International Journal of Innovative Computing, Information and Control
Volume 19, Number 1, February 2023

ICIC International ©2023 ISSN 1349-4198
pp. 73–86

DYNAMIC SURFACE ASYMPTOTIC CONGESTION TRACKING CONTROL FOR TCP/AQM SYSTEMS

Somchai Poonyanirun* and Adirak Kanchanaharuthai

Department of Electrical Engineering
College of Engineering
Rangsit University
52/347 Muang-Ake, Phaholyothin Road, Lak-Hok, Muang, Patumthani 12000, Thailand
adirak@rsu.ac.th
*Corresponding author: somchai.po@rsu.ac.th

Received June 2022; revised September 2022

Abstract. *To deal with the Active Queue Management (AQM) problem, this paper aims to develop a dynamic surface asymptotic control technique for a Transmission Control Protocol (TCP) network. The designed control law for a TCP/AQM nonlinear model can be utilized to handle the congestion tracking problem based on this technique. A nonlinear stabilizing feedback congestion controller is also proposed, which uses the dynamic surface asymptotic control scheme to ensure that the queue length can track the reference queue length and that the window size is stable. In the MATLAB environment, the developed control design is validated. The simulation results are used to verify the effectiveness of the suggested control, which is then compared to a backstepping-like controller and an integral sliding mode controller. Additionally, they show that the proposed technique can handle the desired congestion tracking control problem while also improving transient performance.*
Keywords: Congestion control, Dynamic surface asymptotic control scheme, TCP/AQM network

1. **Introduction.** The Internet is currently experiencing rapid growth, posing an unavoidable network congestion management difficulty in network traffic. It may also result in network collapse, lock-out behavior, and an increase in the likelihood of control-loop synchronization. Consequently, numerous efforts are being made to remedy this issue. Recent years have witnessed a continuous rise in interest in network congestion control. Fortunately, there is a substantial and promising technology known as the Active Queue Management (AQM) system. It has been proposed to reduce packet losses, provide best-effort service with low packet drops, and increase network utilization. Following that, there are multiple AQM approaches with various design concepts. Random Early Detection (RED) was the first AQM approach proposed [1].

The key benefit of this method is that the average queue length may be used to calculate the probability of packet loss. Following that, a variety of methodologies [2-11] based on an analytical fluid-flow model were investigated for TCP/AQM systems to address network congestion issues. To achieve queue length stability and deal with robustness against external disturbances and model perturbation, an LMI-based controller design [2] was proposed, which used a combination of robust active queue management and control. To reduce packet losses and increase network utilization with input saturation, Mohammadi et al. [3] presented a fuzzy-based PID controller of the AQM network for Internet routers. A nonlinear model prediction congestion management strategy [4] was developed

