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A Robust Active Queue Management Scheme Based on Global Sliding Mode Control

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Abstract—**For the problem of transmission control protocol (TCP) network congestion control, on the basis of global sliding mode control, an active queue management (AQM) scheme adaptive to the change of dynamic network flow is presented. The proposed scheme can eliminate the reaching phase from conventional sliding mode control, and guarantee the system robustness during the whole control process. At the same time, it also shows its good transient and steady state responses in practical TCP/IP network systems, such as modeling uncertainties, input saturation, fluctuation of time-varying parameters and network jittering due to non-TCP sessions. Simulation results demonstrate that this scheme enables the queue length to converge to set value quickly and keeps the queue oscillation small, in particular, the scheme proposed outperforms the conventional PI control and sliding mode control when the network conditions change.**

I. INTRODUCTION

WITH the rapid growth and popularity of the Internet, the problem of congestion control has become a major problem. TCP congestion control mechanisms, while necessary and powerful, are not sufficient to provide good services in all circumstances, especially with the rapid growth in size and the strong requirement for quality of service guarantee. Some mechanisms are required in the routers to complement the end-to-end congestion control in the Internet. Active Queue Management (AQM), as the effective mechanism acting on the intermediate nodes, has been recently proposed to support the end system congestion avoidance mechanisms.

Random early detection (RED) [1] was among the first AQM to be introduced into the Internet routers. The scheme is able to reduce link congestion and global synchronization by earlier congestion notification. But some experimental studies have shown that RED scheme is sensitive to traffic load and to its parameter settings. In additional, it is difficult to reduce fluctuations by only adjusting RED's parameters. The drawbacks of RED prompt researchers to propose modifications and alternatives [2], [3]. However these schemes are heuristic, and lack a theoretical design and analysis approach. Recently, many researchers apply a systematic methodology to design new AQM schemes from the control theory point of view. In [4], a nonlinear dynamic model for TCP congestion control was developed. In [5-7], a variable structure AQM controller was designed, and its performance was validated on this model in various simulation environments. The main advantage of the scheme is that, once the system state reaches a sliding surface, the structure of the feedback loop is adaptively altered to sliding the system state along the sliding surface. However, robust characteristic is guaranteed only after the system reaches the sliding surface, and robustness is not guaranteed during the reaching phase. In additional, in practical TCP/IP networks, the packet drop probability can be considered as an input and it is limited to between 0 and 1. This can lead to serious degradation of the network system performance if the controller is not designed appropriately. Therefore, the effect of a saturating actuator must be taken into account in the design phase of the controller. Although several control schemes have been proposed for input saturation system in [8] ~ [9], very few of these schemes are applicable to congestion control of communication network. In [10], two control strategies based on the linear input constraint system are presented, but robustness is rather poor.

To solve the above-mentioned two problems simultaneously, we presents an AQM scheme based on global sliding mode control in this paper. The scheme can be applied to nonlinear network systems with input saturation. The main advantage of the scheme is that the system state is initially located in the sliding surface, and can reduce the time to reach the sliding surface and achieve quick trackability. We show that the proposed scheme possesses asymptotic stability and robust against variations in the member of TCP connections and the RTT.

The remainders of this paper are organized as follows. The TCP nonlinear dynamic model and the control objective are discussed in Section II. Section III presents the stability design for AQM scheme based on the proposed global sliding mode control. Matlab simulation results in different scenarios are presented in section IV, we compare the performance of the proposed controller with that of PI controller and traditional sliding mode controller, where we demonstrate the superiority of the proposed controller. Finally, we conclude our work in section V.

