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Sliding Mode Congestion Control for DiffServ Networks

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***Abstract*—A nonlinear fluid flow model is used in this paper to analyze and control DiffServ Networks. The controller design is based on the integrated dynamic congestion control strategy. In this paper different second order sliding mode controllers are proposed to solve the infinite switching problem. The same as standard sliding mode control, second order sliding mode technique is also robust to model uncertainties and disturbances, meanwhile overcome the inherent chattering problem which is more acceptable in application. The performance of the control algorithms are verified by the simulation results.**

I. Introduction

The DiffServ Network that is under consideration by IETF can provide different services to users of the Internet [1]. It adheres to the basic Internet philosophy and can be seen as a kind of extending of the Internet. There are two important 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 [2], while ordinary traffic is intended for applications that have relaxed delay requirements and allow their rates into the network to be controlled [3].

For DiffServ Network, the fluid flow model is extensively used for network performance evaluation and control, especially for congestion control problems. 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 based on linear control theory. For example, analysis and control design tools are applied to control traffic in ATM networks [4] and analyze the stability of congestion control schemes in TCP/IP networks [5], [6]. 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.

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Sliding mode control (SMC), as a special class of nonlinear systems is accepted as a robust control for dynamic systems. But generally speaking, any sliding mode is a mode of motions on the discontinuity set of a discontinuous dynamic system. Such mode is understood in the Filippov sense and features theoretically-infinite frequency of control switching [7]-[9]. So reduce the chattering is very important for SMC, and second order sliding mode control (SOSMC) [10] is an effective method.

In this paper, our attention is focus on applying second order sliding mode control to address the queue regulation of premium and ordinary buffers in DiffServ Network, as well as reduce the chattering problem obviously and make the controller much more feasible. The continuous SOSMC may be used to achieve robust stabilization in finite time of the sliding variable to zero in the presence smooth disturbance.

The rest of the paper is organized as follows: in section II, illustrate the control problem by giving the fluid flow model and the integrated dynamic congestion control strategy. The second order sliding mode controller is described in section III, three algorithms are used in 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.

II. Problem Statement

Based on fluid flow theory, a validated nonlinear DiffServ Network buffer dynamic is given as follows [3].

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

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.

In system (1) we have assumed that the sources of data are persistent and have ignored the latency of coming traffic. But in fact, the input and output of traffics are shifted in time. So we can reformulate the system in equation (2):

$$\dot{x}(t) = -C(t)\frac{x(t)}{1+x(t)} + \lambda(t-\tau) \tag{2}$$

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

$$\begin{cases} \dot{x}_i(t) = -C_i(t)\dfrac{x_i(t)}{x_i(t)+1} + \lambda_i(t-\tau_i) \\ y_i(t) = x_i(t) \end{cases}. \quad (3)$$

Notice that the index $i=(p,r)$ where p and r indicate premium and ordinary buffers dynamic respectively [11] here and all over this paper.

The control strategy is illustrated in figure 1. For system (2), the state variables are $x_p(t),\ x_r(t)$. 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 through accommodating link capacity let the system output signal $x_p(t)$ trace the desired reference queue length $y_p^d(t)$; 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 $\lambda_r(t)$, the control purpose of ordinary buffer is that through adjusting the arriving rate of data $\lambda_r(t)$ let the output signal $x_r(t)$ trace the desired reference queue length $y_r^d(t)$. C_{server} is the max available or assigned link capacity. τ_p, τ_r are block delays in premium traffic and ordinary traffic, and they capture and correspond to any delay in the network due to propagation, processing, transmission.

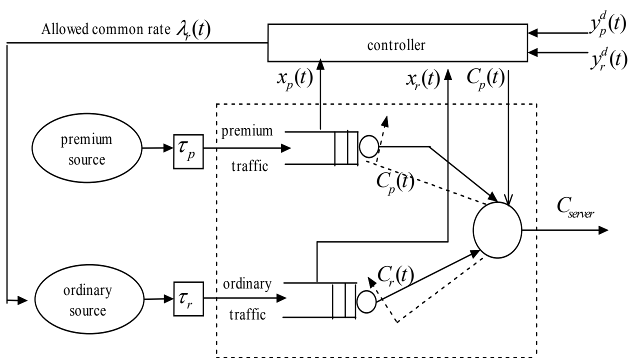

Fig. 1. Schematic diagram of the control strategy

III. PROPOSED SECOND ORDER SLIDING MODE CONTROLLER

Consider an uncertain nonlinear system

$$\dot{x} = f(t,x,u) \quad (4)$$

with relative degree one, where x is the measurable state vector, u is the control input.

