A BACKSTEPPING-LIKE CONGESTION TRACKING CONTROL FOR TCP/AQM SYSTEMS

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ABSTRACT

This study is aimed to designing a backstepping-like controller for Transmission Control Protocol (TCP) network to deal with the Active Queue Management (AQM) problem. Based on this strategy, the design control law can be used to cope with the congestion tracking problem for a TCP/AQM nonlinear model. Furthermore, with the help of backstepping-like strategy, a nonlinear stabilizing feedback congestion controller is proposed to ensure that the queue length can track the desired queue length and that the window size is stable. The developed control design is validated in the MATLAB environment. The effectiveness of the proposed control is verified through simulation and compared with an integral sliding mode controller and a conventional sliding mode controller. The simulation results indicate that the presented strategy is able to not only solve the desired congestion tracking control problem, but also provide improved transient performances.

KEYWORDS: Nonlinear congestion control, backstepping-like control, TCP/AQM network.

1. Introduction

The Internet is now undergoing tremendous expansion, resulting in an inescapable network congestion management challenge in network traffic. Furthermore, it may cause network collapse, lock-out behavior, and an increase in the likelihood of control-loop synchronization. As a result, several attempts are being made to address this issue. Recently, there has been a steady increase in interest in the topic of network congestion control. Fortunately, a significant and promising technique exists, which is called Active Queue Management (AQM) scheme. It has been suggested to reduce packet losses, ensure best-effort service with low packet drop, and increase network usage. Afterward, there are several AQM methods with different design ideas. The first AQM strategy proposed was Random Early Detection (RED) [1]. The main advantage of this technique is that the average queue length may be used to compute the chance of losing packets. Following that, a range of approaches [2-11] based on an analytical fluid-flow model for TCP/AQM systems were investigated to deal with network congestion problems. In [2], an LMI-based controller design was proposed by using a combination of robust active queue management and $\mathcal{H}_\infty$ control to ensure the queue length stability and to deal with robustness against the external disturbances and model perturbation. Mohammadi et al. [3] proposed a fuzzy-based PID controller of AQM network for Internet routers to alleviate packet losses and to enhance network utilization with input saturation. With the help of Lynpunov-Krasovskii functional, a nonlinear model prediction congestion control approach [4] was developed for networks to cope with the adverse effects of nonlinear disturbance uncertainties, time-varying delay and input constraint. On basis of the minimax strategy, Li et al. [5] presented an adaptive backstepping congestion controller for TCP network with user datagram protocol (UDP) flows. Due to the unknown UDP flows regarded as the external disturbances, it is necessary to compute the minimax UDP flow. Based on a combination of integral backstepping design and minimax scheme, a nonlinear AQM controller [6] for TCP networks was reported to address the undesired effects of the disturbances arising from UDP flows. A nonlinear congestion tracking control strategy [7] for TCP/AQM network model was designed by using a combination of integral backstepping and $\mathcal{H}_\infty$ design. However, even if external disturbances and modeling uncertainties were included in the network model, the corresponding controller can guarantee satisfactory tracking performances of the queue, and all signals of the closed-loop system are asymptotically stable. To guarantee the desired transient and steady state performances, Wang et al. [8] presented an adaptive fuzzy funnel congestion control technique for TCP/AQM network to decrease the congestion tracking errors. Based on the minimax in game theory [9], a backstepping sliding mode design was synthesized for nonlinear TCP network congestion systems including unknown parameter and external disturbances. With the aid of a coordination of practically finite-time theory and a prescribed performance control, an adaptive neural congestion control [10] for TCP/AQM networks was developed to ensure that the queue length track the reference queue length in finite-time. To cope with the noise and variance of the parameters, a sliding mode controller design [11] was designed for TCP/AQM network.

From the above-mentioned researches, it is observed that all nonlinear controller design techniques are rather difficult and complicated. Therefore, this paper continues this line of investigation but proposes an advanced nonlinear design to solve the congestion tracking control problem for the TCP/AQM network model. The developed controller in this paper is based on a backstepping-like strategy. The control objective of the backstepping-like method is to find a stabilizing feedback, which is similar to the backstepping approach [12]. This backstepping-like method relies on adding and subtracting some terms in each design step, which is rather simpler than other nonlinear control methods mentioned previously. Additionally, it can be applied to many practical control systems such as chaotic systems [13] and power systems [14-15].

