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Sliding Mode Control for Uncertain Time-delay TCP/AQM Network Systems

Hongwei Wang*. Yuanwei Jing*. Yucheng Zhou**. Zhaona Chen*.Xiaoping Liu*
** Institute of Information Science & Engineering,*
Northeastern University, Shenyang, Liaoning, 110004, P.R. of China
(e-mail: wanghw0819@ 163.com; ywjjing@ mail.neu.edu.cn; neuzhaona@163.com; liuxp@mail.neu.edu.cn).
*** Department of Research Institute of Wood Industry Chinese*
Academy of Forestry, Beijing, 100091, P.R. of China
(e-mail:zhouyc@ caf.ac.cn).

Abstract: For TCP linear dynamic systems with input time-varying and mismatched uncertainties, we propose an active queue management (AQM) scheme based on sliding mode control (SMC), which is aimed at robust stabilization of delay and uncertainties network system .The original uncertain time-delay system was first transformed into a delay-free system. Then based on the transformed system, an improved sliding mode control (ISMC) strategy is proposed; the robust sliding hyperplane is constructed from LMI with stability. The simulation experiments indicate that this scheme can track queue length very quickly under various network conditions, the system have strong robustness .The results also that this scheme outperformance the known ones with the traditional either proportional-plus-intergral or sliding mode controls.

1. INTRODUCTION

Active queue management (AQM), as one class of packet dropping/marking mechanism in the router queue , has been recently proposed to complement the TCP network congestion control. Random early detection (RED) is regarded as the famous AQM scheme advocated by IETF(Floyd, 1993). It can prevent global synchronization, reduce packet loss ratios, and minimize the bias against bursty sources. However, it is designed in an ad hoc way. Several experimental studies and theoretical analysis of RED's performance have shown that it is very difficult to tune RED parameters to get well performance under various network conditions. In addition, it is difficult to reduce fluctuations by only adjusting RED's parameters. The inefficiency of the original RED as AQM attracted much research work on improving its performance, and led to a number of AQM algorithm, such as Adaptive RED(ARED) (Floyd *et al*.,2001), Fairness RED (FRED)(Lin *et al*.,1997), Stabilized RED (Ott *et al*., 1999) and BLUE(Feng et al.,2002) have been proposed. Most of these are heuristic algorithms and very few systematic and comparion were done until recently.

Recently, control theroy has been widely applied to the analysis and design of TCP networks and congestion controller for them. In (Misra *et al*., 2002) ,the theory of stochastic equations was applied to develop a fluid-based model of the dynamics of the TCP and AQM .This model describes the evolution of the characteristic variable of the network, including the average TCP window size and the average queue length. It was shown that the TCP model accurately captured the qualitative of TCP traffic flows. Several congestion control schemes based on this TCP model have been proposed to improved the performance of communication networks. For example, a proportional-integral (PI) controller was developed for linearized system and implemented using difference equations (Hollot *et al*., 2001). Compared to RED, PI controller is more stable. However, PI controller is sluggish with taking too long time to settle down to the reference queue length. In order to overcome the drawbavks of PI controller, we introduced the differential component in controller structure to advoid the overshoot and improve the damping and rise time of the controller. They do not seem to perform well under highly dynamic environments with diverse connections(responsive or unresponsive, short-lived or longed-lived and large round-trip). The major reason is that such approaches are primarily based on precise mismatches under dynamic network environments. Because the TCP/AQM dynamics have time varying round-trip times (RTT) and uncertainties with respect to the number of active TCP sessions for the designed schemes. (Ren *et al*., 2002; Yan *et al*.,2003) introduced a robust variable structure based AQM schemes that exist good performances and robustness with respect to the uncertainties of the network parameters. But in these paper they analyzed the stability only using a simplified model without considering the time delay of the control signal, and the impact of uncertain time-delay only was discussed through simulation. In (Yin *et al*.,2006), considering the time delay of the control input signal , but they analye the stability only considering matched uncertainties. (Jing *et al*.,2007) designed a robust stabilization of state and input delay for internet network, but they can not consider uncertaities, so existing great conservation. In this paper we consider the problem of robust sliding mode control for a class of linear systems with time delay and mismatched uncertainties. As we know that sliding mode control has attractive features such as fast response and good transient response.

