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Observer-Based Robust Controller Design for Active Queue Management

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Abstract: In this paper, an observer–based controller is designed for the problem of congestion control . In TCP/IP networks, the packets-dropping probability function is considered as a control input. Therefore, the work described here is to design robust observer controller, which is aimed at robust stabilization of network system with uncertainties, input delay and a saturated input. The controller is used to estimate online the average trasmission window and achieve the desired queue length. By applying the Lyapunov-Krasovskii function approach and the linear matrix inequality technique, control law is derived. Simulation experiments have been carrier out and the results demonstrate this scheme can achieve transient and steady-state responses. The results also show that this scheme outperformance the tradition PI controller.

1. INTRODUCTION

With the explosive growth and popularity of the Internet, the problem of congestion control is emerging as a more crucial problem. In the current Internet, TCP implementations detect packet losses and interpret them as indicators of congestion. TCP is necessary and powerful, which can be seen from the explosion increasing of Internet in recent decades. But it adapts the simplicity FIFO queuing mechanism and drop-tail queues that drop incoming packets when the queue is full, this faces with persistent congestion and results in higher delays. In addition, drop-tail queues can also results in burst packet drops, degrading system stability and bandwidth fairness. So it is suggested that the routers must play a key role in order to maintain good network performance. Active Queue management (AQM) scheme which is a router based congestion control method has been proposed to replace drop-tail queue management in order to improve network performance in tern of delay, link utilization, packet loss rate and system fairness. AQM enhance routers to detect and notify preemptively congestion notification to the source for reducing its transmission rate and therefore avoiding buffer overflow. The combination of TCP and AQM is the main approach to solve the problem of current Internet congestion control.

In the past few years, many AQM schemes have been studied in literatures. Random Early Detection (RED) (Floyd *et al.*, 1993) is regarded as the most famons AQM algorithm and has been recommended by IETF for deployment on the Internet (Braden *et al.*, 1998). It can prevent global synchronization, reduce packet loss and minimize the bias against burst sources. However,studies such as (Bonald *et al.*, 2000) and (Christiansen *et al.*,2000) have shown that it is very difficult to tune RED parameters in order to perform well under different traffic condition. In order to eliminate the drawbacks associated with RED, some modified RED schemes, such as ARED(Floyd *et al.*,2001), FRED(Lin et al., 1997), SRED(Ott *et al.*,1999),and BLUE (Feng *et al.*,2002). Most of these are heuristic algorithms and very few systematic and conparion were done until recently, both high netwoks utilization and low packet loss can not be guaranteed.

Recently, some AQM algorithms have been proposed based on control-theoretic analysis and design. In (Misra et al.,2000), a fluid-flow model for TCP/AQM networks has been introduced. This model describes the evolution of the characteristic variables of the network, including the average TCP window size and the average queue length. It is shown that the TCP model accurately captured the qualitative behavior of TCP traffic flows. Hence, several congestions control schemes based on this TCP model have been proposed to improve the performance of communication network. For example, a proportional (P) controller and a proportional-plus-integral (PI) controller for AQM were designed (Hollot *et al.*, 2001). They can not consider time-delay and the uncertainties with respect to the number of active TCP sessions through the congestion AQM router, so a robust controller is required to design. (Yin *et al*,. 2006; Ren *et al*,.2005) introduce a robust variable structure that exist good performance and robustness with respect to the uncertainties of the network parameters. As we known, In TCP networks, the packet-dropping probability function is considered as a control input. Therefore, the effect of a saturated actuator must be taken into account when designing a control scheme. (Chen *et al*,. 2007) has been done in this respect, but ignores the effect of uncertainties.

In this paper, we have design an AQM controller for a time-delayed and uncertainties TCP systems with input saturation. On the basis of the LMI technique and Lyapunov-Krasovskii function approach, robust control law is derived, an observer-based controller (OBC) have been developed for AQM to support the TCP. We have shown that the proposed algorithm has reliable asymptotic stability and robust in various network scenarios.

The remainders of this paper are organized as follows.Section Ⅱgives TCP dynamics flow model. Section Ⅲ presents the stability design for AQM based on observer-based controller scheme, considering the effect of state time-delay and uncertainties. Simulation results of the proposed scheme for various networks condition are shown in section Ⅳ. Finally, we conclud our brief work in sectionⅤ.