As the above discussions, the followings are the main contributions of this work:

- Using a nonlinear TCP/AQM dynamic model, a backstepping-like control technique is proposed to solve the congestion tracking control problem for TCP/AQM network, which has not yet been investigated before,
- With the help of Lyapunov theory, the overall closed-loop system with the developed control law is asymptotically stable at a desired equilibrium point.
- In comparison with both integral sliding mode and conventional sliding mode controllers, the developed design procedure is not complicated, but effective. Also, the proposed controller indicates improved dynamic performances such as smaller overshoot and faster reduction of oscillation.

The rest of this paper is organized as follows. Section 2 is a brief presentation of dynamic model of the TCP/AQM network system and the problem statement. Nonlinear backstepping-like control design is provided in Section 3. In Section 4, the simulation results are given to show the effectiveness of the developed design. Finally, the paper is concluded in Section 5.

2. System Model for TCP/AQM networks

A dynamic model used in this paper depends on the fluid model of TCP congestion-avoidance method reported in [16]-[17]. In accordance with the result reported in [16,17], a nonlinear TCP/AQM model can be expressed as

$$\begin{aligned}
\dot{W}(t) &= \frac{1}{R(t)}(1-p(t)) - \frac{W(t)}{2}\frac{W(t)}{R(t)}p(t),\\
\dot{q}(t) &= \frac{NW(t)}{R(t)} - C(t), q>0 \qquad (1)\\
R(t) &= T_p + \frac{q(t)}{C(t)}
\end{aligned}$$

where $W(t)\in[W_{min},W_{max}]$ denotes the TCP window size, $R(t)$ represents the round-trip delay, N is the number of TCP connections, $p(t)$ denotes the ratio of packets marked as dropping in the queue that satisfies $0\le p(t)\le 1$, $q(t)\in[q_{min},q_{max}]$ denotes the queue length, $C(t)$ represents the link capacity, T_p denotes the propagation delay. For this work, $C(t)$ is assumed constant, denoted by C.

In order to simplify the state-space equation of the system (1), let us define the following state variables:

$$x_1 = q - q_r, x_2 = -C + N\frac{W}{R} \qquad (2)$$

Additionally, to guarantee that the queue length q can track the desired queue length q_r, let us define another state variable to guarantee the zero error between the queue length and the desired queue length as $x_0 = \int_0^t (q(\tau)-q_r)d\tau$ where q_r is constant. Therefore, the vector of the state variables used in this design procedure is defined as follows.

$$x = \begin{bmatrix} x_0 \\ x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \int_0^t (q(\tau)-q_r(\tau))d\tau \\ q-q_r \\ \dfrac{CNW}{(q+CT_p)} - C \end{bmatrix}.$$

By differentiating the state variables above, the dynamic model of the nonlinear TCP/AQM model can be expressed as an affine nonlinear system as follows.

$$\begin{aligned}\dot{x}_0 &= x_1,\\ \dot{x}_1 &= f_1(x_1)+g_1(x_1)x_2,\\ \dot{x}_2 &= f_2(x_1,x_2)+g_2(x_1,x_2)u,\end{aligned} \tag{3}$$

Where

$$\begin{aligned}&f_1(x_1)=0, g_1(x_1)=1,\\ &f_2(x_1,x_2)=\frac{NC^2}{(x_1+T_pC)^2}-\frac{(x_2+C)x_2}{RC}, g_2(x_1,x_2)=-\frac{(x_2+C)^2}{2N}, u=p(t),\end{aligned} \tag{4}$$

Define the region of operation as the set $\mathcal{D}=\{x\in\mathbb{R}\times\mathbb{R}^+\times\mathbb{R}^+\}$. $x_e=\left[x_{1e},x_{2e},x_{3e}\right]^T=\left[0,0,0\right]^T$ represents the open loop operating equilibrium point.

Remark 1: Throughout this work, we assume that all parameters of the nonlinear TCP/AQM are constant and known. For the future work, the authors will extend this approach to a nonlinear TCP/AQM networks model including unknown parameters.

Problem statement: The objective of this work is to find out a nonlinear stabilizing feedback control law $u(x)$ with the help of a backstepping-like methodology such that the resulting closed-loop dynamics are asymptotically stable at the desired equilibrium point x_e and $x\rightarrow x_e$ as $t\rightarrow\infty$. Additionally, the developed controller needs to satisfy (i) the zero error between the queue length and the reference queue one (ii) the window size is stable, and (iii) the control input is small or lies within the interval [0,1].

