lyapunov function. So integrating backstepping algorithm into the design of SMC is an effective method for a kind of nonlinear system with uncertainties and disturbances.

In this paper, our attention is focus on applying backstepping design with adaptive sliding mode control to address the queue regulation of premium and ordinary buffers in DiffServ Network, especially when nonlinear uncertainties and disturbances are involved. An integrated idea is that the sliding surface as a linear combination of the control errors is constructed at the final step of the backstepping design. The sliding mode control term ensures the convergence of the system states to the sliding surface, and then the convergence of control errors is also ensured.

The rest of the paper is organized as follows: in section II, the problem statement is given by changing the fluid flow model into a nonlinear parametric strict feedback form as well as considering the unknown system dynamics and external disturbances. The backstepping design of adaptive SMC is described in section III, the stability analysis is integrated into the design procedure. In section IV simulations are performed in order to illustrate the feasibility of the control scheme and the conclusion is given in the last section.

2. THE CONTROL PROBLEM AND OBJECTIVE

Based on fluid flow theory, a validated nonlinear DiffServ Network buffer dynamic is given as follows (Pisillides *et al.*, 2005)

$$\dot{x}(t) = -C(t)(\frac{x(t)}{1+x(t)}) + \lambda(t) \qquad (1)$$

where $x(t)$ denotes the queue length of the buffer, and it is taken as the state variable; $C(t)$ represents the to-be-assigned capacity, and it is chosen as the control input for premium buffer; while a nonlinear function $\lambda(t)$ is used to denote the average incoming traffic rate, and it is chosen as the control input for ordinary buffer.

For control purpose, the model might be represented as a system of coupled state and output equations

$$\begin{cases} \dot{x}_i(t) = -C_i(t)(\dfrac{x_i(t)}{x_i(t)+1}) + \lambda_i(t) \\ y_i(t) = x_i(t) \end{cases} . \qquad (2)$$

Notice that the indices $i = (p,r)$ represent premium and ordinary buffers dynamic respectively (Bouyoucef *et al.*, 2006) here and all over this paper.

For the purpose of backstepping design, the given model in (2) is transformed into a new nonlinear parametric-strict-feedback form (NPSF), with the following changes of coordinates, $x_{1p} = x_p$, $x_{2p} = -x_p/(x_p+1)$ for the premium buffer and $x_{1r} = x_r$, $x_{2r} = -x_r/(x_r+1)$ for the ordinary buffer. We can have

$$\begin{cases} \dot{x}_{1i} = -x_{2i} + \lambda_i \\ \dot{x}_{2i} = C_i \dfrac{-x_{2i} + \lambda_i}{(x_{1i}+1)^2} \\ y_i = x_{1i} \end{cases} . \qquad (3)$$

With the same indices $i = (p,r)$, we introduce a new state variables $w_{1i} = x_{1i}, w_{2i} = \dot{w}_{1i}$, which after substitution into equation (3), will lead to the following NPSF representation

$$\begin{cases} \dot{w}_{1i} = w_{2i} \\ \dot{w}_{2i} = -C_i \dfrac{w_{2i}}{(w_{1i}+1)^2} + \dot{\lambda}_i \\ y_i = w_{1i} \end{cases} . \qquad (4)$$

Being considered with unknown dynamics and external disturbances in DiffServ network (Mahdi, 2004), the system is reformulated as follows

$$\dot{w}_{2i} = -C_i(\dfrac{w_{2i}}{(w_{1i}+1)^2} + \Delta_{1i}) + \dot{\lambda}_i + \Delta_{2i} \qquad (5)$$

where Δ_{1i} denotes the unknown system dynamics and Δ_{2i} is the uncertain external disturbances.