2. TCP NETEORK DYNAMICAL MODEL

In (Misra *et al.*,2000), a nonlinear dynamic model of TCP behavior was developed using fluid-flow and stochastic differential equation analysis. The simplified version that ignores the TCP timeout mechanism is as follows.

$$\begin{cases} \dot{W}(t) = \dfrac{1}{R(t)} - \dfrac{W(t)W(t-R(t))}{2R(t)} P(t-R(t)) \\ \dot{q}(t) = \dfrac{N(t)}{R(t)} W(t) - C(t) \end{cases} \tag{1}$$

where $W(t)$ is TCP window size; $q(t)$ is the instantaneous queue length on the router; $R(t)$ is round-trip time (RTT), which satisfies $R(t) = T_p + q(t)/C(t)$; T_p is the propagation delay; $p(t)$ is the packet-dropping probability function, which is the control input used to reduce the sending rate and to maintain the bottleneck queue, which satisfies $0 \le p(t) \le 1$; $C(t)$ is the link capacity, $N(t)$ is the number of the active TCP sessions.

For designing the AQM controller, it is assumed that $R(t) = R_0$, $N(t) = N$, $C(t) = C$ to be the nominal values of $R(t)$, $N(t)$, $C(t)$. Using linearization techniques, the operaing point (W_0, q_0, p_0) could be obtained by setting $\dot{W}(t) = 0$ and $\dot{q}(t) = 0$, which implies that (W_0, q_0, p_0) satisies $W_0^2 p_0 = 2$ and $W_0 = R_0 C / N$. Furthermore, Equation (1) was linearized at the operating point such that the nonlinear model could be expressed in the form of the following linear tine-delay model (Braden *et al.*,1998).

$$\begin{cases} \delta \dot{W}(t) = -\dfrac{N}{R_0^2 C}\left(\delta W(t) + \delta W(t-R_0)\right) \\ \qquad - \dfrac{1}{R_0^2 C}\left(\delta q(t) - \delta q(t-R_0)\right) - \dfrac{R_0 C^2}{2N^2}\delta p(t) \\ \delta \dot{q}(t) = \dfrac{N}{R_0}\delta W(t) - \dfrac{1}{R_0}\delta q(t) \end{cases} \tag{2}$$

where $\delta W \doteq W - W_0$, $\delta q \doteq q - q_0$, $\delta p \doteq p - p_0$.

Let $x_1 = \delta W(t)$, $x_2 = \delta q(t)$. The plant (2) can be described as:

$$\begin{cases} \dot{x}(t) = Ax(t) + A_d x(t-\tau) + Bu(t) \\ y(t) = Cx(t) \end{cases} \tag{3}$$

where $x(t) = [x_1 \quad x_2]^{\mathrm{T}}$, $u(t) = \delta p(t)$,which $u(t)$ satisfies $-p_0 \le u(t) \le 1 - p_0$, $R_0 = \tau$, A , A_d , B and C are constant matrices of appropriate demensions expressed in the following forms:

$$A = \begin{bmatrix} -\dfrac{N}{R_0^2 C} & -\dfrac{1}{R_0^2 C} \\ \dfrac{N}{R_0} & -\dfrac{1}{R_0} \end{bmatrix}, \quad A_d = \begin{bmatrix} -\dfrac{N}{R_0^2 C} & \dfrac{1}{R_0^2 C} \\ 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} -\dfrac{R_0 C^2}{2N^2} \\ 0 \end{bmatrix},$$

$C = [0 \quad 1]$.