DOI: 10.24507/ijicic.19.01.73

for networks to cope with the negative impacts of nonlinear disturbance uncertainty, time-varying delays, and input constraints using the Lynpunov-Krasovskii functional. Li et al. [5] presented an adaptive backstepping congestion controller for TCP networks with User Datagram Protocol (UDP) flows based on the minimax method. It is important to compute the minimax UDP flow due to unknown UDP flows that are viewed as external disturbances. A nonlinear AQM controller [6] for TCP networks was published based on a combination of integral backstepping design and a minimax method to handle the undesired effects of UDP flow interruptions. Using a combination of integral backstepping and $\mathcal{H}_\infty$ design, a nonlinear congestion tracking control approach [7] for the TCP/AQM network model was created. However, even if external disturbances and modeling uncertainties were incorporated into the network model, the obtained controller could still guarantee adequate tracking performance of the queue, and all closed-loop system signals are asymptotically stable. Wang et al. [8] presented an adaptive fuzzy funnel congestion management strategy for the TCP/AQM network to reduce congestion tracking errors in order to ensure the desired transient and steady state performance. A backstepping sliding mode design was developed for nonlinear TCP network congestion systems, including unknown parameters and external disturbances, using the minimax from game theory [9]. Using a coordination of practically finite-time theory and a specified performance control, an adaptive neural congestion control [10] was proposed for TCP/AQM networks to ensure that the queue length follows the reference queue length in finite time. For the TCP/AQM network, a sliding mode controller [11] was created to deal with parameter noise and variation. Recently, a backstepping-like method [12] was proposed to handle the congestion tracking problem for the TCP/AQAM nonlinear model and ensure that queue length can track the reference queue length. Even through these methods [2-11] are effective, there were important disadvantages in the control strategies above. In [2], the control law was based on the linearization techniques around the operating point. Mohammadi et al. [3] proposed the fuzzy-based PID control scheme which relied on tuning parameter process and focused on around an operating point. Even though the nonlinear model predictive controller [4] was able to address many problems in congestion management, it was difficult to suitably choose the weighting matrix of the state and the control input, resulting in trade-off issues. In [5-10, 12], the design of the nonlinear control system was based on backstepping and backstepping-like techniques. In each design step, the approaches must determine the time-derivative of virtual control functions, resulting in complexity issues. For [11], the sliding mode design can eliminate the problems of parameter noises and variations, as well as control input chattering issues.

According to the aforementioned research, all nonlinear controller design strategies are quite difficult and complex. This research therefore follows this line of investigation but provides an advanced nonlinear controller design to tackle the congestion tracking control problem for the TCP/AQM network model. A dynamic surface asymptotic control approach [13] is used to design the controller in this paper. The dynamic surface asymptotic control method's control goal is to find a stabilizing feedback controller. The obtained controller in this research can deal with the "explosion of complexity" problem that arises in backstepping and backstepping-like controllers. Furthermore, the presented control outperforms traditional dynamic surface control because it can achieve bounded-error trajectory tracking with asymptotic tracking with zero error, whereas traditional dynamic surface control cannot.

As the above discussion, the followings are the main contributions of this work: (i) A dynamic surface asymptotic control technique is proposed to tackle the congestion tracking control problem for TCP/AQM networks, which has yet to be investigated, using a nonlinear TCP/AQM dynamic model; (ii) With the help of Lyapunov theory, the closed-loop system's signals are all bounded, and the semi-global asymptotic tracking is achieved; (iii) The developed design technique is not complicated but effective when compared to backstepping-like and integral sliding mode controllers. In addition, the suggested controller shows superior dynamic performance, such as less overshoot and faster oscillation reduction.

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 dynamic surface asymptotic 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. **TCP/AQM System Model.** A dynamic model used in this paper depends on the fluid model of TCP congestion-avoidance method reported in [14, 15]. In accordance with the result reported in [16, 17], a nonlinear TCP/AQM model can be expressed as

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

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

Remark 2.1. *The possible application of the TCP/AQM system model considered in (1) can be extended to a nonlinear wireless TCP/AQM model* [18]*, which can be expressed as*

$$\begin{cases} \dot{W}(t) = \dfrac{1}{R(t)}(1-p_{dl}(t)) - (1-p_{dl}(t))\dfrac{W(t)}{2}\dfrac{W(t-R(t))}{R(t-R(t))}p(t-R(t)) \\ \qquad\qquad - p_{dl}(t)(W(t)-1)\dfrac{W(t-R(t))}{R(t-R(t))}p(t) \\ \dot{q}(t) = \dfrac{NW(t)}{R(t)}(1-p_{ul}(t)) - C(t) \end{cases} \tag{2}$$

with $R(t) = T_p + \frac{q(t)}{C(t)}$, where $p_{dl} \in [0,1]$ is the downlink packet loss while $p_{ul} \in [0,1]$ is the uplink packet loss. It can be observed that the major difference between wireless TCP/AQM system in (2) and the TCP/AQM system models considered in this work is the uplink and downlink packet losses together with a neglected system delay. Thus, when both such losses ($p_{ul} = p_{dl} = 0$) disappear, the TCP/AQM model in (2) will become the TCP/AQM system model used in this work.