This paper is organized as followed. In Section Ⅱ, we propose an improved TCP/AQM model including the state delay and nonlinear disturbance, through a particular linear transformation, the original uncertain time-delay system was first transformed into a delay-free system. In Section Ⅲ the sufficient condition for the existence of stable surface is presented in terms of LMI and sliding mode control law is also presented, which guarantees the globle stability of the system. In Section Ⅳ, we compare the performance of the improved sliding mode controller(ISMC) and traditional sliding mode controller (SMC) and traditional PI controller, where we demonstrate the superiority of the ISMC. Finally, we summarize our paper in Section Ⅴ.

2. TCP NETEORK DYNAMICAL MODEL AND WITHOUT TIME-DELAY TRANSFORMATION

In (Misra *et al.*,2002), a non-linear dynamic model of TCP connection through a congestion AQM router was developed based on fluid traffic analysis, the following is a simplified version of that model.

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

where C is the capacity of link (in packets/sec); $W(t)$ is the average TCP window size (in packets) ; $q(t)$ is the instantaneous queue length (in packets) ; P is the packet-dropping probability function ,which is the control input used to reduce the sending rate and to maintain the bottleneck queue ; N is the number of TCP sessions; R is the transmission RTT , equal to $T_p + q(t)/C(t)$.

The characteristics of congestion control based on window and the dynamic queue in the above-mentioned differential equation can be shown by fig.1.

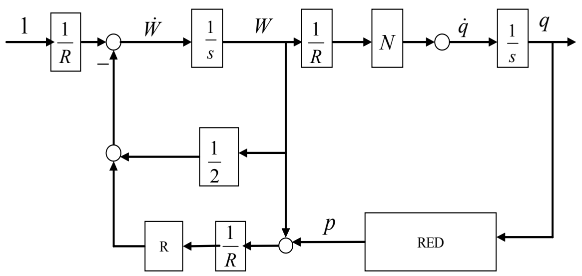

Fig.1.TCP control frame based on window

where W and q for state of system, p for input feedback, suppose $R(t) = R_0$, $N(t) = N$ and $C(t) = C$ is normal value of $R(t)$, $N(t)$ and $C(t)$ .Sequently, we approximated this nonlinear and time-varying system as a linear constant system by small-signal linearization about an equilibrium point (W_0, q_d, p_0) , we get a linear differential equation as follow:

$$\begin{aligned} \delta\dot{W}(t) &= -\frac{2N}{R_0^2 C}\delta W(t) - \frac{R_0 C^2}{2N^2}\delta p(t-h) \\ \delta\dot{q}(t) &= \frac{N}{R_0}\delta W(t) - \frac{1}{R_0}\delta q(t) \end{aligned} \tag{2}$$

where $\delta W(t) = W(t) - W_0, \delta q(t) = q(t) - q_d, \delta p(t) = p(t) - p_0$. It is known that a tracking control problem can be transformed into a stabilization problem in the error form. Let

$$\begin{cases} e = q(t) - q_d \\ x_1 = e \\ x_2 = \dot{e} \end{cases} \tag{3}$$

Since parameter perturbation and external disturbance can not be avoided, therefore Eq. (2) is written as Eq. (4).

$$\dot{x}(t) = Ax(t) + Bu(t-h) + f(t) \tag{4}$$

where

$$x(t) = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, A = \begin{bmatrix} 0 & 1 \\ -\dfrac{2N}{R_0^3 C} & -\left(\dfrac{1}{R_0} + \dfrac{2N}{R_0^2 C}\right) \end{bmatrix}, B = \begin{bmatrix} 0 \\ -\dfrac{C^2}{2N} \end{bmatrix},$$

$R_0 = h$.

where, $x \in R^n$ is the state vector, $u(t) = \delta p(t)$, $u \in R^m$ is the control input, which satisfy $-p_0 \le u(t) \le 1 - p_0$, $f(t) \in R^{n\times m}$ is the external disturbance, $A \in R^{n\times n}$ and $B \in R^{n\times m}$ are known constant matrices with appropriate dimensions.