3. Controller Design

For the purpose of designing a nonlinear stabilizing feedback u such that $\lim\limits_{t\rightarrow+\infty} x_0=\lim\limits_{t\rightarrow+\infty} x_1=\lim\limits_{t\rightarrow+\infty} x_2=0$. With the help of the backstepping-like scheme, the control law is developed step by step below.

Step 1: let us take the following Lyapunov candidate as follows:

$$V_0=\frac{1}{2}x_0^2 \tag{5}$$

By taking the derivative of (5) and then adding and subtracting the term c_0x_0 to $\dot{x}_0$, we have

$$\dot{V}_1 = x_0x_1 = x_0(x_1 - c_0x_0 + c_0x_0) = -c_0x_0^2 + x_0P, \tag{6}$$

where $c_0 > 0$ and $P = c_0x_0 + x_1$. From (6), it is simple to see that the term x_0P is not always negative; thus, this term should be eliminated from the aforementioned equation.

Step 2: In order to do this, the Lyapunov function candidate is defined as:

$$V_1 = \frac{1}{2}x_0^2 + \frac{1}{2}P^2 \tag{7}$$

After taking the derivative of (7), one obtains

$$\begin{aligned}\dot{V}_1 &= -c_0x_0^2 + x_0P + P\dot{P}\\ &= -c_0x_0^2 + P\left(x_0 + \dot{P}\right) = -c_0x_0^2 + P\left(x_0 + c_0x_1 + \dot{x}_1 - c_1P + c_1P\right)\\ &= -c_0x_0^2 - c_1P^2 + P\left(x_0 + c_0x_1 + c_1P + f_1(x_1) + g_1(x_1)x_2\right)\\ &= -c_0x_0^2 - c_1P^2 + PQ\end{aligned} \tag{8}$$

where $c_1 > 0$ and $\dot{P} = c_0x_1 + \dot{x}_1, Q = x_0 + c_0x_1 + c_1P + f_1(x_1) + g_1(x_1)x_2$.

Step 3: Similarly, it can be seen that the last term of (8) is not always negative; thus, it should be cancelled. To this end, we introduce the following term into V_2 and then obtain

$$V_2 = \frac{1}{2}x_0^2 + \frac{1}{2}P^2 + \frac{1}{2}Q^2 \tag{9}$$

By computing the derivative of (9) along the system trajectory, one obtains

$$\begin{aligned}\dot{V}_2 &= -c_0x_0^2 - c_1P^2 + PQ + Q\dot{Q}\\ &= -c_0x_0^2 - c_1P^2 + Q(P + \dot{Q})\\ &= -c_0x_0^2 - c_1P^2 + Q\left(P + \dot{x}_0 + c_0\dot{x}_1 + c_1\dot{P} + \dot{f}_1\left(x_1\right) + \dot{g}_1(x_1)x_2 + g_1(x_1)\dot{x}_2\right)\end{aligned} \tag{10}$$

After pluggin $\dot{x}_2$ back into (10), we have

$$\begin{aligned}\dot{V}_2 = &-c_0 x_0^2 - c_1 P^2 \\ &+ Q\Big(P + \dot{x}_0 + c_0\dot{x}_1 + c_1\dot{P} + \dot{f}_1(x_1) + \dot{g}_1(x_1)x_2 + g_1(x_1)\big(f_2(x_1,x_2) + g_2(x_1,x_2)u\big)\Big)\end{aligned} \tag{11}$$

Therefore, if we choose

$$u = \frac{-1}{g_2(x_1,x_2)}\left[\frac{c_2 Q + P + \dot{x}_0 + c_0\dot{x}_1 + c_1\dot{P} + \dot{f}_1(x_1) + \dot{g}_1(x_1)x_2}{g_1(x_1)} + f_2(x_1,x_2)\right] \tag{12}$$

where $\dot{P} = c_0 x_1 + f_1(x_1) + g_1(x_1)x_2,$

Then, under the feedback control law (12), the equation (11) turns into

$$\begin{aligned}\dot{V}_2 &= -c_0 x_1^2 - c_1 P^2 - c_2 Q^2 \le 0, \\ &\le -cV_2.\end{aligned} \tag{13}$$

where $c = \min\{c_0, c_1, c_2\}$

With the help of Lyapunov stability theory [18], it is obvious that

$$\begin{aligned}&\lim_{t\to+\infty} x_0 = 0, \\ &\lim_{t\to+\infty} P = \lim_{t\to+\infty}(c_1 x_1 + x_2) = 0, \\ &\lim_{t\to+\infty} Q = \lim_{t\to+\infty}\left[x_0 + c_0 x_1 + c_1 P + f_1(x_1) + g_1(x_1)x_2\right] = 0,\end{aligned} \tag{14}$$