For the TCP model defined by Eq. (3), the following time-delay system with saturated input can be derived:

$$\begin{cases} \dot{x}(t) = Ax(t) + A_d x(t-\tau) + Bsat(u(t)) \\ y(t) = Cx(t) \\ x(t) = \varphi(t), \quad t \in [-\tau, 0] \end{cases} \tag{4}$$

The saturated input is expressed by the folowing nonlinearity:

$$sat(u(t)) = \begin{cases} u_{\max} & \text{if } u(t) \ge u_{\max} \\ u(t) & \text{if } u_{\min} \le u(t) < u_{\max} \\ u_{\min} & \text{if } u(t) < u_{\min} \end{cases} \tag{5}$$

where $u_{\min} = -p_0$ and $u_{\max} = 1 - p_0$. From Eq.(5), the saturation term in Eq (4) can be rewritten as:

$$sat(u(t)) = \beta(u(t))u(t) \tag{6}$$

where

$$\beta(u(t)) = \begin{cases} u_{\max}/u(t) & \text{if } u(t) \ge u_{\max} \\ 1 & \text{if } u_{\min} \le u(t) < u_{\max} \\ u_{\min}/u(t) & \text{if } u(t) < u_{\min} \end{cases} \tag{7}$$

and

$$0 \le \beta(u(t)) \le 1 \text{ for all } t \ge 0 \tag{8}$$

The controller design should take into accout the time-delay, at the same time, uncertainties is also considered in the linear TCP model because of changing network parameter. Therefor, based on Eqs.(5)-(8), the system in Eq.(4) can be rewritten in an equivalent form as:

$$\begin{cases} \dot{x}(t) = (A + \Delta A(t))x(t) + (A_d + \Delta A_d(t))x(t-\tau) \\ \qquad + (B + \Delta B)\beta(u(t))u(t) \\ y(t) = Cx(t) \\ x(t) = \varphi(t), \quad t \in [-\tau, 0] \end{cases} \tag{9}$$

where $x(t) \in \mathrm{R}^2$, $u(t) \in \mathrm{R}^1$, and $y(t) \in \mathrm{R}^1$ represent the state, the control input, and the system output, respectively. $\Delta A(t)$, $\Delta A_d(t)$ and ΔB are the uncertainties depending on network parameters.

In process of designing controller, the following assumptions are taken:

Assumption 1: the pairs (A,B) and (A,C) are controllable and observable,respectively.
Assumption 2: The perturbed matrices $\Delta A(t)$ and $\Delta A_d(t)$ satisfy $\Delta A = D_1F_1(t)E_1$, $\Delta A_d = D_2F_2(t)E_2$, $\Delta B = D_3F_3(t)E_3$. where matrices D_i and E_i are constant with appropriate dimensions and the uncertain parameter $F_i(t)$ satisfies $\|F_i(t)\| \le 1$, $i = 1,2,3$.

The objective of this work is to design a controller capable of achieving asymptotic stability of the desired operating point and provide robust performance on the basis of the linear time-delay model with a saturated input and uncetrtainties.

3. DESIGN OF CONTROLLER FOR AQM

Since communication networks are large-scale complex systems, it is impossible to measure the size of the state variable window locally. A more pratice approach to develop an robust observer-based controller (OBC).

The state OBC for practical networks is considered in the following form:

$$\begin{cases} \dot{z}(t) = Az(t) + B\beta(u(t))u(t) + L(y(t) - \hat{y}(t)) \\ \hat{y}(t) = Cz(t) \end{cases} \tag{10a}$$

$$u(t) = -Kz(t) \tag{10b}$$

where $z(t) \in \mathrm{R}^2$ is the estimation of $x(t)$, $y(t) \in \mathrm{R}^1$ is the observer output, $L \in \mathrm{R}^{2\times1}$ is the gain matrix of the observer, $K \in \mathrm{R}^{1\times2}$ is the control gain.

Define the error state

$$e(t) = x(t) - z(t) \tag{11}$$

then it following from (9), (10a) and (11) that

$$\begin{aligned} \dot{e}(t) &= \dot{x}(t) - \dot{z}(t) \\ &= (A + \Delta A)x(t) + (A_d + \Delta A_d)x(t-\tau) + (B + \Delta B)\beta(u(t))u(t) \\ &\quad - Az(t) - B\beta(u(t))u(t) - L(y(t) - \hat{y}(t)) \\ &= (\Delta A - \Delta B\beta K)x(t) + (A - LC + \Delta B\beta K)e(t) + \\ &\quad (A_d + \Delta A_d)x(t-\tau) \end{aligned} \tag{12}$$