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

Assumption 1: the pair (A, B) is controller, the input matrix B has full rank;

Assumption 2: the disturbance $f(t)$ satisfy norm –bounded; $f(t) = B_d f_1(t)$, exist a positive constant β, get $\|f_1(t)\| \le \beta$;

Assumption 3: ΔA satisfy unmatched condition:

$\Delta A = \begin{bmatrix} \Delta A_1 \\ \Delta A_2 \end{bmatrix} = \begin{bmatrix} \Delta A_{11} \Delta A_{12} \\ \Delta A_{21} \Delta A_{22} \end{bmatrix}$,even $\Delta A_1 = DF(t)E = DF(t)\begin{bmatrix} E_1 & E_2 \end{bmatrix}$,

where $F^T(t)F(t) \le I$,$\|\Delta A_2\| \le \alpha$.

Linear transform is presented

$$m(t) = x(t) + \int_{t-h}^{t} e^{A(t-h-\tau)} Bu(\tau) d\tau \tag{5}$$

Take differential for (5) as the following:

$$\dot{m}(t) = \dot{x}(t) + A\int_{t-h}^{t} e^{A(t-h-\tau)} Bu(\tau) d\tau + e^{-Ah} Bu(t) - Bu(t-h) \tag{6}$$

By substituting Eq. (4) and Eq. (5) into Eq. (6), we obtain:

$$\dot{m}(t) = Am(t) + B_d u(t) + f(t) \tag{7}$$

where, $B_d = e^{-Ah} B$.

Make use of Taylor formula, $e^{-Ah} = I + Ah + o(h^2)$, leading to $B_d = \begin{pmatrix} -hA_{12}B_2 & 1 - hA_{22}B_2 \end{pmatrix}^{\mathrm{T}}$.

Considering uncertain of system, according to Assumption 1, system (7) can be transformed into a regular from by applying a linear transformation. Let us consider a transformation matrix T satisfying $\overline{B}_d = TB_d = \begin{bmatrix} 0 & \overline{B}_2 \end{bmatrix}^{\mathrm{T}}$. where $\overline{B}_2 \in R^{1\times 1}$ is non-singular. Eq. (7) is written as followed:

$$\dot{z}(t) = \overline{A}z(t) + \overline{B}_d u(t) + Tf(t) \quad (8)$$

where $\overline{A} = TAT^{-1}$, $z(t) = Tm(t)$, $\overline{B}_d = TB_d$

$$\dot{z}_1(t) = \overline{A}_{11} z_1 + \overline{A}_{12} z_2 + \Delta A_1 z \quad (9)$$

$$\dot{z}_2(t) = \overline{A}_{21} z_1 + \overline{A}_{22} z_2 + \Delta A_2(t) z + \overline{B_2}[u(t) + f_1(t)] \quad (10)$$

In the practical TCP/ IP network, a controller is designed according to the model of the system. The imperfect information will affect the accuracy of the model. so we must use simplified method for practical application. In addition, with varied environment conditional, transmission of the signal will delivers the deviation appear error in the control system, which can bring the influence for the control object.

Note that the plant model (1) is only an approximate model and it ignores the timeout and slow start mechanism. Equation (2) is further made liberalization in the paper. So the system model is strongly uncertain, nonlinear and subject to additive noise. Taking the nonlinearly and the uncertainties into consideration, the sliding mode controller of AQM would be an ideal methodology for a robust AQM. SMC has strong robustness; hence it is suited for the complicated system of network.