Define a proper sliding manifold in the state space

$$\sigma(t,x)=0 \quad (5)$$

Assume that the sliding variable has a relative degree one, which implies that the second derivative of σ can be expressed as

$$\ddot{\sigma} = \varphi(t,y) + \gamma(t,y)\dot{u} \quad (6)$$

The main idea behind second-order sliding mode is to act on the second-order derivative of the sliding variable σ rather than the first derivative as in standard sliding modes. Keeping the main advantages of the standard sliding modes, it has additional advantage that it removes the chattering effect [13]. The second-order sliding mode is determined by the equalities $\sigma=\dot{\sigma}=0$, which forms a 2-dimensional condition on the states of the dynamic system.

In the SOSMC, the time derivative of the control $v(t)=\dot{u}(t)$ is used as the control input, instead of the actual control $u(t)$. If we choose $\sigma(x(t))=0$ as sliding manifold, it turns out that $v(t)$ affects $\ddot{\sigma}(x(t))$ but not $\dot{\sigma}(x(t))$, and the problem becomes that of steering $\sigma(x(t))$ to zero by acting on its second derivative. The new control $v(t)$ is designed to be a discontinuous signal, but its integral (the actual control $u(t)$) is continuous, so that the chattering is eliminated. That characteristic is very important for our control strategy, because in section II we have illustrate our control procedure as follows: first control premium buffer by control signal $C_p(t)$, then control ordinary buffer with input disturbance $C_r(t)=C(t)-C_p(t)$, if the control signal $C_p(t)$ is frequently changed, the disturbance for ordinary buffer will be artificially increased, so decrease chattering is very much important for our control strategy. That is why we design second order sliding mode controller for a system with relative degree one.

The control objective is to design a sliding mode control system for the output of the system shown in (3) to track the reference trajectory, which is, asymptotically. The proposed second order sliding mode control system is designed to achieve the position tracking objective and is described as follows.

A. Lyapunov based second order sliding mode controller

First choose a sliding variable as conventional sliding mode control,

$$\sigma_i(t) = x_i(t) - y_i^d(t) \quad (7)$$

The sliding variable dynamics are derived

$$\dot{\sigma}_i(t) = \dot{x}_i(t) - \dot{y}_i^d(t) = -C_i(t)\frac{x_i(t)}{x_i(t)+1} + \lambda_i(t-\tau_i) - \dot{y}_i^d(t) \quad (8)$$

Here the delay signal $\lambda_i(t-\tau_i)$ is approximated in its first-order as $\lambda_i(t-\tau_i)=\lambda_i(t)-\tau_i\dot{\lambda}_i$ with τ_i is unknown but constant delay coefficient. And assume that τ_i is bounded as $\tau_i \le d_i$, $\lambda_i(t)$ is second order derivable, $\dot{\lambda}_i$ is bounded as $\dot{\lambda}_i \le D_{1i}$ and $\ddot{\lambda}_i$ is bounded as $\ddot{\lambda}_i \le D_{2i}$.

$$\begin{aligned}\ddot{\sigma}_i(t) &= \ddot{x}_i(t) - \ddot{y}_i^d(t) \\ &= -\dot{C}_i(t)\frac{x_i(t)}{x_i(t)+1} - C_i(t)\frac{\dot{x}_i(t)}{(x_i(t)+1)^2} + \dot{\lambda}_i(t-\tau_i) - \ddot{y}_i^d(t)\end{aligned} \quad (9)$$

The Lyapunov function is chosen as

$$V(\sigma_i,\dot{\sigma}_i) = \frac{1}{2}\rho_i\sigma_i^2 + \frac{1}{2}\dot{\sigma}_i^2 + \varepsilon_i|\sigma_i| \quad (10)$$

where ρ_i and ε_i are positive constant.

