Active Queue Management: A New Robust Fuzzy Second-Order Sliding Mode Control Applied to

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Abstract: - Active Queue Management (AQM) takes a trade-off between link utilization and delay experienced by data packets. From control point of view, it is rational to regard AQM as a typical regulation system. In this paper, a new fuzzy adaptive second order sliding mode controller is designed for the objective of AQM. In the proposed method, the sliding parameter is adapted using fuzzy logic. Some computer simulations are provided to show the effectiveness of the proposed control action. Simulation results show the fuzzy logic based adaptive second order sliding mode has better performance in comparison with classic second order sliding mode control action in providing efficient queue management.

Key-Words: - Active queue management, robust control, second order sliding mode, fuzzy logic.

1 Introduction

TCP congestion control mechanism, while necessary and powerful, are not sufficient to provide good service in all circumstances, specially with the rapid growth in size and the strong requirements to Quality of Service (QoS) support, because there is a limit to how much control can be accomplished at end system. It is needed to implement some measures in the intermediate nodes to complement the end system congestion avoidance mechanisms. Active Queue Management (AQM), as one class of packet dropping/marking mechanism in the router queue, has been recently proposed to support the end-to-end congestion control in the Internet [1]. It has been a very active research area in the Internet community. The goals of AQM are (1) reduce the average length of queue in routers and thereby decrease the end-to-end delay experimented by packets, and (2) ensure the network resources to be used efficiently by reducing the packet loss that occurs when queues overflow. AQM highlights the tradeoff between delay and throughput. By keeping the average queue size small, AQM will have the ability to provide greater capacity to accommodate nature-occurring burst without dropping packets, at the same time, reduce the delays seen by flow, this is very particularly important for real-time interactive applications. RED [2] was originally proposed to achieve fairness among sources with different burst attributes and to control queue length, which just meets the requirements of AQM. However, many subsequent studies verified that RED is unstable and too sensitive to parameter configuration, and tuning of RED has been proved to be a difficult job [3,4].

During the last two decades, Variable Structure Control (VSC) and Sliding Mode Control (SMC) have gained significant interest and are gradually accepted by practicing control engineers [5-8]. There are two main advantages of this approach. Firstly, the dynamic behavior of the system may be tailored by the particular choice of switching functions. Secondly, the closed-loop response becomes totally insensitive to a particular class of uncertainty. In addition, the ability to specify performance directly makes sliding mode control attractive from the design perspective [9]. A phenomenon that usually occurs in SMC is the problem of chattering that can be greatly reduced using higher order sliding controllers [10,11].

Fuzzy logic controllers have been developed and applied to nonlinear system for the last two decades. Although a fuzzy logic controller is similar to a SMC [12], the combination of fuzzy logic control and sliding mode control still is of research interest due to the fact that the stability of a general fuzzy logic controller is difficult to prove whereas the stability of a sliding mode controller is inherent. In recent years many applications of fuzzy sliding mode control have been introduced [13]. The majority of research effort of combining fuzzy logic control and sliding mode control has been spent on how to use fuzzy logic to approximate the control command as a nonlinear function of sliding surface within the boundary layer [12,13,14].

The intuition and heuristic design is not always scientific and reasonable under any conditions. Of

course, since Internet is a rather complex huge system, it is very difficult to have a full-scale and systematic comprehension, but importance has been considerably noted. The mathematical modeling of the Internet is the first step to have an in-depth understanding, and the algorithms designed based on the rational model should be more reliable than one original from intuition. In some of the references, the nonlinear dynamic model for TCP flow control has been utilized and some controllers like PI and Adaptive Virtual Queue Algorithm have been designed for that [15-19]. Although PI controller successfully related some limitations of RED, for instance, the queue length and dropping/marking probability are decoupled, whenever the queue length can be easily controlled to the desired value; the system has relatively high stability margin. The shortcomings of PI controller are also obvious. The modification of probability excessively depends on buffer size. As a result, for small buffer the system exhibits sluggishness. Secondly, for small reference queue length, the system tends to performance poorly, which is unfavorable to achieve the goal of AQM because small queue length implies small queue waiting delay. Thirdly, the status of actual network is rapidly changeable, so we believe that it is problematic and unrealistic, at least inaccurate, to take the network as a linear and constant system just like the designing of PI controller. Affirmatively, the algorithm based on this assumption should have limited validity, such as inability against disturbance or noise. We need more robust controller to adapt complex and mutable network environment, which will be our motivation and aim in this study. In the research, we will apply one of the advanced robust control theory, variable structure second order sliding mode control, to design the AQM controller. The sliding parameter of second order sliding mode controller is adapted using fuzzy logic [14], which results in better and more robust response in comparison with classic second order sliding mode control action.