3. DESIGN OF CONTROLLER FOR AQM

Sliding mode control (SMC) makes systems very robust with respect to parameter perturbation and external disturbances. Switching converters constitute an important case of sliding mode system and different sliding mode strategies to control this class of circuits have been reported in the last years. The design of these strategies is performed in two steps. In the first step, we choose among different sliding surface that one which provides the desired asymptotic behavior when the converter dynamics is forced to evolve over it. In the second step, the feedback circuit which directs the converter dynamics to sliding surface is designed.

Sliding mode control is a robust nonlinear feedback control technique, a key point in the design of sliding mode controllers is to introduce a proper sliding surface so that tracking errors and output deviations can be reduced to a satisfactory lever. Unfortunately, an ideal sliding mode controller has a discontinuous switching function and it is assumed that the control signal can be switching from one value to another infinitely fast switching control because of finite time delays for the control computation and limitations of physical actuators.

In this paper, the robust stabilization of the network system is discussed. A linear dynamical model of TCP network is obtained by control theories, the sliding surface $S(t)$ corresponds to a combination of the queue length error, the error between incoming traffic rate and link capacity and a predictor. Designing a control input $u(t)$ to maintain system states on the surface $S(t)$ for all $t > 0$ will satisfy the tracking requirements $q \to q_d$ and $\dot{q} \to \dot{q}_d$. Indeed, it will force x_1 and x_2 to approach zero under any bounded initial conditions. So it can carry out accurate track, and maintain the highly utilization of the circuit and the low average time-delay.

3.1 designing sliding mode surface

Without loss of generality, a sliding surface is defined as:

$$s(t) = Cz(t) = \begin{bmatrix} -K & I \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = 0 \quad (11)$$

where $C \in R^{m \times n}, K \in R^{m \times (n-m)}$,

In sliding mode, it will regard z_2 as virtual input control of subsystem (11), designing state feedback:

$$z_2 = Kz_1 \quad (12)$$

By substituting Eq. (12) into Eq. (9), we obtain as follow:

$$\dot{z}_1(t) = (\overline{A}_{11} + \Delta A_{11}) z_1 + (\overline{A}_{12} + \Delta A_{12}) K z_1 \quad (13)$$

If uncertainties ΔA satisfy matching condition, $\Delta A_{11}, \Delta A_{12}$ can not appear in Eq. (13), if $(\overline{A}_{11}, \overline{A}_{12})$ is controllable, making use of pole assignment to find out K , which can make the system stabilization.

If uncertainties ΔA satisfied unmatched condition, in the paper, we will recur to LMI technology for K , consequently designing a stable sliding mode surface of system (13).

Lemma（Khargoneker *et al*.,1990）given constant matrix with appropriate dimensions Y, D and E， where Y is a symmetric constant matrix ， the following inequality holds: $Y + DEF + E^T F^T D^T < 0$ for $F^T(t)F(t) \le I$ ， if and only if for some constant $\varepsilon < 0$, $Y + \varepsilon DD^T + \varepsilon^{-1} E^T E < 0$.

Theorem 1: if there exist a symmetric and positive definite matrix P ， some matrix W and some positive e, such that the following LMI are satisfied， then the reduced-order system Eq. (11) is asymptotically stabilizable via the sliding mode function (13).

$$\begin{bmatrix} \Phi & \varepsilon D & \left(E_1 X + E_2 W\right)^T \\ \varepsilon D^T & -\varepsilon I & 0 \\ E_1 X + E_2 W & 0 & -\varepsilon I \end{bmatrix} < 0 \quad (14)$$

where $\Phi = \left(\overline{A}_{11} X + \overline{A}_{12} W\right)^T + \overline{A}_{11} X + \overline{A}_{12} W$, $X = P^{-1}, W = KP^{-1}$.