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II. TCP NETWORK DYNAMICAL MODEL

In [4], the TCP model is given by coupled non-linear differential equations that reflect the dynamics behavior of TCP accurately. This mode relates the average values of the characteristic network variables, such as the transmission rate per unit time and the instantaneous queue length, which are described as follows:

$$\begin{cases} \dot{r}(t) = \dfrac{M}{R^2(t)} - \left(\dfrac{M}{R^2(t)} + \dfrac{r^2(t)}{2M} \right) p(t) \\ \dot{q}(t) = r(t) - C_0 \end{cases} \tag{1}$$

and

$$R(t) = \frac{q(t)}{C_0} + T_P \tag{2}$$

where $q(t)$ is the instantaneous queue length on the router (in packets), $r(t)$ is the transmission rate per unit time, T_p is the propagation delay (in seconds), C_0 is the link capacity (packets/second), M denotes the number of TCP sessions, $R(t)$ is the round-trip time, and $0 \le p(t) \le 1$ is the probability of a packet being marked, which is considered as a control input used to reduce the sending rate and regulate the bottleneck of the queue.

For nonlinear model (1), some important parts of TCP are even not included: 1) nonresponsive UDP flows are not modeled and 2) the impact of short-lived connections (the so called web mice), such as Telnet and HTTP. Taking the nonlinearity and the unmodeled uncertainty into consideration, we believe that sliding mode control would be an ideal methodology for a robust AQM.

The objective of this work is to design a global sliding mode controller to achieve asymptotic stability of the network described by the non-linear system with a saturated input .The overall GSMC-AQM control system is depicted in Fig.1.

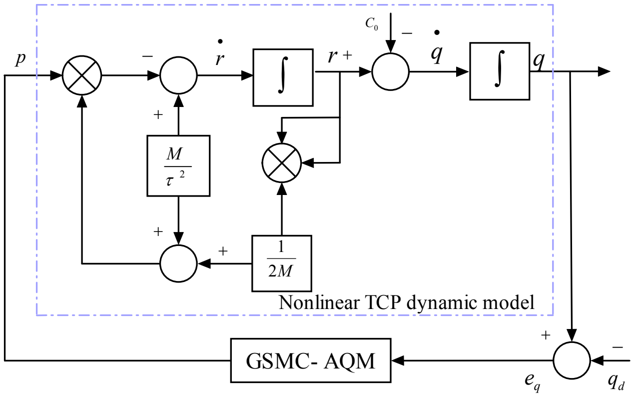

Fig.1. The block diagram of TCP dynamics with GSMC-AQM controller

III. DESIGN OF CONTROLLER FOR AQM

In the proposed GSMC, the sliding surface is designed such that the initial state is located on it; then the system is constrained to the sliding surface by a sliding mode controller.

Therefore, the sliding mode invariably exists and robust performance is ensured throughout an entire response.

Let $e_q(t) = q(t) - q_d$, where, q_d is the desired queue length, $e_q(t)$ is the queue length error. By denoting $x_1(t) = e_q(t)$, $x_2(t) = \dot{e}_q(t)$, we have

$$x_2(t) = \dot{e}_q(t) = \dot{q}(t) = r(t) - C_0 \tag{3}$$

and system (1) can be rewritten as follows:

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = g(t) - h(t)p(t) \end{cases} \tag{4}$$

where

$$g(t) = \frac{M}{R^2(t)}, h(t) = \frac{M}{R^2(t)} + \frac{(x_2(t) + C_0)^2}{2M},$$

and these are all positive for all times $t \ge 0$.

Then a robust AQM scheme is design based on global sliding mode control to stabilize the queue size of the router around a given target queue q_d. So the link under-utilization and the buffer overflow can be significantly reduced, a predictable QoS can be provided.

The design of conventional SMC involves two major phases. First, it is necessary to select an appropriate switching surface for the system. Second, it is necessary to determine a control law, such that the existence of the sliding mode can be guaranteed.

A linear sliding mode surface is chosen as

$$s(x,t) = cx_1(t) + x_2(t) \tag{5}$$

where $c > 0$.

For this conventional design, there are several drawbacks, such as, robust performance is not ensured, because the sliding regime may occur only the origin of the phase plane and response is sensitive to system perturbation during the reaching phase.

Motivated by the sliding surface proposed by [11], we define the global sliding surface as

$$s(x,t) = cx_1(t) + x_2(t) - F(t) \tag{6}$$

where $c > 0$. To guarantee sliding mode motion of the system lie on the sliding surface on the beginning, the function $F(t)$ drives the system states in arbitrary state space directly to the sliding surface without a reaching phase.