2 TCP flow control model

In [15], a nonlinear dynamic model for TCP flow control has been developed based on fluid-flow theory. This model can be stated as follows

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

The above nonlinear and time-varying system was approximated as a linear constant system by small-signal linearization about an operating point [20] (Fig. 1). In the block diagram, $C(s)$ and $G(s)$ are the controller and the plant, respectively. The meaning of parameters presented in Fig. 1 are as following

$$
K(t) = \frac{[R(t)C(t)]^3}{[2N(t)]^2}, \quad T_1(t) = R(t),
$$
$$
T_2(t) = \frac{R^2(t)C(t)}{2N(t)}
\tag{2}
$$

where
$C(t)$: Link capacity (packets/sec)
q_o : Queue reference value
$N(t)$: Load factor, i.e., number of active sessions
$R(t)$: Round-trip time (RTT), $R(t) = 2(q(t)/C(t) + T_p)$, T_p is the fixed propagation delay
$p(t)$: Dropping/marking probability
$q(t)$: Instantaneous queue

We believe that the AQM controller designed with the simplified and inaccurate linear constant model should not be optimal, because the actual network is very changeful; the state parameters are hardly kept at a constant value for a long time. Moreover, the equations (1) only take consideration into the fast retransmission and fast recovery, but ignore the timeout mechanism caused by lacking of enough duplicated ACK, which is very usual in burst and short-lived services. In addition to, there are many non-respective UDP flows besides TCP connections in networks; they are also not included in equations (1). These mismatches in model will have negative impact on the performance of controller designed with the approach depending with the accurate model. For the changeable network, the robust control should be an appropriate choice to design controller for AQM. The variable structure sliding mode control action is one of the best that can help us.
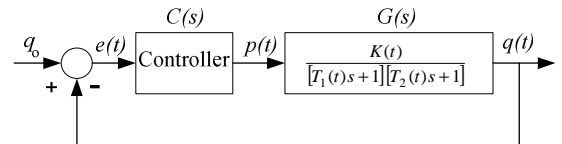

Fig. 1. Block diagram of AQM control system.

3 Fuzzy second order sliding mode controller design

The accompanying (sometimes dangerous) vibrations are termed "chattering". The higher the order of an output variable derivative where the high frequency discontinuity first appears, the less visible the vibrations of the variable itself will be. Thus, the remedy to avoid chattering is to move the switching to the higher order derivatives of the control signal. The problem is how to preserve the main feature of sliding modes: exact maintenance of constraints under conditions of uncertainty. Such sliding modes were discovered and termed "higher order sliding modes" (HOSM) [9,10,11]. These sliding modes may attract trajectories in finite time like the standard ones or may be asymptotically stable. Being moved to the higher derivatives of the control, the switching is no longer dangerous, since it takes place within the inner circuits of the control system (mostly in a computer) and not within the actuator. HOSM may provide for up-to-its-order precision with respect to the measurement time step, as compared to the standard (first order) sliding mode whose precision is proportional to the measurement step.
Consider a nonlinear system

$$\dot{x}(t) = f(t,x) + g(t,x)u(t) \tag{1}$$

where $f(t,x)$ and $g(t,x)$ are smooth uncertain functions and $u(t)$ is the control command. In the design of sliding mode, sliding surface is defined as a function of state variables

$$s = s(x,t). \tag{2}$$

Consider local coordinates $y_1 = s$ and $y_2 = \dot{s}$, after a proper initialization phase, the second order sliding mode control problem is equivalent to the finite time stabilization problem for the uncertain second order system

$$\begin{cases} \dot{y}_1 = y_2 \\ \dot{y}_2 = \varphi(y_1, y_2, x_2, u, t) + \gamma(y_1, y_2, t)\nu(t) \end{cases} \tag{3}$$

where $\nu(t) = \dot{u}(t)$.