Proof: consider Lyapunov function candidate

$$V(t) = z_1^T P z_1 \quad (15)$$

where P is a symmetric and positive definite matrix.

$$\dot{V}(t) = \dot{z}_1^T(t) P z_1(t) + z_1^T(t) P \dot{z}_1(t) \quad (16)$$

By substituting Eq. (13) and assumption (3) into Eq. (16), we obtain as follow:

$$\dot{V} = z_1^T (\overline{A}_{11} + \overline{A}_{12} K + DF(E_1 + E_2 K))^T P + P(\overline{A}_{11} + \overline{A}_{12} K + DF(E_1 + E_2 K)) z_1$$

$$= z_1^T \left((\bar{A}_{11} + \bar{A}_{12}K)^T P + P(\bar{A}_{11} + \bar{A}_{12}K) \right) z_1 +$$
$$z_1^T \left((E_1 + E_2K)^T F^T D^T P + PDF(E_1 + E_2K) \right) z_1$$
$$= z_1^T [\bar{A}_{11} + \bar{A}_{12}K)^T P + P(\bar{A}_{11} + \bar{A}_{12}K) +$$
$$(E_1 + E_2K)^T F^T D^T P + PDF(E_1 + E_2K)] z_1$$

where $\psi = \left(\bar{A}_{11} + \bar{A}_{12}K\right)^T P + P\left(\bar{A}_{11} + \bar{A}_{12}K\right)$

If the right-hand of Eq.(12) is negative definite uniformly for all z_1 except at $z_1 = 0$, then the reduced-order dynamics Eq. (13) is asymptotic stabilization. Therefore, the following inequality is valid.

$$\psi + (E_1 + E_2K)^T F^T D^T P + PDF(E_1 + E_2K) < 0 \qquad (17)$$

According to Lemma 1, the matrix inequality Eq. (17) holds for all F satisfying $F^T(t)F(t) \le I$ if and only if there exists a constant $\varepsilon > 0$ such that

$$\psi + \varepsilon PD(PD)^T + \varepsilon^{-1}(E_1 + E_2K)^T (E_1 + E_2K) < 0 \qquad (18)$$

Applying Schur to Eq. (18) result in

$$\begin{bmatrix} \psi & (PD)^T & (E_1 + E_2K) \\ PD & -\varepsilon^{-1}I & 0 \\ (E_1 + E_2K)^T & 0 & \varepsilon I \end{bmatrix} < 0 \qquad (19)$$

The matrix inequality Eq. (19) is not a LMI, but a QMI, Define the following transformation matrix as $T = diag\left[P^{-1}, \varepsilon I, I\right]$, we make a toolbox to solve K in the MATLAB, denoting $X = P^{-1}, W = KX$, , yields the LMI Eq. (14).

3.2 Designing sliding mode control law

In the previous section, the designed sliding mode surface can guarantee the asymptotic stability of the system in terms of LMI; next, we need find feedback control law u to drive state trajectories of the system onto the sliding surface. The designed control law can satisfy the reaching condition.

Theorem 2: For uncertain system (7), sliding mode function (11) is selected; sliding mode control law is chosen as follow:

$$u = u_N + u_m$$
$$u_m = -\left(\overline{B_2}\right)^{-1} \left[K\bar{A}_{11}z_1 + K\bar{A}_{12}z_2 + \bar{A}_{21}z_1 + \bar{A}_{22}z_2 + \varepsilon_1 \operatorname{sgn}(s) + \varepsilon_2 s \right]$$
$$u_N = -\left(\overline{B_2}\right)^{-1} (\|KD\|\|Ez\| + \alpha\|z\| + \beta|B_2|)\operatorname{sgn}(s) \qquad (20)$$

where, ε_1 and ε_2 are both greater than zero, which is able to satisfy reaching condition $s^T\dot{s} < 0$ for system with any state, if and only if $s = 0$, $s^T\dot{s} = 0$ .The system will approach to sliding mode surface.