In order to simplify the state-space equation of the system (1), let us introduce the following state variables: $x_1 = q - q_r$, $x_2 = -C + \frac{NW}{R}$. Additionally, to ensure 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 $x_0 = \int_0^t (q(\tau) - q_r)d\tau$. Therefore, we have the vector of the state variables used in this design procedure as $x = [x_0, x_1, x_2]^T = \left[\int_0^t (q(\tau) - q_r)d\tau, q - q_r, -C + \frac{NW}{R}\right]^T$. After differentiating the state variables above, the dynamic model of the nonlinear TCP/AQM dynamic model can be expressed as an affine nonlinear system as follows:

$$\dot{x} = f(x) + g(x)u(x) \tag{3}$$

with

$$f(x) = \begin{bmatrix} f_0(x_0) \\ f_1(x_0, x_1) \\ f_2(x_0, x_1, x_2) \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ \dfrac{N}{R^2} \end{bmatrix}, \quad x = \begin{bmatrix} x_0 \\ x_1 \\ x_2 \end{bmatrix}$$

$$g(x) = \begin{bmatrix} 0 \\ 0 \\ g_2(x) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -\left(\dfrac{N}{R^2} + \dfrac{(x_2 + C)^2}{2N}\right) \end{bmatrix}, \quad u(x) = p(t) \tag{4}$$

Additionally, the region of operation is defined in the set $\mathcal{D} = \{x \in \mathbb{R} \times \mathbb{R} \times \mathbb{R}\}$. The open loop operating equilibrium is denoted by $x_e = [x_{0e},\ x_{1e},\ x_{2e}]^T = [0,\ 0,\ 0]^T$.

Problem statement: The objective of this paper is to design a nonlinear controller p capable of solving the queue tracking problem for congestion control scheme with the help of dynamic surface asymptotic control method. The developed controller satisfies the following desired requirements: (i) the queue length q is able to track the desired queue length q_r; (ii) the window size W is stable and bounded; (iii) the ratio of packets marked as dropping in the queue is as small as possible; (iv) the overall closed-loop system is asymptotically stable at the only equilibrium x_e and all the resulting closed-loop signals are bounded.

The following assumption and lemmas are established in order to satisfy these required objectives above.

Assumption 2.1. *All state variables $x_0, x_1, x_2 \in \mathbb{R}$, are assumed to be measurable.*

Lemma 2.1. [16] *If the constants $p > 1$ and $q > 1$ are such that $(p-1)(q-1) = 1$, then for all $\epsilon > 0$ and all $(x, y) \in \mathbb{R}^2$ we have*

$$xy \leq \frac{\epsilon^p}{p}|x|^p + \frac{1}{q\epsilon^q}|y|^q \tag{5}$$

If choosing $p = q = 2$ and $\epsilon^2 = 2\kappa$, the inequality above becomes

$$xy \leq \kappa x^2 + \frac{1}{4\kappa}y^2 \tag{6}$$

For simplicity, provided that $\kappa = \frac{1}{2}$, it is straightforward to obtain the following inequality

$$xy \leq \frac{x^2}{2} + \frac{y^2}{2} \tag{7}$$

Lemma 2.2. [17] *The following inequality holds for any $\epsilon > 0$ and for any $z \in \mathbb{R}$*

$$0 \leq |z| - \frac{z^2}{\sqrt{z^2 + \epsilon^2}} < \epsilon \tag{8}$$

For the developed design procedure in the next section, the dynamic surface asymptotic control design will be developed to obtain a feedback stabilizing nonlinear control. In the following section, the developed control is designed step by step to achieve the desired performances.