That is

$$\begin{cases} \dot{w}_{1i} = w_{2i} \\ \dot{w}_{2i} = -C_i(\dfrac{w_{2i}}{(w_{1i}+1)^2}) + \dot{\lambda}_i + F_i \\ y_i = w_{1i} \end{cases} \qquad (6)$$

where F is the lumped uncertainty defined by

$$F_i = \Delta_{2i} - C_i \Delta_{1i}. \qquad (7)$$

3. PROPOSED ADAPTIVE SMC BACKSTEPPING CONTROLLER

3.1 The Control Strategy

For system (6), the state variables are w_{1i} w_{2i} , the control strategy is shown in Fig.1. For premium buffer the control signal is link capacity $C_p(t)$ and the data coming rate $\lambda_p(t)$ can be treated as disturbance of the system, so the control purpose is that thru accommodating link capacity let the

system output signal w_{1p} trace the desired reference queue length y_p^d ; For ordinary buffer the link capacity $C_r(t)$ is the left over capacity calculated from $C_r(t) = C(t) - C_p(t)$ which is uncontrolled, so the control signal is $\dot{\lambda}_r(t)$, the control purpose of ordinary buffer is that thru adjusting the arriving rate of data $\lambda_r(t)$ let the output signal w_{1r} trace the desired reference queue length y_r^d .
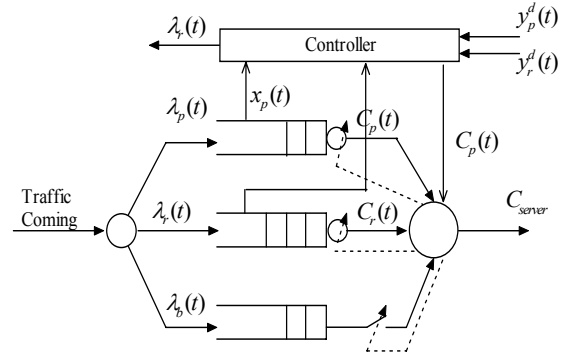

Fig. 1. Schematic diagram of the control strategy

3.2 Backstepping Design Procedures

The control objective is to design an adaptive backstepping sliding mode control system for the output of the system shown in (6) to track the reference trajectory, which is asymptotically. Assume that its first two derivatives are all bounded functions of time. The proposed adaptive backstepping sliding mode control system is designed to achieve the position-tracking objective and is described step by step as follows.

Step 1): For the tracking objective, define the tracking error as

$$z_{1i} = w_{1i} - y_i^d \qquad (8)$$

and its first derivative is

$$\dot{z}_{1i} = \dot{w}_{1i} - \dot{y}_i^d = w_{2i} - \dot{y}_i^d . \qquad (9)$$

Treating w_{2i} as a control signal for (9), the control law w_{2i}^d for w_{2i} which stabilizes w_{1i} would be

$$w_{2i}^d = -c_{1i} z_{1i} + \dot{y}_i^d . \qquad (10)$$

Define z_{2i} as the difference between w_{2i} and w_{2i}^d , we get

$$z_{2i} = w_{2i} - w_{2i}^d = w_{2i} + c_{1i} z_{1i} - \dot{y}_i^d . \qquad (11)$$

Substituting (10) into (11)

$$\dot{z}_{1i} = w_{2i} - \dot{y}_i^d = z_{2i} - c_{1i} z_{1i} . \qquad (12)$$

Then let

$$\alpha_{1i} = c_{1i} z_{1i} , \qquad (13)$$

z_{2i} is written as

$$z_{2i} = w_{2i} + \alpha_{1i} - \dot{y}_i^d . \qquad (14)$$

The first Lyapunov function is chosen as

$$V_{1i} = \frac{1}{2} z_{1i}^2 , \qquad (15)$$

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and the derivative of V_{1i} is

$$\dot{V}_{1i} = z_{1i}\dot{z}_{1i} = z_{1i}(-c_{1i}z_{1i} + z_{2i}) = -c_{1i}z_{1i}^2 + z_{1i}z_{2i}. \qquad (16)$$

Step 2): The derivative of z_{2i} is expressed as

$$\dot{z}_2 = \dot{w}_2 + \dot{\alpha}_1 - \ddot{y}_i^d = -C_p\frac{w_2}{(w_1+1)^2} + \dot{\lambda} + F_i + \dot{\alpha}_1 - \ddot{y}_i^d . \qquad (17)$$

Here, to design the backstepping controller, the uncertainty is assumed to be bounded, $|F_i| \le \overline{F}_i$, and define the sliding surface as

$$s_i = g_{1i}z_{1i} + z_{2i} \qquad (18)$$

where g_{1i} is a positive constant.