Proof: By substituting Eq. (20) into sliding mode reaching condition:

$$s^T\dot{s} = s^T \left[K\bar{A}_{11}z_1 + K\bar{A}_{12}z_2 + K\Delta A_1 z + \bar{A}_{21}z_1 + \bar{A}_{22}z_2 + \overline{B_2}(u + f_1) \right]$$
$$= s^T \left[K\Delta A_1 z + \Delta A_2 z + \overline{B_2} f_1 \right] + s^T \overline{B_2} u_N + s^T \left[-\varepsilon_1 \operatorname{sgn}(s) - \varepsilon_2 s \right]$$
$$\le \|s^T\| \left[\|KD\|\|Ez\| + \alpha\|z\| + \left|\overline{B_2}\right|\beta \right] + s^T \overline{B_2} u_N + s^T \left[-\varepsilon_1 \operatorname{sgn}(s) - \varepsilon_2 s \right]$$
$$\le s^T \left[-\varepsilon_1 \operatorname{sgn}(s) - \varepsilon_2 s \right]$$
$$\le -\varepsilon_1 s^T \operatorname{sgn}(s) - \varepsilon_2 s^T s$$
$$\le 0$$

Sliding mode reaching condition is satisfied.

3.3 stability analysis of the AQM system

The designed sliding mode surface guarantee the asymptotic stabilization of system, the stabilization of transformation system adopted the control law (20) is researched. The original system and the transformation system have the same poles and equivalent map. So we may use the transformed system to study the original system,

Theorem 3: the system (7) is asymptotic stabilization, so the system (4) is also asymptotic stabilization.

Proof: Form (5), we obtain

$$\|x(t)\| \le \|m(t)\| + \left\| \int_{t-h}^{t} e^{A(t-h-\tau)} Bu(\tau) d\tau \right\| \qquad (21)$$

$$\|x(t)\| \le \|m(t)\| + h\left[\max_{-h\le\theta\le 0} \left\|e^{A\theta}\right\| \|B\| \|u(t)\| \right] \qquad (22)$$

By substituting Eq. (20) into Eq. (22), we obtain as follow:

$$\|x(t)\| \le \|m(t)\| + h\{\max_{h\le\theta\le 0} \left\|e^{A\theta}\right\| \|B\| . \|u_m + u_N\| \qquad (23)$$

If external disturbance and parameter perturbation satisfy assumption condition, the designed sliding mode surface with LMI can guarantee the asymptotic stabilization of system (7), from Theorem 3, we can get $s(t) = 0$, $\operatorname{sgn} s(t) = 0$. Therefore, $\lim_{t\to\infty} x(t) \to 0$, the system(4) is asymptotic stabilization .

4. SIMULATION RESULTS

In this section we validate the effectives and performance of the scheme of this paper by simulation. During the designing of the controller, the two conflicting requirement must be taken into consideration at the same time. The first requires the controller to have good transient response. The second emphasizes the steady performance. In this simulation, we will draw comparisons among PI controller , SMC and the controller proposed in this paper (ISMC) about the performance under the variations of network parameters.

The choosing of the parameters are based on (Quet *et al.*,2004), $N = 50$, $C = 300$ packets/s, $R_0 = 50ms$, $q_d = 100$ packets. To PI-AQM, the choosing of parameters is $k_p = 0.0023$, $k_I = 0.004$;To SMC-AQM and ISMC-AQM, the choosing of parameters as $\varepsilon_1 = 0.5$, $\varepsilon_2 = 5$,in addition, for ISMC-SMC, $\beta = 2.5$.

Following we make simulation of the network system with Matlab/Simlink, Fig.2-Fig.4 plot the simulation results of different parameters of network.

In Fig.2, we choose the parameters of network as above, we can see that ISMC can obtain fast and stability responses.

SMC has big chattering. PI controller exhibits strongly oscilation and instability.