These also imply that $\lim\limits_{t\to+\infty} x_0 = \lim\limits_{t\to+\infty} x_1 = \lim\limits_{t\to+\infty} x_2 = 0.$ According to the above-mentioned results, the following theorem obvious holds.

Theorem 1: Consider the nonlinear TQM/AQM network model in (3)-(4). If the nonlinear controller is designed by (12), then the equilibrium point x_e of the system (3)-(4) is asymptotically stable. This implies that $\lim\limits_{t\to+\infty} x_i = 0, (i = 1, 2, 3).$

Proof: The proof of Theorem 1 is based on the argument given above.

Figure 1 shows its structure involved in its implementation of the proposed control.

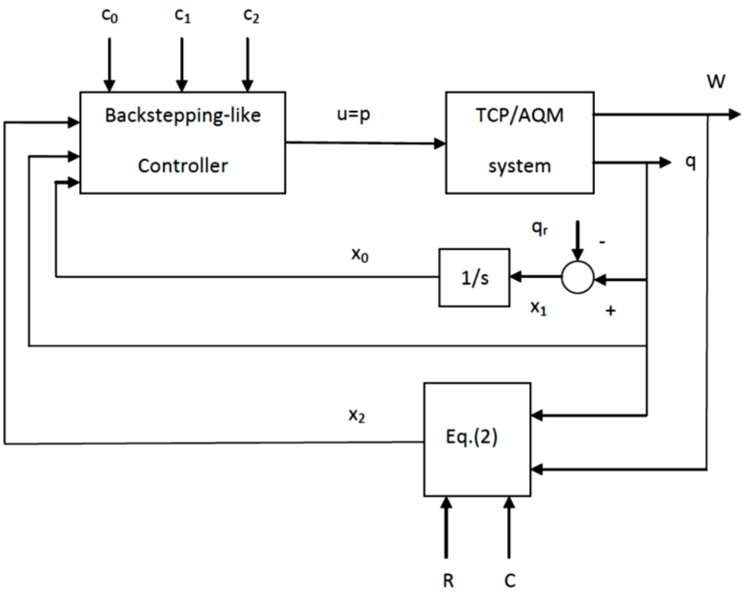

Figure 1 **Block diagram of the proposed backstepping strategy for the TCP/AQM system.**

4. Simulation Results

The presented design strategy is applied for nonlinear TCP/AQM network system. The desirable transient performances of the control system are illustrated to achieve the dynamic performance improvement and tracking congestion control. The MATLAB environment is used for the time-domain simulation of the controlled system. The parameters of the networks utilized in this paper are as follows.

$$C = 1750 \text{ parameter/s},\ T_p = 0.1 \text{ s},\ N = 60,\ W = 4.58 \text{ packets}.$$

The initial state variables are set as $\begin{bmatrix} x_0 & x_1 & x_2 \end{bmatrix}^T = \begin{bmatrix} 0 & 95 & 5 \end{bmatrix}^T$ and the desired queue length is given as $q_r = 100$ packets. The tuning parameters of the designed controller are $c_0 = c_1 = c_2 = 0.5.$

The simulation results are used to exhibit the effectiveness and superiority of the developed scheme by using the following issues: (i) the zero error between the queue length and the reference queue one (ii) the window size is stable, and (iii) the control input is bounded within the interval [0,1]. Besides, the proposed control scheme (backstepping-like control) is compared with the following two nonlinear controllers:

- Integral sliding mode controller (ISDM)

$$u = p = -\frac{(Ksign(S) + c_1\left(f_1(x_1) + g_1(x_1)x_2 \right) + c_2 f_2(x_1, x_2))}{c_2 g_2(x_1, x_2)} \tag{15}$$

where $S(x) = c_1x_1 + c_2x_2$. The control parameters of the integral sliding mode design are set as: $c_1 = c_2 = 1$.