In the above equations $y_2(t)$ is generally unknown, but $\varphi(t,x)$ and $\gamma(t,x)$ can be bounded as

$$|\varphi(t,x)| \le \Phi, \quad 0 < \Gamma_m < \gamma(t,x) < \Gamma_M, \quad \Phi > 0. \tag{4}$$

Being historically the first known second order sliding controller, that algorithm features twisting around the origin of second order sliding phase plane $y_1 - y_2$. The trajectories perform an infinite number of rotations while converging in finite time. The vibration magnitudes along the axes as well as the rotation times decrease in geometric progression. The control derivative value

commutes at each axis crossing, which requires availability of the sign of the sliding-variable time-derivative y_2.

The control algorithm is defined by the following control law, in which the condition on $|u|$ provides for $|u| \le 1$

$$\dot{u}(t) = \begin{cases} -u & if \quad |u| > 1 \\ -V_m sign(y_1) & if \quad y_1 y_2 \le 1, |u| \le 1 \\ -V_M sign(y_1) & if \quad y_1 y_2 > 1, |u| \le 1 \end{cases} \tag{5}$$

The corresponding sufficient conditions for the finite-time convergence to the sliding surface are

$$V_M > V_m, V_M > \frac{\Gamma_M V_m + 2\Phi}{\Gamma_m}, V_m > \frac{\Phi}{\Gamma_m}, V_m > \frac{4\Gamma_M}{s_0} \tag{6}$$

where $s_0 > |s|$.

Fuzzy logic is mainly introduced to provide tools for dealing with uncertainty [21]. We cannot determine the change of C with respect to the system action precisely. Thus, we will use a fuzzy logic controller to supervise the sliding controller. In order to obtain fuzzy rules of updating the slope of the sliding curve $s = Cx_1 + x_2$, the approximate form of the phase plane around the sliding surface is depicted in Fig. 2. For the operating points A to H we can define the slope change as presented in Table 1. The fuzzy rules are presented in Table 2 and the corresponding membership functions are shown in Fig. 3.
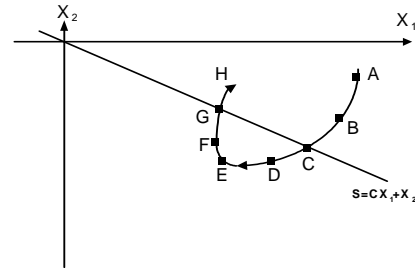

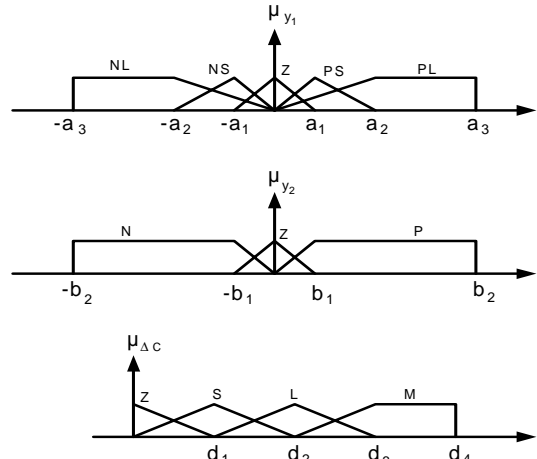**Fig. 2.** Phase trajectory around sliding surface.

Fig. 3. Fuzzy membership functions.

**Table 1.** Proper change in *C* for different operating points.

ΔC	$y_2(t)$	$y_1(t)$	*Operating point*
Zero	Negative	Positive and large	A
Small	Negative	Positive and small	B
Medium	Negative	Zero	C
Large	Negative	Negative and small	D
Medium	Zero	Negative and large	E
Small	Positive	Negative and small	F
Zero	Positive	Zero	G
Zero	Positive	Positive and small, large	H

Table 2. Fuzzy rules.