The derivative of $V(\sigma_i,\dot{\sigma}_i)$ is

$$\dot{V}(\sigma_i,\dot{\sigma}_i)=\dot{\sigma}_i[\rho_i\sigma_i+\ddot{\sigma}_i+\varepsilon_i\,\mathrm{sgn}(\sigma_i)] \tag{11}$$

In order to guarantee the stability condition, choose

$$\ddot{\sigma}_i=-\gamma_i\dot{\sigma}_i-\rho_i\sigma_i-\varepsilon_i\mathrm{sgn}(\sigma_i) \tag{12}$$

where γ_i is a positive constant.

Then $\dot{V}(\sigma_i,\dot{\sigma}_i)=-\gamma_i\dot{\sigma}_i^2\le 0$ .The second order surface is reachable and the auxiliary output system will be asymptotically stable in $\sigma_i=\dot{\sigma}_i=0$, see [15].

According to (12), a second order sliding mode controller is designed as

$$\dot{C}_P(t)=\frac{x_p+1}{x_p}\begin{pmatrix}\dot{\lambda}_p(t)-C_P(t)\dfrac{\dot{x}_p}{(x_p+1)^2}-\ddot{y}_p^d(t)-d_pD_{2p}\\ +\gamma_p\dot{\sigma}_p+\rho_p\sigma_p+\varepsilon_p\mathrm{sgn}(\sigma_p)\end{pmatrix}, \tag{13}$$

$$\begin{aligned}\dot{\lambda}_r(t)&=C_r(t)\frac{\dot{x}_r}{(x_r+1)^2}+\dot{C}_r(t)\frac{x_r}{x_r+1}+\ddot{y}_r^d(t)+d_rD_{2r}\\&\quad-\gamma_r\dot{\sigma}_r-\rho_r\sigma_r-\varepsilon_r\mathrm{sgn}(\sigma_r)\end{aligned}. \tag{14}$$

B. Exponential reaching law SOSM controller design

Choose a second-order sliding manifold as

$$\Sigma_i=\dot{\sigma}_i+\mu_i\sigma_i \tag{15}$$

where $\mu_i>0$.

The derivative of Σ_i is

$$\dot{\Sigma}_i=\ddot{\sigma}_i+\mu_i\dot{\sigma}_i$$

and from (8) (9) we can get that

$$\begin{aligned}\dot{\Sigma}_i&=-\dot{C}_i(t)\frac{x_i(t)}{x_i(t)+1}-C_i(t)\frac{\dot{x}_i(t)}{(x_i(t)+1)^2}+\dot{\lambda}_i(t-\tau_i)-\ddot{y}_i^d(t)\\&\quad+\mu_i[-C_i(t)\frac{x_i(t)}{x_i(t)+1}+\lambda_i(t-\tau_i)-\dot{y}_i^d(t)]\\&=-\dot{C}_i(t)\frac{x_i(t)}{x_i(t)+1}-C_i(t)[\frac{\dot{x}_i(t)}{(x_i(t)+1)^2}+\mu_i\frac{x_i(t)}{x_i(t)+1}]\\&\quad+\dot{\lambda}_i(t-\tau_i)-\ddot{y}_i^d(t)+\mu_i[\lambda_i(t-\tau_i)-\dot{y}_i^d(t)]\end{aligned} \tag{16}$$

Then choose the exponential reaching law of sliding mode as in the conventional sliding mode control

$$\dot{\Sigma}_i=-\omega_{1i}\Sigma_i-\omega_{2i}\,\mathrm{sgn}(\Sigma_i) \tag{17}$$

Because $\Sigma_i\dot{\Sigma}_i\le 0$, the second-order sliding manifold is reachable. And in the sliding manifold $\Sigma_i=\dot{\sigma}_i+\mu_i\sigma_i=0$, σ_i is exponential stable.