Choose the second Laypunov function as:

$$V_{2i} = V_{1i} + \frac{1}{2}s_i^2. \qquad (19)$$

The derivative of V_{2i} can be derived as follows:

$$\begin{aligned}\dot{V}_{2i} &= \dot{V}_{1i} + s_i\dot{s}_i \\ &= -c_1z_{1i}^2 + z_{1i}z_{2i} + s_i\dot{s}_i \\ &= -c_1z_{1i}^2 + z_{1i}z_{2i} + s_i(g_{1i}\dot{z}_{1i} + \dot{z}_{2i}) \\ &= -c_1z_{1i}^2 + z_{1i}z_{2i} + s_i[g_{1i}(-c_{1i}z_{1i} + z_{2i}) - C_i\frac{w_{2i}}{(w_{1i}+1)^2} \\ &\quad + \dot{\lambda}_i + F_i + \dot{\alpha}_1 - \ddot{y}_i^d].\end{aligned} \qquad (20)$$

According to (20), a backstepping sliding mode controller is designed as

$$\begin{aligned}C_P &= -\frac{(w_{1p}+1)^2}{w_{2p}}[-\dot{\lambda}_p - g_{1p}(-c_{1p}z_{1p} + z_{2p}) - \overline{F}_p\,\mathrm{sgn}(s_p) \\ &\quad - K_p s_p - \varepsilon_p\,\mathrm{sgn}(s_p) - \dot{\alpha}_{1p} + \ddot{y}_p^d],\end{aligned} \qquad (21)$$

$$\begin{aligned}\dot{\lambda}_r &= -g_{1r}(-c_{1r}z_{1r} + z_{2r}) + C_r\frac{w_{2r}}{(w_{1r}+1)^2} - \overline{F}_r\,\mathrm{sgn}(s_r) \\ &\quad - K_r s_r - \varepsilon_r\,\mathrm{sgn}(s_r) - \dot{\alpha}_{1r} + \ddot{y}_r^d.\end{aligned} \qquad (22)$$

Step 3): Since the lumped uncertainty F is unknown in practical application, the upper bound $\overline{F}$ is difficult to determine; therefore, an adaptive law is proposed to adapt the value of the lumped uncertainty.

Then, the third Lyapunov function is chosen as

$$V_{3i} = V_{2i} + \frac{1}{2\gamma_i}\tilde{F}_i^2 \qquad (23)$$

where $\tilde{F}_i = F_i - \hat{F}_i$, $\hat{F}_i$ is the prediction of system uncertainty and γ_i is a positive constant.

The derivative of V_{3i} is

$$\dot{V}_{3i} = \dot{V}_{2i} - \frac{1}{\gamma_i}\tilde{F}_i\dot{\hat{F}}_i$$

$$\begin{aligned} &= -c_{1i}z_{1i}^2 + z_{1i}z_{2i} + s_i[g_{1i}(-c_{1i}z_{1i} + z_{2i}) - C_i\frac{w_{2i}}{(w_{1i}+1)^2} \\ &\quad + \dot{\lambda}_i + F_i + \dot{\alpha}_{1i} - \ddot{y}_i^d] - \frac{1}{\gamma_i}\tilde{F}_i\dot{\hat{F}}_i \end{aligned}$$

$$\begin{aligned} &= -c_{1i}z_{1i}^2 + z_{1i}z_{2i} + s_i[g_{1i}(-c_1z_1 + z_2) - C_i\frac{w_{2i}}{(w_{1i}+1)^2} \\ &\quad + \dot{\lambda}_i + \hat{F}_i + \dot{\alpha}_{1i} - \ddot{y}_i^d] - \frac{1}{\gamma_i}\tilde{F}_i(\dot{\hat{F}}_i - \gamma_i s_i). \end{aligned} \qquad (24)$$