By substituting Eq.(10b) into Eq.(9), we obtain as follow:

$$\begin{aligned} \dot{x}(t) &= (A + \Delta A)x(t) + (A_d + \Delta A_d)x(t-\tau) + (B + \Delta B)\beta(-Kz(t)) \\ &= (A + \Delta A)x(t) + (A_d + \Delta A_d)x(t-\tau) + (B + \Delta B)\beta(-Kz(t)) \\ &\quad + (B + \Delta B)\beta Kx(t) - (B + \Delta B)\beta Kx(t) \\ &= (A + \Delta A - B\beta K - \Delta B\beta K)x(t) + (B\beta K + \Delta B\beta K)e(t) + \\ &\quad (A_d + \Delta A_d)x(t-\tau) \end{aligned} \tag{13}$$

The objection of this section is to design observer gain matrix L and feedback gain matrix K, the augmented system (12) and (13) is asymptotically stable . The following choose the Lyapunov-Krasovskii function, using the linear matrix inequality technology to guarantee the stability of the observer and to reduce the effect of model uncertainties on the estimated state.

The following lemma will be useful in designing an robust observer for the uncertain linear time-delay system (9).

Lemma. (Li et al.,1997) (1) For any $z, y \in \mathrm{R}^{n\times n}$,

$$\pm 2z^{\mathrm{T}}y \le z^{\mathrm{T}}z + y^{\mathrm{T}}y .$$

(2) For any $x, y \in \mathrm{R}^{n\times n}$ and $F(t)$ is real matrices of appropriate dimensions with $\|F(t)\| \le 1$,

$$\pm 2x^{\mathrm{T}}Fy \le x^{\mathrm{T}}x + y^{\mathrm{T}}y .$$

The following theorem offers the theoretical basis for achieving the desired design goal.

Theorem . Consider the augmented system (12) and (13). This system is stabilized by OBC in Eq.(10) for any constant delay τ if the observer gain L is chosen such that $L = Q^{-1}C^{\mathrm{T}}$. There exist symmetric positive definite matrices P and Q which satisfy the following matrix inequality:

$$\begin{bmatrix} A^{\mathrm{T}}P + PA + \Omega & P & W \\ P & -S_1^{-1} & 0 \\ W^{\mathrm{T}} & 0 & -S_2^{-1} \end{bmatrix} < 0 \tag{14}$$

$$\begin{bmatrix} A^{\mathrm{T}}Q + QA & Q & W \\ Q & -H_1^{-1} & 0 \\ W^{\mathrm{T}} & 0 & -H_2^{-1} \end{bmatrix} < 0 \tag{15}$$

where
$\Omega = 2E_1^{\mathrm{T}}E_1 + 2E_2^{\mathrm{T}}E_2 + 2I$, $W = K^{\mathrm{T}}$,
$S_1 = \left(D_1D_1^{\mathrm{T}} + D_2D_2^{\mathrm{T}} + 2D_3D_3^{\mathrm{T}} + 2BB^{\mathrm{T}} + A_dA_d^{\mathrm{T}}\right)$,
$S_2 = H_2 = 2E_3^{\mathrm{T}}E_3 + 2I$, $H_1 = D_1D_1^{\mathrm{T}} + D_2D_2^{\mathrm{T}} + 2D_3D_3^{\mathrm{T}} + A_dA_d^{\mathrm{T}}$.

Proof: Choose the following Lyapunov-Krasovskii function:

$$V(t) = V_1(t) + V_2(t) + V_3(t) \tag{16}$$

where

$$V_1(t) = x^{\mathrm{T}}(t)Px(t) \tag{17}$$

$$V_2(t) = e^{\mathrm{T}}(t)Qe(t) \tag{18}$$

$$V_3(t) = \int_{t-\tau}^{t} x^{\mathrm{T}}(s)\left(2E_2^{\mathrm{T}}E_2 + 2I\right)x(s)\,\mathrm{d}s \tag{19}$$

P and Q are symmetry positive matrices. I is unit matrix.