So we can get the control law as follows:

$$\begin{aligned}\dot{C}_P(t)&=\frac{x_p+1}{x_p}(-C_p(t)[\frac{\dot{x}_p(t)}{(x_p(t)+1)^2}+\mu_p\frac{x_p(t)}{x_p(t)+1}]+\dot{\lambda}_p(t)\\&\quad-d_pD_{2p}-\ddot{y}_p^d(t)+\mu_p[\lambda_p(t)-d_pD_{1p}-\dot{y}_p^d(t)]\\&\quad+\omega_{1p}\Sigma_p+\omega_{2p}\,\mathrm{sgn}(\Sigma_p))\end{aligned} \tag{18}$$

$$\begin{aligned}\dot{\lambda}_r(t)&=\dot{C}_r(t)\frac{x_r(t)}{x_r(t)+1}+C_r(t)[\frac{\dot{x}_r(t)}{(x_r(t)+1)^2}+\mu_r\frac{x_r(t)}{x_r(t)+1}]\\&\quad+d_rD_{2r}+\ddot{y}_r^d(t)-\mu_r[\lambda_r(t)-d_rD_{1r}-\dot{y}_r^d(t)]\\&\quad-\omega_{1r}\Sigma_r-\omega_{2r}\,\mathrm{sgn}(\Sigma_r)\end{aligned} \tag{19}$$

C. A twisting SOSM controller design

Consider sliding variable dynamics degree one system

$$\dot{\sigma}=h(t,x)+g(t,x)u \tag{20}$$

with $|h|\le C,\ 0<K_m\le g\le K_M$.

The 'twisting' algorithm is one of the first proposed algorithms belonging to the considered class of SOSMC. It is based on the knowledge of the sign of both σ and $\dot{\sigma}$.

Refer to [8], the controller which can establish and keep $\sigma\equiv 0$ is designed as follows:

$$u=-k\mathrm{sign}\sigma \tag{21}$$

with the condition

$$kK_m-C>0 \tag{22}$$

Consider $\dot{u}$ as a new control in order to overcome the chattering, differentiating (20) achieves

$$\ddot{\sigma}=h_1(t,x,u)+g_1(t,x)\dot{u} \tag{23}$$

where $h_1=h_t'+h_x'x'$, $g_1=g_t'+g_x'x'$.

And define the function

$$\Sigma=\dot{\sigma}+\beta|\sigma|^{1/2}\,\mathrm{sgn}\,\sigma \tag{24}$$

Let

$$\dot{u}=\begin{cases}-u, & |u|>k,\\ -\alpha\mathrm{sign}\,\Sigma, & |u|\le k.\end{cases} \tag{25}$$

Then with sufficiently large α controller (25) provides for the establishment of the finite time stable second order mode $\sigma\equiv 0$. It is shown in the work [16] that the control law (21) and (25) stabilizing the nonlinear dynamic sliding variable to zero in finite time so that the SOSM-based control achieves desired finite time convergence of the sliding manifold.

In a router buffer, all the signals are positive, and from system model (2), we can calculate the scope of the signals. Then the controller can be adopted for the buffer management. First choose a sliding variable (7) as conventional sliding mode control, and the sliding variable dynamics are derived as (8) and (9).

Suppose the max of the arriving rate $\lambda_i(t)$ is Γ and the queue length $x_i(t)$ is at least 1, then we have $\frac{1}{2}\le\frac{x_i(t)}{x_i(t)+1}\le 1$.

For the premium traffic

$$\dot{\sigma}_p(t)=\lambda_p(t-\tau_p)-\dot{y}_p^d(t)-\frac{x_p(t)}{x_p(t)+1}C_p(t), \tag{26}$$

compare with (20), there are

$$|h(t,x)|=|\lambda_p(t)-\dot{y}_p^d(t)|\le\Gamma-d_pD_{1p}-\dot{y}_r^d(t),$$

$$g(x,t)=\frac{x_p(t)}{x_p(t)+1}.$$

so we can get $K_m=1/2,\ K_M=1$.