3. **Nonlinear Control Design.** In this section, the control law for congestion tracking control scheme is developed. The main control development can be achieved in the following two subsections. The first subsection is a presentation of dynamic surface asymptotic control scheme used in this paper. The second subsection is to focus on the stability analysis of the overall closed-loop system.

3.1. **Dynamic surface asymptotic control design.** The proposed control procedure is developed step by step as follows.

Step 1: First, let us define the first error surface $S_0 = x_0$, and the time derivative of S_0 is defined as

$$\dot{S}_0 = \dot{x}_0 = x_1 \tag{9}$$

then a Lyapunov function candidate is chosen as

$$V_0 = \frac{1}{2}S_0^2 \tag{10}$$

Then the time derivative of V_0 along the first subsystem in (3) and (4) becomes

$$\dot{V}_0 = S_0\dot{S}_0 = S_0(x_1 - x_{1d} + x_{1d} - \alpha_0 + \alpha_0) = S_0(S_1 + e_1 + \alpha_0) \tag{11}$$

where $S_1 = x_1 - x_{1d}$ denotes the error surface and $e_1 = x_{1d} - \alpha_0$ is the boundary layer error. In addition, let us introduce a state variable x_{1d} and let α_0 pass through a first-order filter with time constant τ_1 to obtain x_{1d}

$$\begin{cases} \tau_1\dot{x}_{1d} + x_{1d} = \alpha_0 - \dfrac{\tau_1\hat{M}_1^2 e_1}{\sqrt{\left(\hat{M}_1 e_1\right)^2 + \sigma^2(t)}} - \tau_1 S_0, \quad x_{1d}(0) = \alpha_0(0) \\ \dot{x}_{1d} = -\dfrac{e_1}{\tau_2} - \dfrac{\hat{M}_1^2 e_1}{\sqrt{\left(\hat{M}_1 e_1\right)^2 + \sigma^2(t)}} - S_0 \end{cases} \tag{12}$$

where $\hat{M}_1$ denotes the estimation of M_1, which will be mentioned in the next subsection. Additionally, $\sigma(t)$ is any positive uniform continuous and bounded function satisfying two conditions:

$$\lim_{t\to+\infty}\int_0^t \sigma(\tau)d\tau \le \sigma_1 < +\infty, \quad |\dot{\sigma}(t)| \le \sigma_2 < +\infty \tag{13}$$

where σ_1 and σ_2 denote any positive constants.

We assume that α_0 is a virtual control variable corresponding to the first subsystem of (3) to drive S_0 to zero

$$\alpha_0 = -c_0 S_0 \tag{14}$$

where c_0 is a positive design constant.

Step 2: Let us consider the second surface as follows:

$$S_1 = x_1 - x_{1d} \tag{15}$$

We choose the Lyapunov function candidate as

$$V_1 = \frac{1}{2}S_1^2 \tag{16}$$

By calculating the derivative of (16), we have

$$\dot{V}_1 = S_1\dot{S}_1 = S_1(x_2 - x_{2d} + x_{2d} - \alpha_1 + \alpha_1) = S_1(S_2 + e_2 + \alpha_1) \tag{17}$$

where $S_2 = x_2 - x_{2d}$ denotes the error surface and $e_2 = x_{2d} - \alpha_1$ is the boundary layer error. $\hat{M}_2$ denotes the estimation of M_2, which will be mentioned in the next subsection. Once again, let us consider a state variable x_{2d}; therefore, we pass α_1 through the first-order filter, with time constants τ_2 to obtain x_{2d}.

$$\begin{cases} \tau_2 \dot{x}_{2d} + x_{2d} = \alpha_1 - \dfrac{\tau_1 \hat{M}_2^2 e_2}{\sqrt{\left(\hat{M}_2 e_2\right)^2 + \sigma^2(t)}} - \tau_2 S_1, \quad x_{2d}(0) = \alpha_1(0) \\ \dot{x}_{2d} = -\dfrac{e_2}{\tau_2} - \dfrac{\hat{M}_2^2 e_2}{\sqrt{\left(\hat{M}_2 e_2\right)^2 + \sigma^2(t)}} - S_1 \end{cases} \tag{18}$$

where $\hat{M}_2$ denotes the estimation of M_2, which will be mentioned in the next subsection.