According to (24), an adaptive backstepping sliding mode control law is proposed as follows

$$\begin{aligned}C_P &= -\frac{(w_{1p}+1)^2}{w_{2p}}[-\dot{\lambda}_p - g_{1p}(-c_{1p}z_{1p} + z_{2p}) - \hat{F}_p\,\mathrm{sgn}(s_p) \\ &\quad - K_p s_p - \varepsilon_p\,\mathrm{sgn}(s_p) - \dot{\alpha}_{1p} + \ddot{y}_p^d],\end{aligned} \qquad (25)$$

$$\begin{aligned}\dot{\lambda}_r &= -g_{1r}(-c_{1r}z_{1r} + z_{2r}) + C_r\frac{w_{2r}}{(w_{1r}+1)^2} - \hat{F}_r\,\mathrm{sgn}(s_r) \\ &\quad - K_r s_r - \varepsilon_r\,\mathrm{sgn}(s_r) - \dot{\alpha}_{1r} + \ddot{y}_r^d.\end{aligned} \qquad (26)$$

The adaptation law for $\dot{\hat{F}}_i$ is designed as

$$\dot{\hat{F}}_i = \gamma_i s_i. \qquad (27)$$

3.3 Stability Analysis

Theorem 1: For the dynamic system in (6), the tracking error $x_{1i} - y_i^d$ converges to zero asymptotically with the control of premium buffer link capacity C_P in (25) and ordinary buffer arriving rate $\dot{\lambda}_r$ in (26) if the coefficients satisfy $K(c_1 + g_1) > 1/4$.

Proof: Substitute (25) (27) and (26) (27) into (24) seperately, for both premium and ordinary buffer the expressions are the same, here to be brief, omit the indices $i = (p, r)$, then we can get

$$\begin{aligned}\dot{V}_3 &= -c_1z_1^2 + z_1z_2 + s(-Ks - \varepsilon\,\mathrm{sgn}(s)) \\ &= -c_1z_1^2 + z_1z_2 - Ks^2 - \varepsilon|s|.\end{aligned} \qquad (28)$$

Note that (28) can be written as

$$\dot{V}_3 = -\mathbf{z}^T\mathbf{P}\mathbf{z} - \varepsilon|s| \qquad (29)$$

where $\mathbf{P}$ is a symmetric matrix with the following form

$$\mathbf{P} = \begin{bmatrix} c_1 + Kg_1^2 & Kg_1 - 1/2 \\ Kg_1 - 1/2 & K \end{bmatrix} \qquad (30)$$

and $\mathbf{z}^T = [z_1 \ z_2]$.

Note that if $\mathbf{P}$ is positive then $\dot{V}_3$ is negative and a sufficient condition to guarantee that $\mathbf{P}$ is positive definite is

$$\begin{aligned}|\mathbf{P}| &= K(c_1 + Kg_1^2) - (Kg_1 - 1/2)^2 \\ &= K(c_1 + g_1) - 1/4 > 0.\end{aligned} \qquad (31)$$

That is

$$K(c_1 + g_1) > 1/4, \qquad (32)$$

then $\dot{V}_3 < 0$.

Such that z_1 and z_2 will converge to zero when $t \to \infty$. As a result, the stability of the proposed adaptive backstepping sliding mode control system can be guaranteed. Moreover, since the condition holds $s\dot{s} < 0$, sliding mode is guaranteed on the sliding surface $s = 0$. So it is true that $x_{1p} - y_p^d \to 0$

and $x_{1r} - y_r^d \to 0$, asymptotically.

4. SIMULATION RESULTS

Simulation results for premium buffer and ordinary buffer are showed separately. During the simulation, $x_p(0) = 90$ and $x_r(0) = 22$. The controller design parameters are set to $c_{1i} = 1$, $g_{1i} = 1$ and $\gamma_i = 0.2$. While to avoid infinite frequency switching of the control signal, a boundary layer method is used.