Taking the time derivative of V_1 and using (13) to obtain

$$\begin{aligned}\dot{V}_1 &= \dot{x}^{\mathrm{T}}(t)Px(t)+x^{\mathrm{T}}(t)P\dot{x}(t)\\ &= x^{\mathrm{T}}(t)\left(A+\Delta A-B\beta K-\Delta B\beta K\right)^{\mathrm{T}}Px(t)+\\ &\quad e^{\mathrm{T}}(t)\left(B\beta K+\Delta B\beta K\right)^{\mathrm{T}}Px(t)+x^{\mathrm{T}}(t-\tau)\left(A_d+\Delta A_d\right)^{\mathrm{T}}Px(t)\\ &\quad +x^{\mathrm{T}}(t)P\left(A+\Delta A-B\beta K-\Delta B\beta K\right)x(t)\\ &\quad +x^{\mathrm{T}}(t)P\left(B\beta K+\Delta B\beta K\right)e(t)+x^{\mathrm{T}}(t)P\left(A_d+\Delta A_d\right)x(t-\tau)\\ &= x^{\mathrm{T}}(t)\left(A^{\mathrm{T}}P+PA\right)x(t)+2x^{\mathrm{T}}(t)P\Delta Ax(t)-2x^{\mathrm{T}}(t)PB\beta Kx(t)\\ &\quad -2x^{\mathrm{T}}(t)P\Delta B\beta Kx(t)+2x^{\mathrm{T}}(t)PB\beta Ke(t)+2x^{\mathrm{T}}(t)P\Delta B\beta Ke(t)\\ &\quad +2x^{\mathrm{T}}(t)PA_dx(t-\tau)+2x^{\mathrm{T}}(t)P\Delta A_dx(t-\tau)\end{aligned} \tag{20}$$

Using lemma , assumption 2 and (8) , we have the following form:

$$\begin{aligned}&2x^{\mathrm{T}}(t)P\Delta Ax(t)\\ &=2x^{\mathrm{T}}(t)PD_1F_1(t)E_1x(t)\\ &\le x^{\mathrm{T}}(t)PD_1D_1^{\mathrm{T}}Px(t)+x^{\mathrm{T}}(t)E_1^{\mathrm{T}}E_1x(t)\end{aligned} \tag{21}$$

$$\begin{aligned}&-2x^{\mathrm{T}}(t)PB\beta Kx(t)\\ &=\beta\left(-2x^{\mathrm{T}}(t)PBKx(t)\right)\\ &\le\beta\left(x^{\mathrm{T}}(t)PBB^{\mathrm{T}}Px(t)+x^{\mathrm{T}}(t)K^{\mathrm{T}}Kx(t)\right)\\ &\le\left(x^{\mathrm{T}}(t)PBB^{\mathrm{T}}Px(t)+x^{\mathrm{T}}(t)K^{\mathrm{T}}Kx(t)\right)\end{aligned} \tag{22}$$

$$\begin{aligned}&-2x^{\mathrm{T}}(t)P\Delta B\beta Kx(t)\\ &=-2x^{\mathrm{T}}(t)PD_3F_3(t)E_3\beta Kx(t)\\ &=\beta\left(-2x^{\mathrm{T}}(t)PD_3F_3(t)E_3Kx(t)\right)\\ &\le\beta\left(x^{\mathrm{T}}(t)PD_3D_3^{\mathrm{T}}Px(t)+x^{\mathrm{T}}(t)K^{\mathrm{T}}E_3^{\mathrm{T}}E_3Kx(t)\right)\\ &\le x^{\mathrm{T}}(t)PD_3D_3^{\mathrm{T}}Px(t)+x^{\mathrm{T}}(t)K^{\mathrm{T}}E_3^{\mathrm{T}}E_3Kx(t)\end{aligned} \tag{23}$$

$$\begin{aligned}&2x^{\mathrm{T}}(t)PB\beta Ke(t)\\ &=\beta\left(2x^{\mathrm{T}}(t)PBKe(t)\right)\\ &\le\beta\left(x^{\mathrm{T}}(t)PBB^{\mathrm{T}}Px(t)+e^{\mathrm{T}}(t)K^{\mathrm{T}}Ke(t)\right)\\ &\le x^{\mathrm{T}}(t)PBB^{\mathrm{T}}Px(t)+e^{\mathrm{T}}(t)K^{\mathrm{T}}Ke(t)\end{aligned} \tag{24}$$