The response of the conventional sliding mode control is sensitive to system perturbations during the reaching phase. One of the advantages of the global sliding mode control is that it can have sliding mode characteristics over the entire range without a reaching phase. For this, the conditions of the function $F(t)$ should be satisfied, that is

$$F(0) = cx_1(0) + x_2(0) \tag{7a}$$

$$F(t) \to 0 \text{ as } t \to \infty \tag{7b}$$

$$\dot{F}(t) \text{ exits and is bounded} \tag{7c}$$

In Eq.(7), condition (7a) represents the initial location of the states on the sliding surface, (7b) represents asymptotic stability, and (7c) represents the existence of the sliding mode.

According to these conditions, we choose $F(t)$ as

$$F(t) = F(0)e^{-\lambda t} \tag{8}$$

where $\lambda > 0$, and λ is small enough.

From the expression of $F(t)$, we can see that the system state is initially located in the sliding regime. The asymptotic stability of the closed-loop system and the existence of a sliding mode are all satisfied.

Next, we will design a control input $p(t)$ to guarantee the system trajectories still stay on the sliding surface if the following condition is satisfied

$$S\dot{S} < 0 \tag{9}$$

We introduce the following global sliding control law

$$p(t) = p_{eq}(t) + p_s(t) \tag{10}$$

According to sliding mode equivalent control condition $\dot{S} = 0$, the equivalent term $p_{\mathrm{eq}}(t)$ is designed to keep the system on the sliding surface. When $\dot{S} \neq 0$, the switching term $p_{\mathrm{s}}(t)$ is designed to compensate the discontinuous control.

Theorem: Considering system (4), if the control law (10) is chosen as follows.

$$p_{eq}(t) = \frac{1}{h(t)}\left(cx_2(t) + g(t) - \dot{F}(t)\right) = \frac{1}{h(t)} \cdot p_1 \tag{11}$$

$$p_s(t) = \frac{1}{h(t)} \cdot \left[K_s sgn(s) + \dot{F}(t)\right] \tag{12}$$

where

$$K_s = \begin{cases} h(t) - p_1 & s > 0 \\ p_1 & s < 0 \\ 0 & s = 0 \end{cases} \tag{13}$$

and the coefficient of sliding mode surface c satisfies $0 < c < {C_0}/{M}$, then the closed-loop system will be stable.

Proof: We choose the Lyapunov function

$$V(t) = \frac{1}{2}s^2(t) \tag{14}$$

The time derivative of $V(t)$ along the trajectories of the system (4) is

$$\begin{aligned} \dot{V} &= s\dot{s} \\ &= s\left(c\dot{x}_1 + \dot{x}_2 - \dot{F}(t)\right) \\ &= s\left(cx_2 + g(t) - h(t)p(t) + \lambda F(0)e^{-\lambda t}\right) \end{aligned} \tag{15}$$

Substituting (10)-(13) into Eq.(15) yields

$$\begin{aligned} \dot{V} &= -sK_s \operatorname{sgn}(s) - \lambda F(0)e^{-\lambda t}s \\ &= -K_s|s| - \lambda F(0)e^{-\lambda t}s \end{aligned} \tag{16}$$

Since $0 < c < {C_0}/{M}$, which implies that $0 < p_1 < h(t)$ and $K_s \geq 0$. If $\lambda > 0$, and λ is small enough, $\lambda F(0)e^{-\lambda t}s$ may be ignored. We can obtain

$$\dot{V}(t) \leq 0 \tag{17}$$

From the negativity of Eq.(17), we can conclude that the instantaneous queue length in the router will track the set value by choosing the proposed controller (10).

IV. SIMULATION RESULTS

In this section we validate the effectiveness and performance of the proposed scheme by Matlab simulation for the dumbbell network topology [9]. In this topology, multiple TCP connections share a single bottleneck link. During the designing of the controller, the two conflicting requirements must be taken into consideration at the same time. The first requires the controller to have good transient response. The regulating time is rather short and the overshot is very small. The second emphasizes the steady performance, such as small steady error and accurately tracking capability. In the simulation, we will draw comparisons among PI controller, sliding mode controller (SMC) and the controller proposed in this paper (GSMC) about the performance under the various network parameters.