- Sliding mode controller (SDM)

$$u = p = -\frac{(Ksign(S) + cz_2 + \dot{f}_1(x_1) + \dot{g}_1(x_1)x_2 + g_1(x_1) f_2(x_1, x_2))}{g_1(x_1)g_2(x_1, x_2)} \tag{16}$$

where $S(x) = cz_1 + z_2, z_1 = x_1, z_2 = f_1(x_1) + g_1(x_1)x_2$ and $g_1(x_1)g_2(x_1, x_2) \neq 0$. The control parameters of the integral sliding mode design are set as: $c = 1$.

Remark 2: It is observed from both the ISDM and the SDM controllers that the sliding surface may be not uniquely selected differently, leading to different dynamic performances. However, it is obvious that the developed scheme is not only systematic, but also simple and effective.

The simulation results are discussed and given in Figures 2-4. To indicate the effectiveness of the proposed controller through the simulations, time responses of the integral of tracking error x_0, the queue length q, the window size W, the state variable x_2 and the packet loss ratio under the developed design are presented in Figures 1. Under the ISDM and the SDM techniques, Figures 2-4 exhibits time responses of the integral of tracking error x_0, the queue length q, the window size W, the state variable x_2 and the packet loss ratio.

It can be observed from Figures 2-4 that under the developed scheme, the time response of the queue length q smoothly settles down to the desired queue length q_r while those of the other schemes cannot. From Figures 2-3, the integral of tracking error x_0 under the proposed control converges to zero while that of the ISDM control still oscillates and cannot settle down to zero. It is apparent from three controllers that the window size W are all stable, the state variables x_2 converge to the equilibrium point, and the packet loss ratios (the control input) are bounded with the interval [0,1], as desired. It can be seen that the presented control law enables us to improve dynamic performances more than the other two approaches. In particular, it is seen that with based on the proposed design, the tracking error can rapidly converge to zero. This means that the queue length q smoothly tracks the desired queue length q_r. Also, dynamic (transient) performances, such as the reduction of oscillatory overshoot, smaller rising time, and shorter settling time, are clearly enhanced.