		$y_1(t)$				
		NL	NS	Z	Z	PL
$y_2(t)$	P	M	S	Z	Z	Z
	Z	M	M	M	Z	Z
	N	M	L	M	S	Z

4 Simulation results

The network topology used for simulation, is depicted in Fig. 4. The only bottleneck link lies between node A and node B. the buffer size of node A is 300 packets, and default size of the packet is 500 bytes. All sources are classed into three groups. The first one includes N_1 greedy sustained FTP application sources, the second one is composed of N_2 burst HTTP connections, each connection has 10 sessions, and the number of pages per session is 3. The thirds one has N_3 UDP sources, which follow the exponential service model, the idle and burst time are 10000msec and 1000msec, respectively, and the sending rate during "on" duration is 40kbps. We introduced short-lived HTTP flows and non-responsive UDP services into the router in order to generate a more realistic scenario, because it is very important for a perfect AQM scheme to achieve full bandwidth utilization in the presence of noise and disturbance introduced by these flows. The links between node A and all sources have the same capacity and propagation delay pair (L_1, τ_1). The pair (L_2, τ_2) and (L_3, τ_3) define the parameter of links AB and BC, respectively.
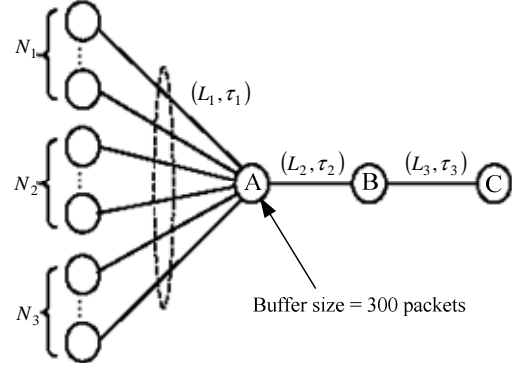

**Fig. 4.** The simulation network topology.

In the first study, we will use the most general network configuration to testify whether the Fuzzy Adaptive Second-Order Sliding-Mode Controller (FASOSMC) can reach the goals of AQM, and freely control the queue length to stabilize at the arbitrary expected value. Therefore, given that $(L_1, \tau_1) = (10Mbps, 15ms)$, $(L_2, \tau_2) = (15Mbps, 15ms)$, $(L_3, \tau_3) = (45Mbps, 15ms)$. $N_1 = 270$, $N_2 = N_3 = 0$. Let the expected queue length equal to 75 packets. The initial value of *C* is set to 5. The fuzzy controller values are chosen as follows:

$a_1 = 1$ $a_2 = 5$ $a_3 = 400$ $b_1 = 0.5$ $b_2 = 400$
$d_1 = 0.05$ $d_2 = 0.2$ $d_3 = 0.5$ $d_4 = 2$

The instantaneous queue length using the proposed FASOSMC is depicted in Fig. 5. After a very short regulating process, the queue settles down its stable operating point. RED algorithm is unable to accurately control the queue length to the desired value. The queue length varies with network loads. The load is heavier the queue length is longer. Attempting to control queue length through decreasing the interval between high and law thresholds, then it is likely to lead queue oscillation. Although Second-Order Sliding-Mode controller (SOSMC) could regulate the queue to the fixed point, the integrated performance needs to be improved, such as the transient process is too long and the fluctuation in steady state is great, for small queue length, which lows the link utilization. The queue evaluation of router A, controlled by SOSMC controller (q_o=75packets), is plotted in Fig. 6. Evidently, SOSMC controller takes the longer time to settle down the reference point.
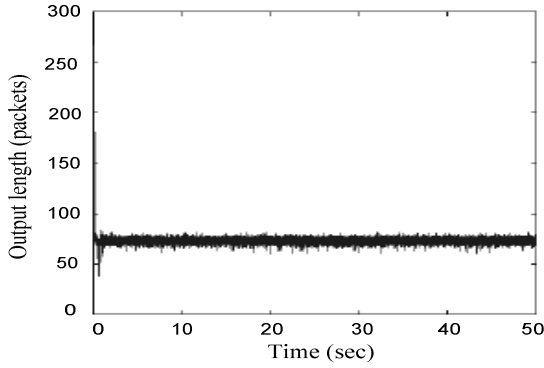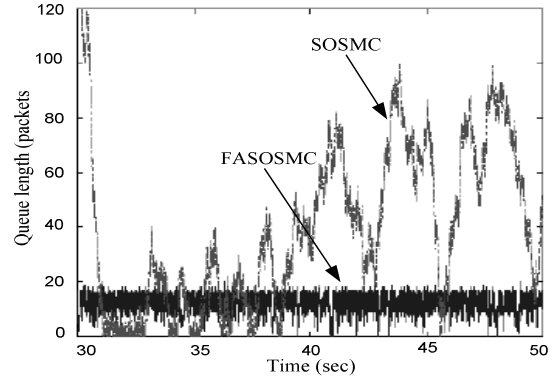
Fig. 5. Queue evaluation (FASOSMC).
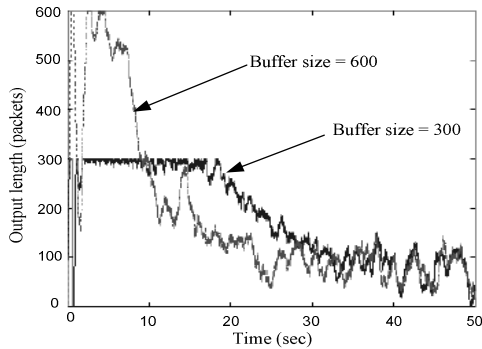
Fig. 6. Queue evaluation (SOSMC).