We choose the virtual control variable α_1 to drive $S_1 \to 0$ as follows:

$$\alpha_1 = -c_1 S_1 + \dot{x}_{1d} = -c_1 S_1 - \frac{e_1}{\tau_2} - \frac{\hat{M}_1^2 e_1}{\sqrt{\left(\hat{M}_1 e_1\right)^2 + \sigma^2(t)}} - S_0 \tag{19}$$

where c_1 is a positive constant.

Step 3: Let us define the third surface error to be

$$S_2 = x_2 - x_{2d} \tag{20}$$

Then, the Lyapunov function candidate is chosen as

$$V_2 = \frac{1}{2} S_2^2 \tag{21}$$

Then the time derivative of V_2 along the system trajectories turns into the following:

$$\dot{V}_2 = S_2 \left(\dot{x}_2 - \dot{x}_{2d}\right) = S_2 \left(f_2(x_0, x_1, x_2) + g_2(x_0, x_1, x_2) u - \dot{x}_{2d}\right) \tag{22}$$

Thus, a suitable control law u is selected as follows:

$$\begin{aligned} u &= \frac{1}{g_2(x)} \left(-c_2 S_2 - f_2(x_0, x_1, x_2) + \dot{x}_{2d}\right) \\ &= \frac{1}{g_2(x)} \left(-c_2 S_2 - f_2(x_0, x_1, x_2) - \frac{e_2}{\tau_2} - \frac{\hat{M}_2^2 e_2}{\sqrt{\left(\hat{M}_2 e_2\right)^2 + \sigma^2(t)}} - S_1\right) \end{aligned} \tag{23}$$

where c_2 is a positive design parameter.

3.2. **Stability analysis.** In this subsection, the stability analysis for the presented scheme is investigated. The objective of this part is to indicate that all signals of the closed-loop system are semi-globally bounded. First, consider the time derivative of the surface errors S_i and the boundary layer errors e_k as follows:

$$\begin{cases} \dot{S}_0 = -c_0 S_0 + S_1 + e_1 \\ \dot{S}_1 = -c_1 S_1 + S_2 + e_2 \\ \dot{S}_2 = -c_3 S_3 \\ \dot{e}_1 = -\dfrac{e_1}{\tau_1} - \frac{\hat{M}_1^2 e_1}{\sqrt{\left(\hat{M}_1 e_1\right)^2 + \sigma^2(t)}} - S_0 + B_1(S_0) \\ \dot{e}_2 = -\dfrac{e_2}{\tau_2} - \frac{\hat{M}_2^2 e_2}{\sqrt{\left(\hat{M}_2 e_2\right)^2 + \sigma^2(t)}} - S_1 + B_2\left(S_0, S_1, e_1, \hat{M}_1, \sigma(t), \dot{\sigma}(t)\right) \end{cases} \tag{24}$$

where $B_1(\cdot)$ and $B_2(\cdot)$ are continuous functions defined as follows:

$$\begin{cases} B_1(\cdot) = -\dot{\alpha}_0 = -\dfrac{\partial \alpha_0}{\partial x_0}\dot{x}_0 \\ B_2(\cdot) = -\dot{\alpha}_1 = -\dfrac{\partial \alpha_1}{\partial x_0}\dot{x}_0 - \dfrac{\partial \alpha_1}{\partial x_1}\dot{x}_1 - \dfrac{\partial \alpha_1}{\partial \hat{M}_1}\dot{\hat{M}}_1 - \dfrac{\partial \alpha_1}{\partial e_1}\dot{e}_1 - \dfrac{\partial \alpha_1}{\partial \sigma(t)}\dot{\sigma}(t) \end{cases} \tag{25}$$

Therefore, the main result of this work can be summarized in the following theorem.