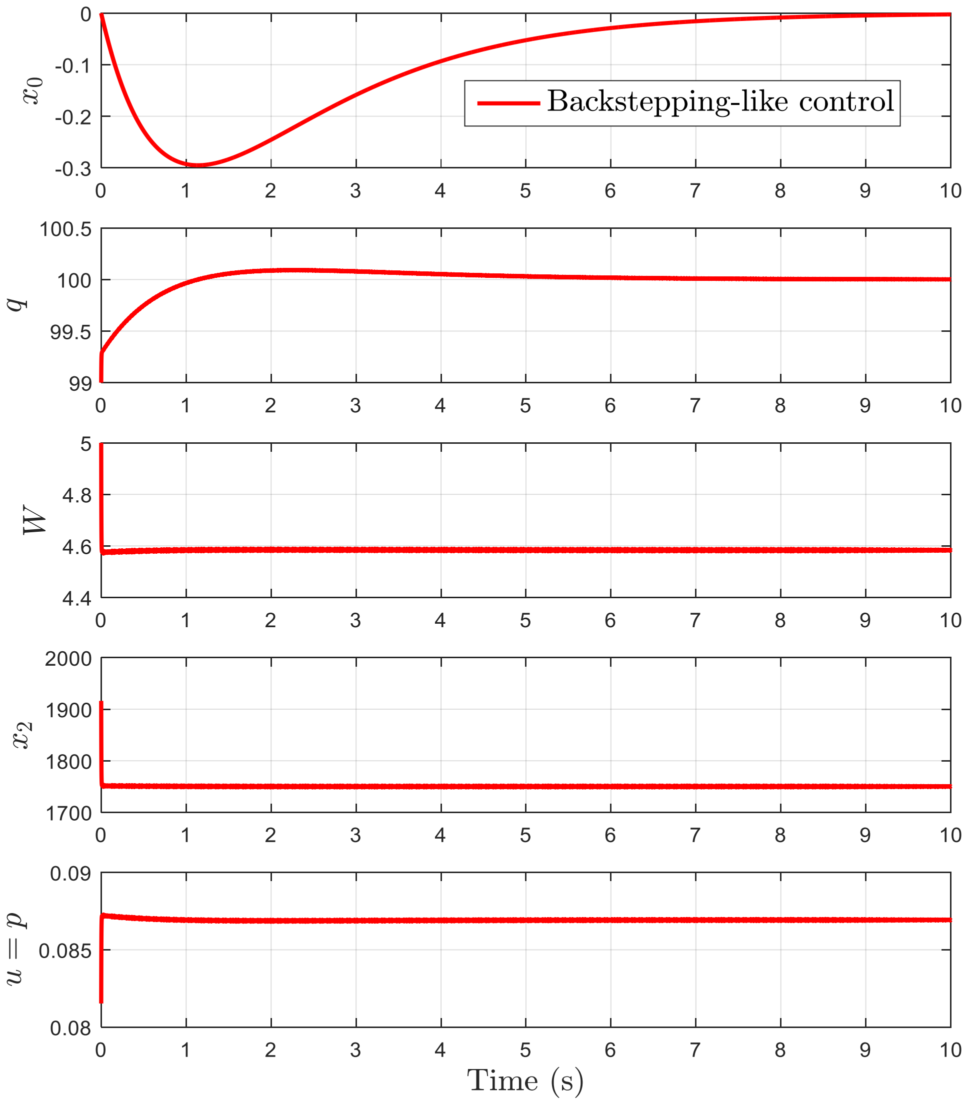

Figure 2 Time responses of the integral term x_0, the queue length q, the window size W, the state variable x_2, and the ratio of packets marked as dropping in the queue (control input) $u = p$