The controller is designed as

$$C_p(t) = k_p \text{sign}\sigma_p , \quad (27)$$

with $k_p > 2(\Gamma - d_p D_{1p} - \dot{y}_p^d)$,

and

$$\dot{C}_p(t) = \begin{cases} C_p, & C_p > k_p \\ \alpha_p \text{sign}(\dot{\sigma}_p + \beta_p |\sigma_p|^{1/2} \text{sign}\sigma_p), & C_p \le k_p \end{cases} . \quad (28)$$

For the ordinary traffic control,

$$\dot{\sigma}_r(t) = -\frac{x_r(t)}{x_r(t)+1} C_r(t) - \dot{y}_r^d(t) + \lambda_r(t-\tau_r), \quad (29)$$

compare with (20),

$$|h(t,x)| = \left| \frac{x_r(t)}{x_r(t)+1} C_r(t) + \dot{y}_r^d(t) + \tau_r \dot{\lambda}_r \right| ,$$
$$< C_{server} - C_p + \dot{y}_r^d(t) + d_r D_{1r}$$
$$g(t,x) = 1 .$$

The proposed controller is

$$\lambda_r(t) = -k_r \text{sign}\sigma_r \quad (30)$$

with $k_r > C_{server} - C_p + \dot{y}_r^d(t) + d_r D_{1r}$.

For the condition $\lambda_r > k_r$ does not exist, so we can get

$$\dot{\lambda}_r(t) = -\alpha_r \text{sign}(\dot{\sigma}_r + \beta_r |\sigma_r|^{1/2} \text{sign}\sigma_r) . \quad (31)$$

For all the proposed controllers, the actual control is $u = \int v dt$, which can eliminate the chattering obviously. And the stability of the proposed second order sliding mode control system can be guaranteed on the sliding manifold $\Sigma = 0$, and $\sigma = \dot{\sigma} = 0$. So it is true that $x_p - y_p^d \to 0$ and $x_r - y_r^d \to 0$, asymptotically.

IV. Simulation Results

In this simulation, we will compare these three controllers in the same network condition. And the simulation results for premium buffer and ordinary buffer are showed separately.

The router parameters are $C_{server} = 4000$, $\Gamma = 400$, $d_p = 0.05s$, $d_r = 0.1s$, $D_{1p} = D_{1r} = 100$, $D_{2p} = D_{2r} = 10$, . During the simulation, $\tau_p = 0.02s, \tau_r = 0.06s$, $x_p(0) = 10$, $x_r(0) = 10$. To the Lyapunov based controller, $\gamma_i = 15, \rho_i = 80, \varepsilon_i = 7$. To the exponential controller, $\mu_i = 1, \omega_1 = 50, \omega_2 = 2$. To the twisting SOSM, the controller parameters are set to $k_p = 2000$, $k_r = 4000$ $\alpha_p = \alpha_r = 3000$, and $\beta_p = \beta_r = 150$.

For premium buffer the desired reference queue length $y_p^d(t)$ is a constant 100, and the traffic incoming rate which is the disturbance is set to be a sine wave with amplitude=50 and periods=0.1s. The desired and actual trajectories are shown in figure 2. It is showed that $x_p(t)$ converges to $y_p^d(t) = 100$ very quickly, in which the twisting controller and the exponential controller are faster than the Lyapunov one to reach stable state. And the control signals $C_p(t)$ for these three methods are presented in figure 3.

For ordinary buffer the desired reference queue length $y_r^d(t)$ is a sine wave showed in figure 4 in green. It is showed that the actual trajectories $x_r(t)$ converge to $y_r^d(t)$ very quickly and the twisting controller has better transient performance than the other two. The control signal $\lambda(t)$ is presented in figure 5.