For premium buffer the desired reference queue length y_p^d is a constant 100, the desired and actual trajectories are showed in Fig. 2. It is showed that $x_p(t)$ converges to $y_p^d = 100$ very quickly. The locus of tracking errors z_{1p}, z_{2p} and the sliding surface that converge to zero are showed in Fig. 3 and the control signal $C_p(t)$ is presented in Fig. 4.
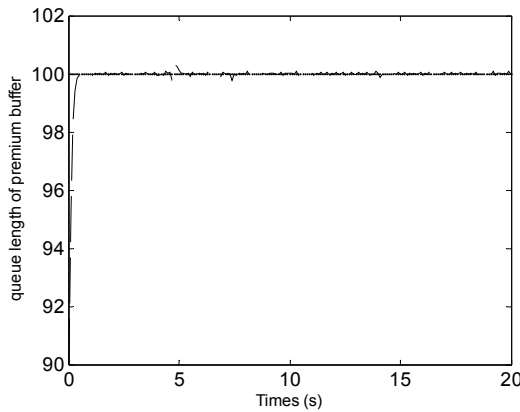
Fig. 2. Buffer length of premium traffic $x_p(t)$ and y_p^d
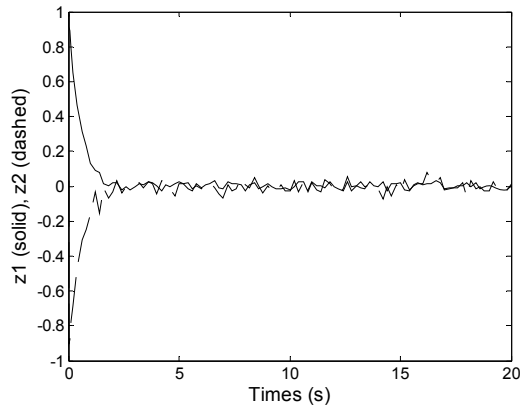
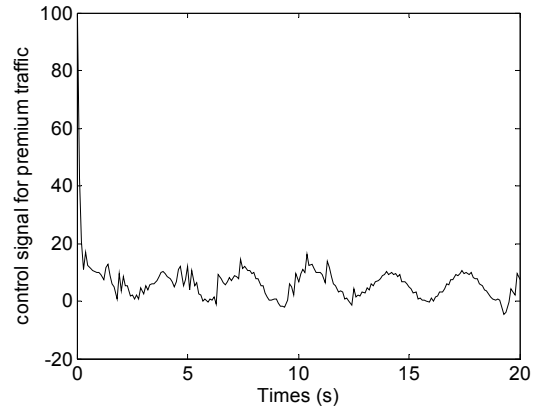Fig. 3. Tracking error of premium traffic z_{1p} and z_{2p}

Fig. 4. Control signal for premium traffic

For ordinary buffer the desired reference queue length y_r^d is a sine wave showed in Fig. 5 in solid and the actual trajectory is in dashed. It shows that $x_r(t)$ converges to y_r^d very quickly. The tracking errors z_{1r} and z_{2r} and the control signal $\dot{\lambda}(t)$ are presented in Fig. 6 and Fig. 7, respectively.
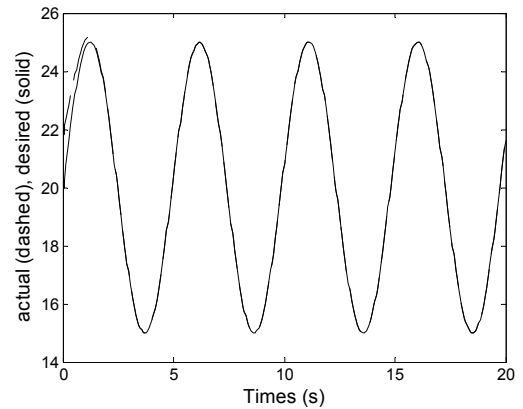

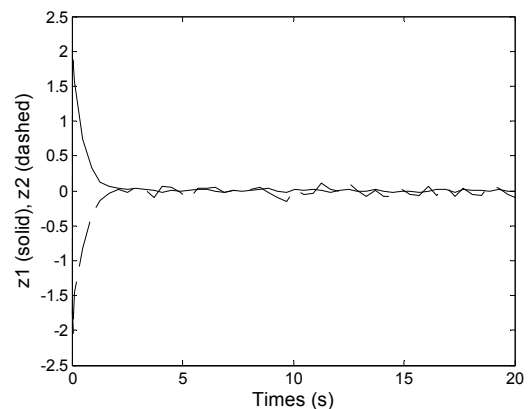Fig. 5. Buffer length of ordinary traffic $x_r(t)$ and y_r^d.