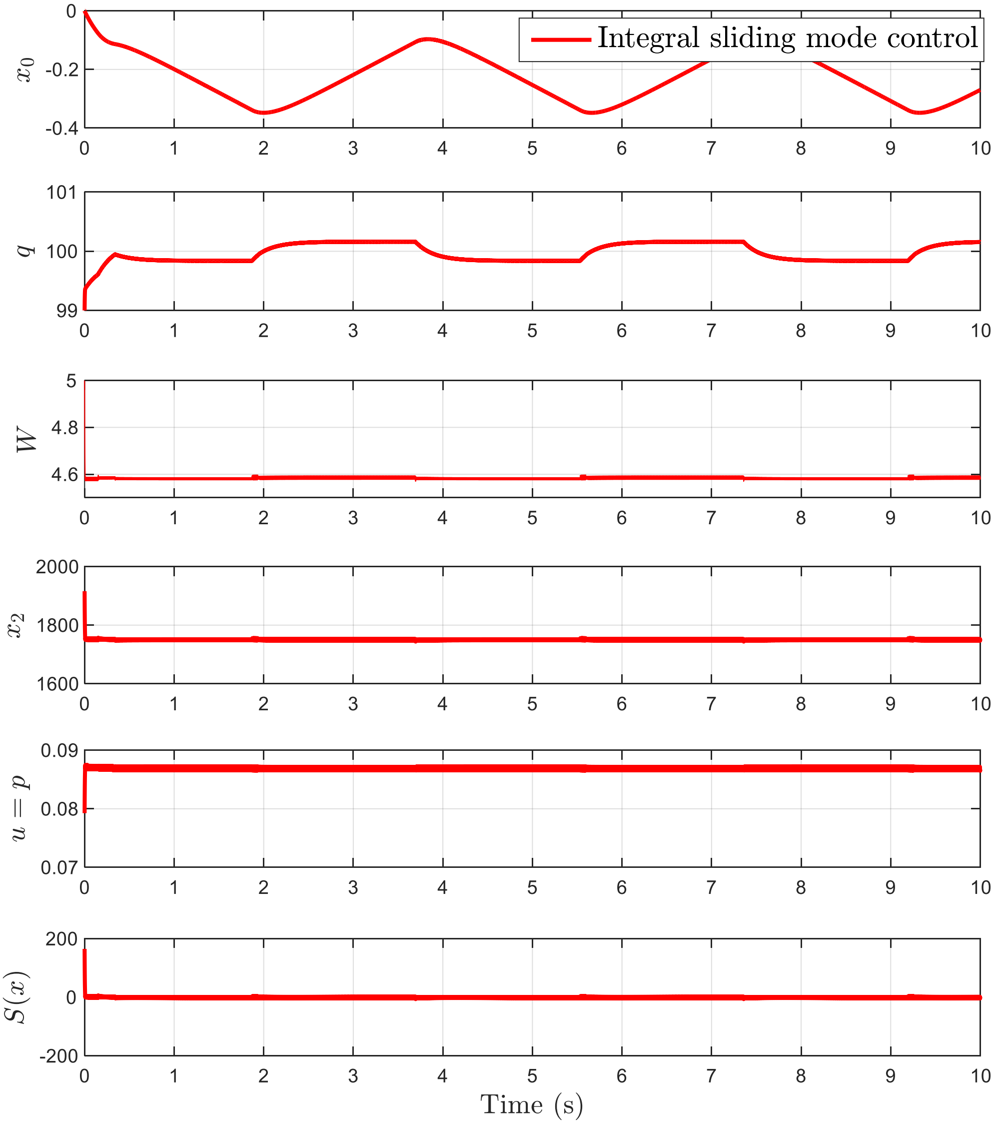

Figure 3 Time responses of the integral term x_0, the queue length q, the window size W, the state variable x_2, and the ratio of packets marked as dropping in the queue (control input) $u = p$

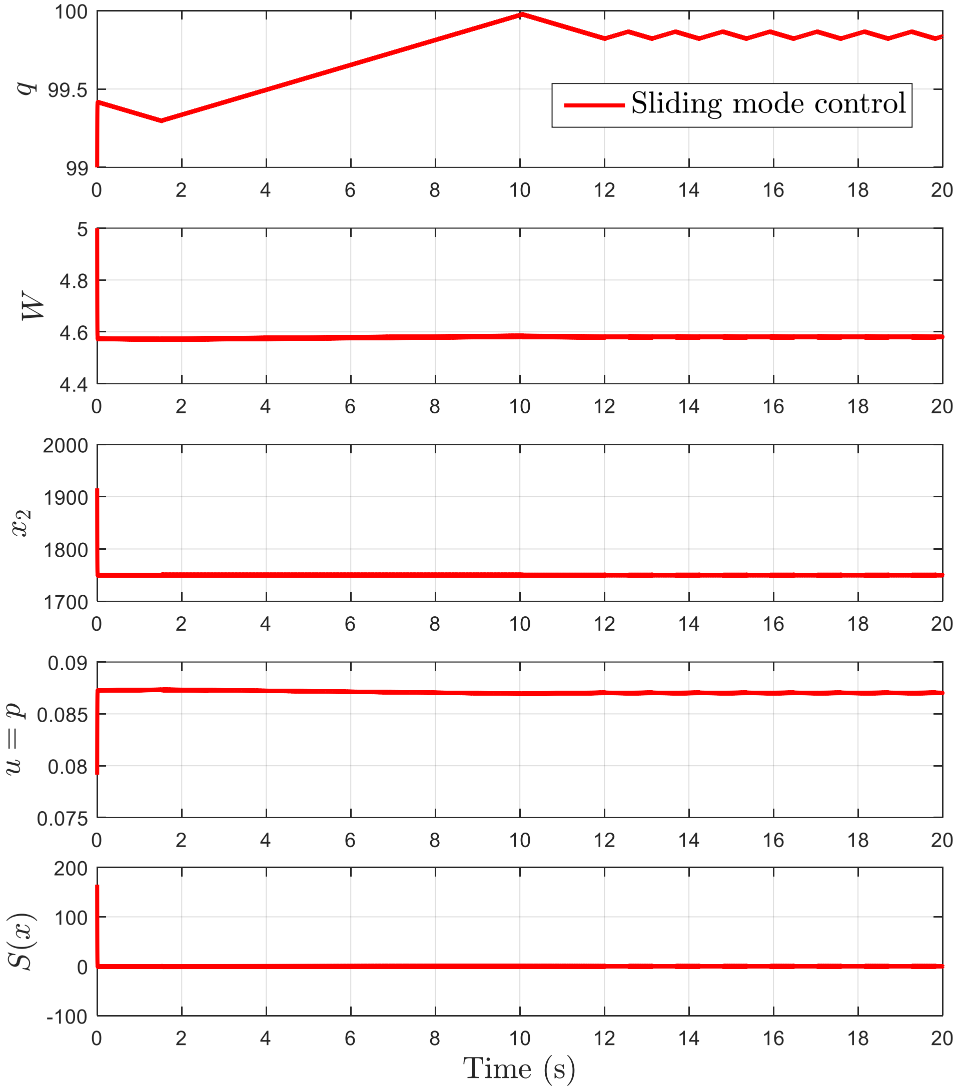

Figure 4 Time responses of the integral term x_0, the queue length q, the window size W, the state variable x_2, and the ratio of packets marked as dropping in the queue (control input) $u = p$