$$\begin{aligned}&2x^{\mathrm{T}}(t)P\Delta B\beta Ke(t)\\ &=\beta\left(2x^{\mathrm{T}}(t)PD_3F_3(t)E_3Ke(t)\right)\\ &\le\beta\left(x^{\mathrm{T}}(t)PD_3D_3^{\mathrm{T}}Px(t)+e^{\mathrm{T}}(t)K^{\mathrm{T}}E_3^{\mathrm{T}}E_3Ke(t)\right)\\ &\le x^{\mathrm{T}}(t)PD_3D_3^{\mathrm{T}}Px(t)+e^{\mathrm{T}}(t)K^{\mathrm{T}}E_3^{\mathrm{T}}E_3Ke(t)\end{aligned} \tag{25}$$

$$\begin{aligned}&2x^{\mathrm{T}}(t)PA_dx(t-\tau)\\ &\le x^{\mathrm{T}}(t)PA_dA_d^{\mathrm{T}}Px(t)+x^{\mathrm{T}}(t-\tau)x(t-\tau)\end{aligned} \tag{26}$$

$$\begin{aligned}&2x^{\mathrm{T}}(t)P\Delta A_dx(t-\tau)\\ &=2x^{\mathrm{T}}(t)PD_2F_2(t)E_2x(t-\tau)\\ &\le x^{\mathrm{T}}(t)PD_2D_2^{\mathrm{T}}Px(t)+x^{\mathrm{T}}(t-\tau)E_2^{\mathrm{T}}E_2x(t-\tau)\end{aligned} \tag{27}$$

Substituting (21)-(27) into (20), we have the following inequality:

$$\begin{aligned}\dot{V}_1 &\le x^{\mathrm{T}}(t)\big(A^{\mathrm{T}}P+PA+PD_1D_1^{\mathrm{T}}P+PD_2D_2^{\mathrm{T}}P+2PD_3D_3^{\mathrm{T}}P+\\ &2PBB^{\mathrm{T}}P+PA_dA_d^{\mathrm{T}}P+E_1^{\mathrm{T}}E_1+K^{\mathrm{T}}K+K^{\mathrm{T}}E_3^{\mathrm{T}}E_3K\big)x(t)\\ &+e^{\mathrm{T}}(t)\left(K^{\mathrm{T}}K+K^{\mathrm{T}}E_3^{\mathrm{T}}E_3K\right)e(t)+x^{\mathrm{T}}(t-\tau)\left(I+E_2^{\mathrm{T}}E_2\right)x(t-\tau)\end{aligned} \tag{28}$$

Taking the time derivative of V_2 and using (12) to obtain:

$$\begin{aligned}\dot{V}_2 &= \dot{e}^{\mathrm{T}}(t)Qe(t)+e^{\mathrm{T}}(t)Q\dot{e}(t)\\ &= e^{\mathrm{T}}(t)\left(A^{\mathrm{T}}Q+QA\right)e(t)+e^{\mathrm{T}}(t)\left((-LC)^{\mathrm{T}}Q+Q(-LC)\right)e(t)\\ &\quad +2e^{\mathrm{T}}(t)Q\Delta B\beta Ke(t)+2e^{\mathrm{T}}(t)Q\left(\Delta A-\Delta B\beta K\right)x(t)\\ &\quad +2e^{\mathrm{T}}(t)QA_dx(t-\tau)+2e^{\mathrm{T}}(t)Q\Delta A_dx(t-\tau)\end{aligned} \tag{29}$$

By lemma and assumption 2 , choosing $L=Q^{-1}C^{\mathrm{T}}$, we get:

$$\begin{aligned}\dot{V}_2 &\le e^{\mathrm{T}}(t)\big(A^{\mathrm{T}}Q+QA+2QD_1D_1^{\mathrm{T}}Q+QD_2D_2^{\mathrm{T}}Q+2QD_3D_3^{\mathrm{T}}Q+\\ &\quad QA_dA_d^{\mathrm{T}}Q+K^{\mathrm{T}}E_3^{\mathrm{T}}E_3K\big)e(t)+x^{\mathrm{T}}(t)\left(E_1^{\mathrm{T}}E_1+K^{\mathrm{T}}E_3^{\mathrm{T}}E_3K\right)x(t)+\\ &\quad x^{\mathrm{T}}(t-\tau)\left(I+E_2^{\mathrm{T}}E_2\right)x(t-\tau)\end{aligned} \tag{30}$$