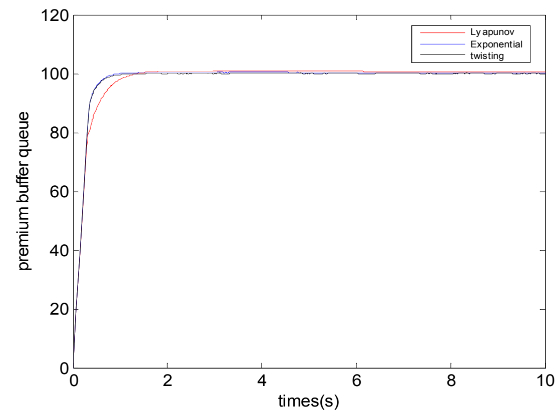

Fig. 2. Buffer length of premium traffic $x_p(t)$ and $y_p^d(t)$

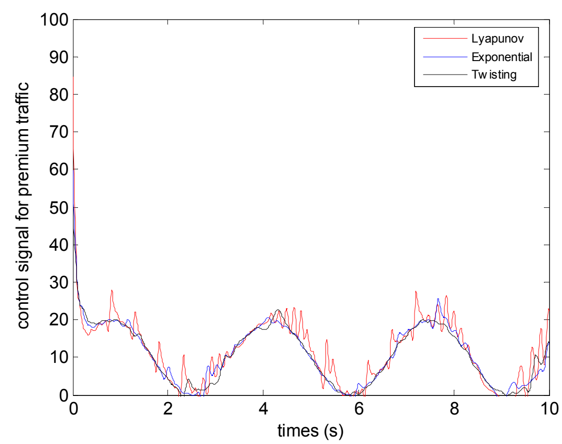

Fig. 3. Control signal for premium traffic

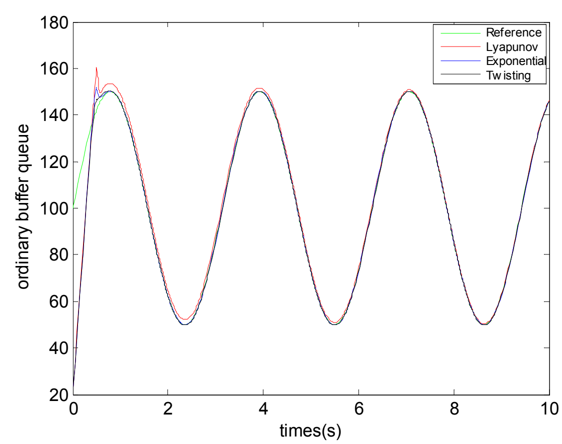

Fig. 4. Buffer length of ordinary traffic $x_r(t)$ and $y_r^d(t)$

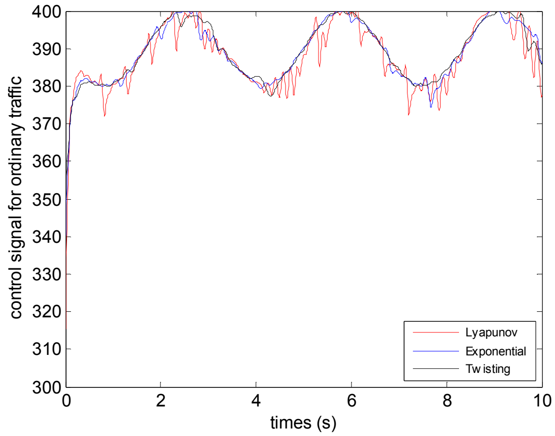

Fig. 5. Control signal for ordinary traffic

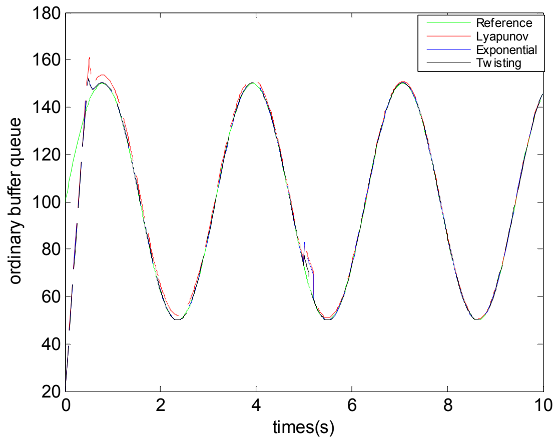

Fig. 6. Ordinary buffer length with a disturbance

Remark: In ordinary traffic a step disturbance is added when t=5s. Figure 6 shows that the queue length has no difficulty to trace the reference length. The tracking errors converge to zero as well.

V. Conclusion

This paper is concerned with the second order sliding mode controller 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.

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