The performance and effectiveness of the proposed GSMC was verified in a series of numerical simulations via Matlab/Simulink. The parameters are chosen based on [9]. The number of the active TCP sessions $M = 50$, C_0 =300 packets/s, request queue length $q_{\mathrm{d}} = 100$ packets, the range of RTT variation is $40ms \leq R(t) \leq 100ms$. To PI-AQM, the choosing of parameters is $k_p = 0.0023$, $k_I = 0.0004$; To SMC-AQM and GSMC-AQM, we set the coefficient of sliding surface given by $c = 0.5$, which satisfies the condition $0 < C = 0.5 < {C_0}/{M} = 300/50 = 6$. To GSMC-AQM, the choosing of parameters is $\lambda = 0.0005$.

For alleviating chattering phenomena caused by the sliding mode control, we will introduce an approximation

$$\operatorname{sgn}(S) = \frac{S}{|S| + \mu}$$

where $\mu = 0.01$.

It is obvious that the state trajectory is held on the sliding mode surface under the GSMC-AQM controller from Fig.3. In the experiment, the parameters of network are the same as the above settings. Fig.4-Fig.7 plot the simulation results of difference parameters of network.

In Fig.4 we choose the parameters of network as above, and an inherent propagation delay of 50ms. We can see that the GSMC can obtain fast and stable responses, SMC has high rising time plus big chattering. PI controller exhibits strong oscillation.