The time derivative of V_3 can be computed as

$$\begin{aligned}\dot{V}_3 &= x^{\mathrm{T}}(t)\left(2E_2^{\mathrm{T}}E_2+2A_d^{\mathrm{T}}A_d\right)x(t)-\\ &\quad x^{\mathrm{T}}(t-\tau)\left(2E_2^{\mathrm{T}}E_2+2A_d^{\mathrm{T}}A_d\right)x(t-\tau)\end{aligned} \tag{31}$$

Then, by using Eqs.(25),(30) and (31), it can be shown that

$$\begin{aligned}\dot{V} &= \dot{V}_1+\dot{V}_2+\dot{V}_3\\ &\le x^{\mathrm{T}}(t)R_1x(t)+e^{\mathrm{T}}(t)R_2e(t)\end{aligned} \tag{32}$$

where

$$\begin{aligned}R_1 &= A^{\mathrm{T}}P+PA+PD_1D_1^{\mathrm{T}}P+PD_2D_2^{\mathrm{T}}P+2PD_3D_3^{\mathrm{T}}P+2PBB^{\mathrm{T}}P+\\ &\quad PA_dA_d^{\mathrm{T}}P+2E_1^{\mathrm{T}}E_1+K^{\mathrm{T}}K+2K^{\mathrm{T}}E_3^{\mathrm{T}}E_3K+2I+2E_2^{\mathrm{T}}E_2\\ R_2 &= A^{\mathrm{T}}Q+QA+QD_1D_1^{\mathrm{T}}Q+QD_2D_2^{\mathrm{T}}Q+2QD_3D_3^{\mathrm{T}}Q+\\ &\quad QA_dA_d^{\mathrm{T}}Q+2K^{\mathrm{T}}E_3^{\mathrm{T}}E_3K+K^{\mathrm{T}}K\end{aligned}$$

By Schur complements, it can be shown that (14) and (15) imply $\dot{V}<0$, Therefore, from the Lyapunov-Krasovskii stability theorem, it can be concluded that the system (12) and is uniformly asymptotically stable. We can complete the proof.

4. SIMULATION RESULTS

In this section, computer simulations are carried out to confirm the validity of the proposed algorithm. For comparison purposes, we also simulation the PI AQM scheme introuduce recently in (Yin et al., 2006). the performance of the proposed OBC is compare with the PI algorithm. The network parameters of simulation model are refers to scenario with a single bottleneck router running AQM schemes.

The choosing of the parameters are followed as: $N=50$, $C=300$ packets/s, $R_0=50ms$,request q_d =100 packets,the desired window size is $W_0=2.5$ packets, $P_0=2/2.5^2$ =3.2, therefor, $u_{\min}=-0.32$, $u_{\max}=0.68$. To PI-AQM, the choosing of parameters is $K_P=0.0023$, $K_I=0.0004$. From theorem, we use LMI toolbox in the matlab to solove matrices P and Q .

$$P=\begin{bmatrix}9.4467 & 0.3238\\ 0.3238 & 0.2468\end{bmatrix},\ Q=\begin{bmatrix}9.2691 & 0.2767\\ 0.2767 & 0.2415\end{bmatrix}.$$

We can verify that matrices P and Q are symmetry positive , so they satisfy the demand of theorem. The following observer and feedback gains are obtained.

$$K = \begin{bmatrix} 0.0378 & 0.0013 \end{bmatrix},\ L = \begin{bmatrix} -0.1280 \\ 4.2873 \end{bmatrix}.$$

The parameters have been obtained by applying the proposed OBC. The trajectories of the queue length with PI and OBC are depicted in Fig.1 and Fig. 2,respectively.