Fig. 6. Tracking error of ordinary traffic z_{1r} and z_{2r}.
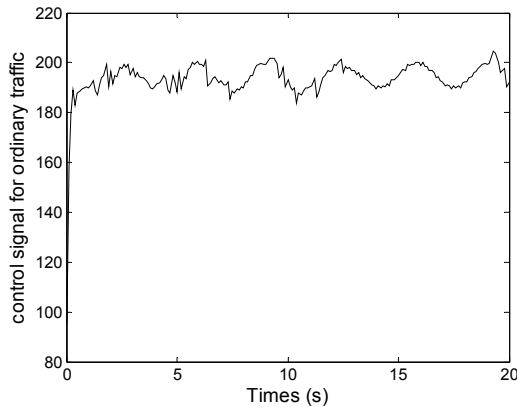
Fig. 7. Control signal for ordinary traffic.

Remark1: In ordinary traffic a step disturbance is added when $t = 10s$. Fig. 8 shows that the queue length has no difficulty to trace the reference length. The tracking error converges to zero as well. However, a classical backstepping controller will probably fail dealing with disturbances (Freeman *et al.,* 1996).
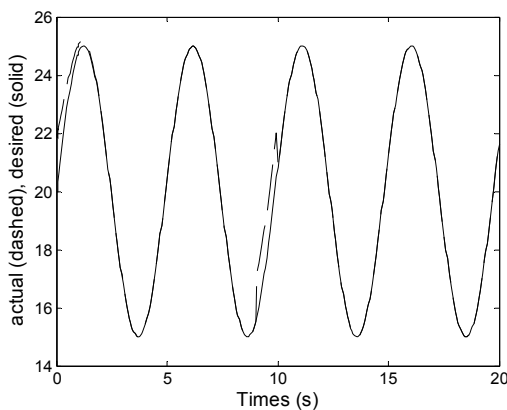

Fig. 8. Ordinary buffer length with a disturbance.

5. CONCLUSIONS

This paper is concerned with the adaptive sliding mode control by using backstepping design for DiffServ Network. The robustness of the proposed controller guarantees the regulation of the queue length with unknown model dynamics and uncertain external disturbances. In effect, the simulation results demonstrate that in both premium and ordinary buffer the proposed method can obtain faster transients and less oscillatory responses under dynamic network conditions, which translates into higher link utilization, low packet loss rate and small queue fluctuations.

REFERENCES

Blake S. *et al*. (1998). An architecture for Differentiated Services. *Request for Comments RFC 2475,* Internet Engineering Task Force.

Bouyoucef K., K. Khorasani (2006). Robust feedback linearization-based congestion control using a fluid flow model. *Proceedings of the 2006 American Control Conference,* Minneapolis, Minnesota, USA, 4882-4887.

Chait Y., C.V. Hollot (2005). Throughput differentiation using coloring at the network edge and preferential marking at the core. *IEEE/ACM Trans. on Networking,* **13(4),** 743-754.

Ebrahimirad Hassan and M.J. Yazdanpanah (2004). Sliding mode congestion control in Differentiated Service communication networks. *WWIC,* 99-108.

Freeman R.A. and P.V. Kokotovic′ (1996). *Robust nonlinear control design,* Birkhäuser, Boston.

Hollot, C. V., V. Misra, D.Towsley, and W. B. Gong (2001). A control theoretic analysis of RED. *Proc. IEEE INFOCOM,* 1510-1519.

Imer, Q.C., S. Compans, T. Basar, and R. Srikant (2001). ABR congestion control in ATM networks. *IEEE Control Systems Magazine,* **21(1),** 38-56.

Mahdi Jalili-Kharaajoo (2004). Robust H_∞ congestion avoidance in Differentiated Services communication networks. *10th Asia-Pacific Conference on Communications and 5th International Symposium on Multi-Dimensional Mobile communications,* 509-513.

Paganini F. (2002). A global stability result in network flow control. *Systems and Control Letters,* **46(3),** 153-163.

Pitsillides A., P. Ioannou, M. Lestas and L. Rossides (2005). Adaptive nonlinear congestion controller for a Differentiated-Services framework. *IEEE/ACM Transaction on Networking,* **13(1),** 94-107.

Quet, P. F. and H. Ozbay (2004). On the design of AQM supporting TCP flows using robust control theory. *IEEE Trans. Automatic Control,* **49(6),** 1031-1036.

Wen, J.T. and M. Arcak (2004). A unifying passivity framework for network flow control. *IEEE Trans. Automatic Control,* **49(2),** 162-174.