Considering the requirement of the steady state performance, it is impractical to increase the difference between *a* and *b* to speed up the response of SOSMC. With the higher sampling frequency, the computation will be significantly exhausted. The only feasible way is to add the buffer size. In order to illustrate this ability, we redo the above simulation with 600 packets buffer size, which the results are also plotted in Fig. 6. Indeed, the large buffer is able to enhance the responsibility of SOSMC, but this ability is limited, moreover it seems to be wasteful. Conversely, the FASOSMC has the ideal performance without any additional regulation mechanism. In order to evaluate the performance in steady state, we calculate the average and the standard deviation of the queue length in steady state. For the convenience of comparison, choose the queue length between 40 and 50 seconds as sample data. In this case, the standard deviation of SOSMC (32.3336) is much larger than that of FASOSMC (2.5928). Fig. 7 presents the case of small reference queue length. Except $q_o = 15$, the other parameters are unchangeable.


Fig. 7. Small expected queue ($q_o=15$).

In this section, Firstly, let $N_1 = 270, N_2 = 400, N_3 = 0$, the evaluation of queue size is shown in Fig. 8. As it can be seen, the proposed FASOSMC has better performance than that of SOSMC. Next, given that $N_1 = 270, N_2 = 0, N_3 = 50$, we further investigate performance against the disturbance caused by the non-responsive UDP flows. Fig. 9 shows the results, obviously, SOSMC is very sensitive to this disturbance, while FASOSMC operates in a relatively stable state. The queue fluctuation increases with introducing the UDP flows, but the variance is too much smaller comparing with SOSMC.
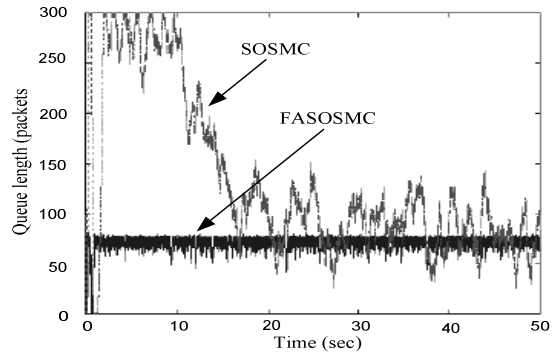
Fig. 8. Queue evaluation (FTP+HTTP).
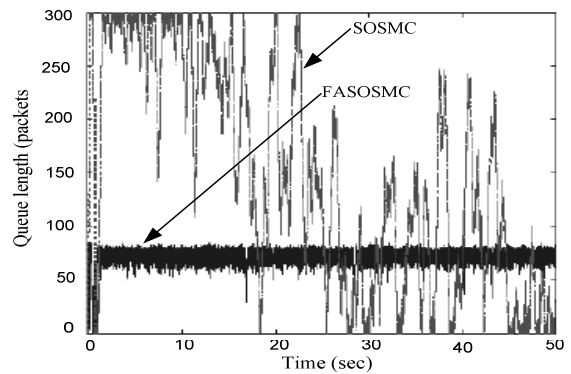
Fig. 9. Queue evaluation (FTP+UDP).

5 Conclusion

In this paper, a fuzzy adaptive second-order sliding-mode controller was designed for the objective of active queue management. For this purpose, a linearized model of the TCP flow was considered. We applied FASOSMC to this system because this advanced robust control methodology is insensitive to system dynamic parameters and is capable of being against disturbance and noise, which is very suitable for the mutable network environment. We took a complete comparison between performance of the proposed FASOSMC and classical SOSMC under various scenarios. The conclusion was that the integrated performance of FASOSMC was superior to that of SOSMC. FASOSMC was very responsive, stable and robust, especially for the small reference queue system, but its performance was inferior when active TCP sessions were relatively small. Thus, it will be very imperious to design the controller suitable for light load, and then integrate it with FASOSMC using classical adaptive control technology.

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