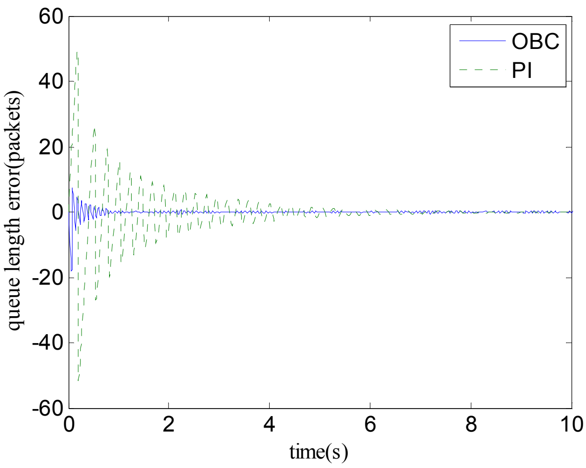

Fig. 1. Queue length error responses with nominal values

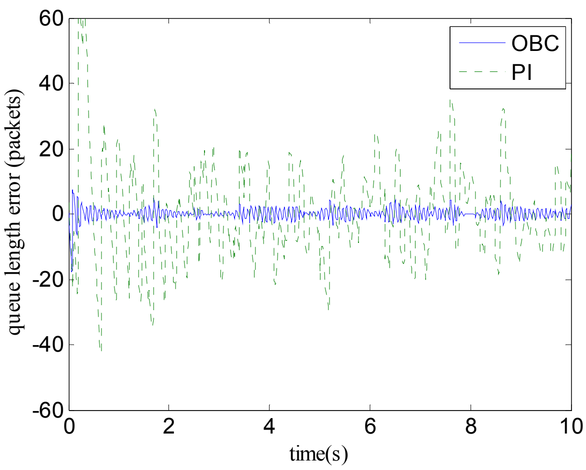

Fig.2.Queue length error responses with varied network parameters

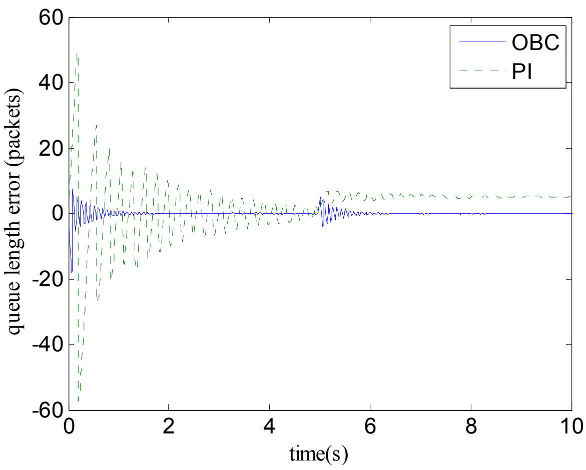

Fig3. Queue length error responses with nominal value and bursting flows

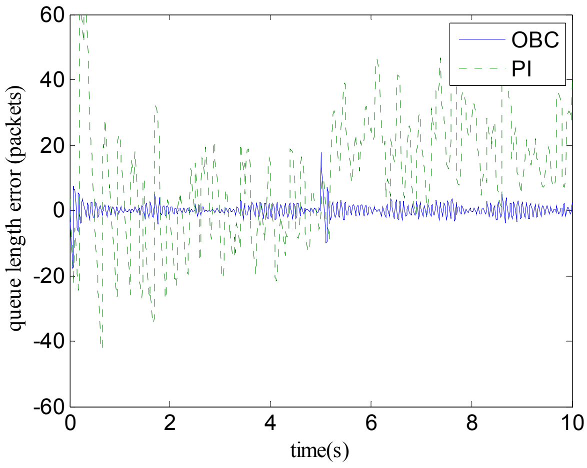

Fig.4. Queue length error responses with varied network parameters disturbance and bursting flows

In Fig.3-4. we add to the TCP flows for UDP flows (transmitting on 1Mbit / s) from 5 *th* second , respectively choosing fixed and varied network parameters. We can see that PI controller performance badly when UDP flows go down. Again, the OBC controller shows better performance, with exhibiting faster responses and better regulation properties.

5. CONCLUSIONS

In this paper, we use linearization to analyze a previously developed nonlinear model of TCP. For TCP network with the time-delayed and uncertainties, we design an OBC with a saturated input. On the basis of the Lyapunov-Krasovskii functional approach , by solving two linear matrice inequalities, the corresponding control laws is developed to achieve asymptotic stability. The simulation results demonstrate that the proposed AQM congestion control schemes can obtain well performance in various networks conditions.

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