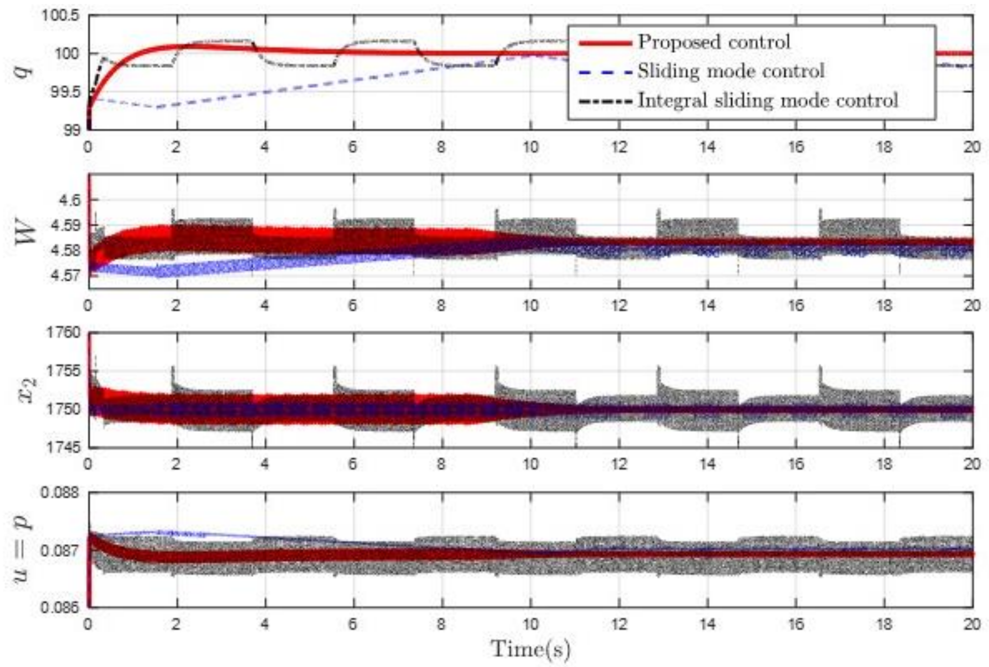

Figure 5 Time responses of the queue length q, the window size W, the state variable x_2, and the ratio of packets marked as dropping in the queue (control input) $u = p$ (Solid: the proposed backstepping-like control, Dotted: Sliding mode control, Dashdotted: Integral sliding mode control)

Note that although the other controllers can accomplish the desired requirements mentioned in the objective of this paper, they provide rather poor transient performances as compared with the developed controller. It is seen from Figures 3-4 that the tracking error between the queue length and the desired queue length does not converge to zero due to the chattering effects. Apart from that, the sliding surfaces $S(x)$ of both the ISDM and the SDM techniques do not settle down to zero. However, both still have unavoidable chattering effects. Figure 5 shows time responses of the queue length q, the window size W, the state variable x_2, and the ratio of packets marked as dropping in the queue (control input) under the proposed control, the SDM, and the ISDM control methods. It is worth noting that the queue length of the developed control converges to the desired queue while the SDM method does not approach the desired queue and the ISDM control method oscillates around the desired queue instead. Furthermore, time responses of the SDM and ISDM techniques exhibit the undesirable chattering behavior as a result of the sign function used in equations (15)-(16), whereas the designed method does not.

From these figure 2-5, it is evident that the developed control offers significantly fast suppression of oscillation, shorter settling time, and smaller rise time as compared with both the SDM and the ISDM. Therefore, it can enhance transient performances. Further, it is straightforward to conclude that the performance of the presented backstepping-like control is superior to that the SDM and the ISDM control methods.

5. Conclusions

A nonlinear stabilizing feedback control law has been proposed via a backstepping-like strategy. The design procedure is simple but effective. Improved dynamic performances such as smaller overshoot, smaller rise time, and shorter settling time have been achieved with the help of the developed control method. The controller design procedure has shown that the proposed scheme is rather easier compared with both the ISDM control and the SDM one because it is not necessary to select the sliding surfaces. The presented control law also offers satisfactory transient performances and outperforms the rest of controllers. Moreover, the simulations exhibit the effectiveness and superiority of the developed controller over both the ISDM control and the SDM one in terms of dynamic (transient) performances. In the future study, this approach can be extended to the TCP/AQM network model including unknown parameters.

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