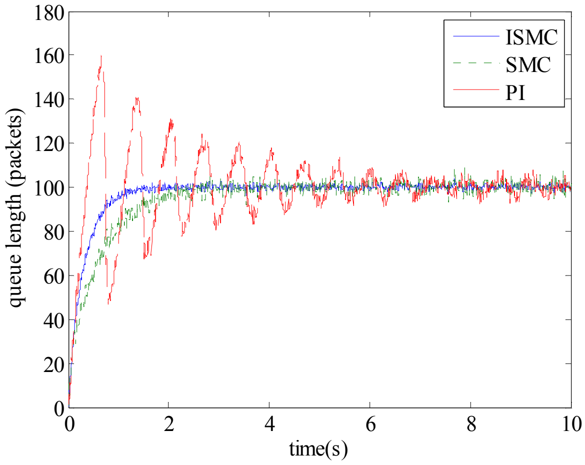

Fig.2. Queue length responses with fixed parameters of network

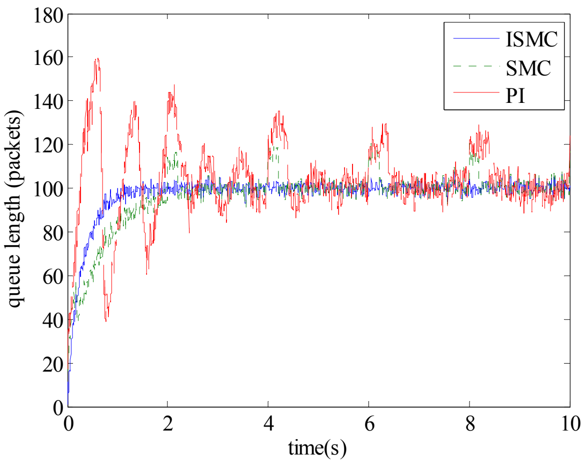

Fig.3.Queue length responses with varied network parameters

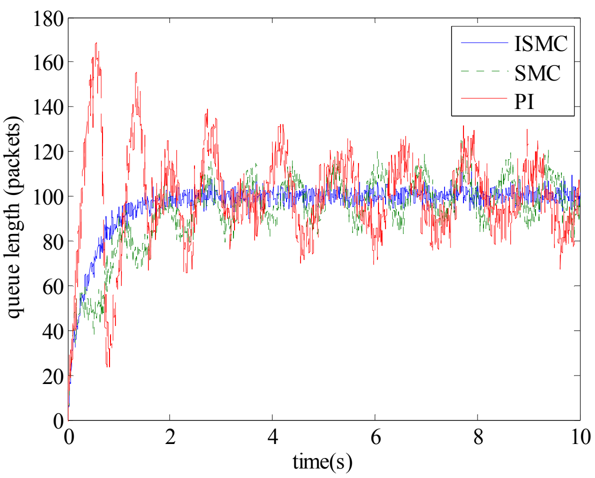

Fig.4. Queue length responses with varied time delay and network parameters

In order to test the robust performance of PI controller, SMC and ISMC for varied parameters, we vary N from 50 to 100; C from 300 to 250; the simulation results are given in Fig.3. The superior performance of ISMC is observed when network parameters change, but PI controller and SMC have strong instability.

In Fig.4, we increase delay from 50ms to 100ms, and considering varied the network parameters, PI control scheme makes a longer response time and has oscillation, SMC is seriously influenced by the improper parameters and results in the instability of the control system, especially vibration. But ISMC gets short regulating time and maintains the queue length closed to the target. So we can conclud that only ISMC scheme performs well under varid network parameters.

5. CONCLUSIONS

Active queue manage is a hot technology in the TCP research field of congestion control from end to end. Most of AQM algorithm which existent at present do not consider the influence of unmatched uncertainties in the course of designing controller. For TCP linear dynamic systems with input time-varying and mismatched uncertainties, an AQM scheme based on a sliding mode control is proposed, and the robust sliding hyper plane is constructed from LMI with stabilization. ISMC algorithm can overcome the disadvantages to the stability, and can restrain the influence of chattering. Further more, when network parameters change, the control capability of ISMC algorithm is better than SMC, and can realize fast, true tracking, which translate into higher link utilization and small queue fluctuations.To avoid the network congestion better. So it is indicated that ISMC algorithm have fine practical value to adapt the uncertainty of actual network.

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