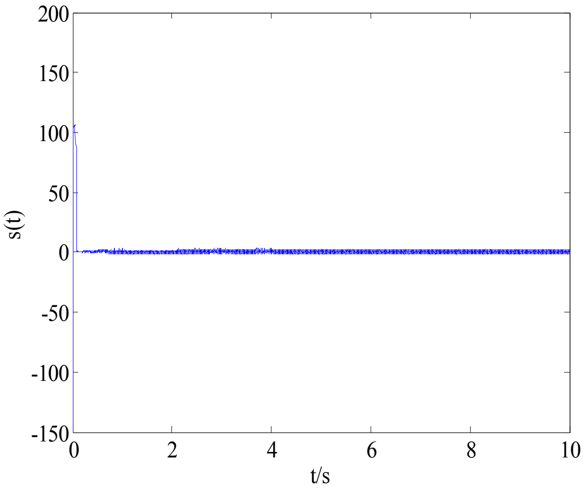

Fig.2. System response using the global sliding mode control

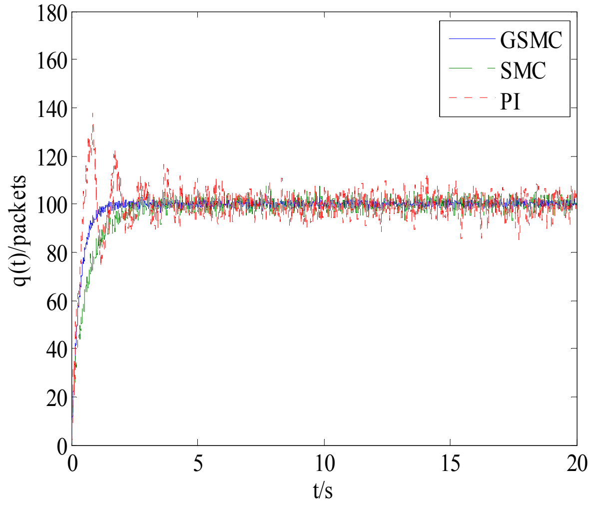

Fig.3. The instantaneous queue length for fixed parameters of network

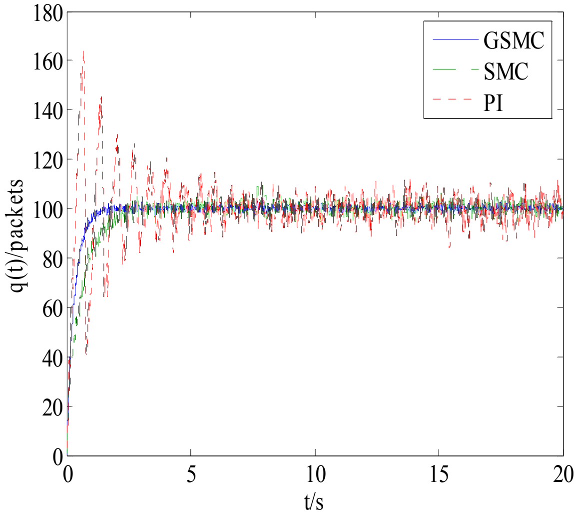

Fig.4. The instantaneous queue length for varied parameters of network have strong instability.

In order to test the robust performance of PI controller, SMC and GSMC AQM scheme against variations of the network parameters, we vary M from 50 to 80; C_0 from 300 to 250; the simulation results are given in Fig.5. The superior steady performance of GSMC is observed when network parameters change, but PI-AQM and SMC-AQM perform poor steady performance and longer regulating time.

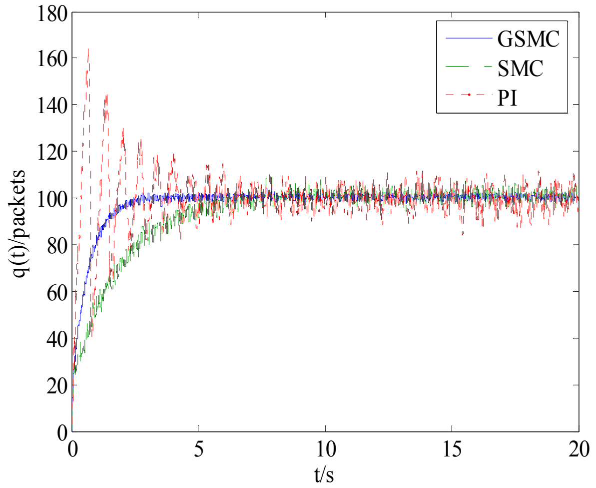

Fig.5. The instantaneous queue length for varied time delay of network

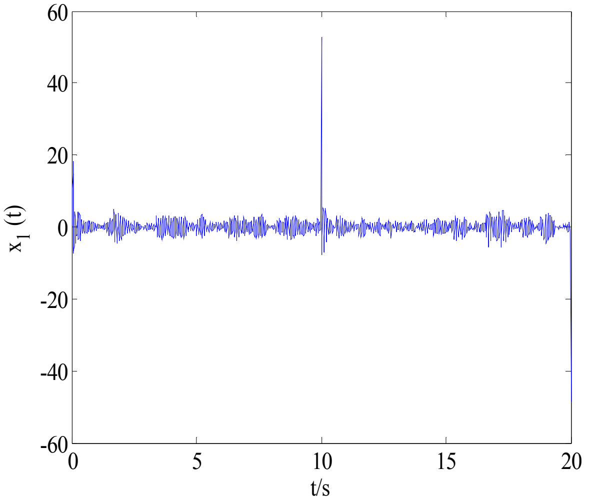

Fig6. Queue error with network parameter variation and disturbance

In Fig.6 we increase delay from 50ms to 80ms with fixed the network parameters. The 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 GSMC gets short regulating time and maintains the queue length closed to the target. So we can conclude that only GSMC scheme performs well under varied network parameters and given time delay. In Fig.7 we consider the arbitrary flows and varied network parameters to examine the robustness of the global sliding mode controller. We add UDP flow to the TCP flows at 10^{th} second and arbitrary multimedia flows unresponsive to congestion control as disturbances for the system. It is observed that the global sliding mode controller shows better performance, with exhibiting faster responses and better regulation properties.

V. CONCLUSION

An active queue management scheme based on global sliding mode control is proposed to solve the problem of the Internet congestion for the nonlinear systems with a saturated input. By the using a function augmented sliding surface, the proposed controller eliminates the reaching phase problem so that the closed-loop system always shows the invariance property to network parameter uncertainties. Simulation results have confirmed that the proposed method can obtain global robustness in all the response time, which can provide higher link utilization, low packet loss rate and small queue fluctuations.

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