Theorem 3.1. *Under Assumption 2.1, we consider the closed-loop dynamics consisting of the TCP/AQM dynamic model (3) and (4), the control law (23), and linear filters (12) and (18). If there exists a set of suitable design parameters* c_i, τ_k ($i = 0, 1, 2,\ k = 1, 2$) *satisfying*

$$\bar{c}_1 = c_1 - 0.5 > 0, \quad \bar{c}_2 = c_2 - 1 > 0, \quad \bar{c}_3 = c_3 - 0.5 > 0, \quad \bar{c}_k = \frac{1}{\tau_k} > 0 \tag{26}$$

such that all trajectories of the overall closed-loop dynamics are semi-globally bounded and the tracking error $q - q_r$ *settles to zero asymptotically.*

Proof: Let us define the following compact set: $\Omega = \{V(t) \le p\}$ and $\sigma(t)$ and $\dot{\sigma}(t)$ are bounded. Additionally, there exist positive constants M_k such that $|B_k(\cdot)| \le M_k$ on Ω. It is observed from (25) that the explicit values of M_k are unknown, which can be estimated by $\hat{M}_k$, $k = 1, 2$.

Let us define the Lynapunov function as

$$V = \frac{1}{2}\left(\sum_{i=0}^{2} S_i^2 + \sum_{k=1}^{2}\left(e_k^2 + \frac{\tilde{M}_k^2}{\beta_k}\right)\right) \tag{27}$$

where $\tilde{M}_k = M_k - \hat{M}_k$.

The time derivative of V along trajectories (24) is as follows:

$$\begin{aligned} \dot{V} &= \sum_{i=0}^{2} S_i\dot{S}_i + \sum_{k=1}^{2}\left(e_k\dot{e}_k - \frac{\tilde{M}_k\dot{\hat{M}}_k}{\beta_k}\right) \\ &= S_0(-c_0S_0 + S_1 + e_1) + S_1(-c_1S_1 + S_2 + e_2) - c_2S_2^2 \\ &\quad + e_1\left(-\frac{e_1}{\tau_1} - \frac{\tau_1\hat{M}_1^2e_1}{\sqrt{\left(\hat{M}_1e_1\right)^2 + \sigma^2(t)}} - S_0 + B_1(S_0)\right) - \frac{\tilde{M}_1\dot{\hat{M}}_1}{\beta_1} - \frac{\tilde{M}_2\dot{\hat{M}}_2}{\beta_2} \\ &\quad + e_2\left(-\frac{e_2}{\tau_2} - \frac{\tau_2\hat{M}_2^2e_2}{\sqrt{\left(\hat{M}_2e_2\right)^2 + \sigma^2(t)}} - S_1 + B_1\left(S_0, S_1, e_1, \hat{M}_1, \sigma(t), \dot{\sigma}(t)\right)\right) \end{aligned} \tag{28}$$

For $i = 0, 1, 2$, $k = 1, 2$ and $p > 0$, the set $\Omega := \sum_{i=0}^{2} V_i + \sum_{k=1}^{2}\frac{1}{2}\left(e_k^2 + \frac{\tilde{M}_k^2}{\beta_k}\right) \le p$ is the compact set. According to the property of continuous function, we know that $B_k(\cdot)$ has a bound on Ω, such that $|B_k(\cdot)| \le M_k$, $k = 1, 2$. Based on Lemma 2.1, we have the following inequalities:

$$S_0S_1 \le \frac{S_0^2}{2} + \frac{S_1^2}{2}, \quad S_1S_2 \le \frac{S_1^2}{2} + \frac{S_2^2}{2} \tag{29}$$

From the inequalities above, one has

$$\dot{V} \le -(c_0 - 0.5)S_0^2 - (c_1 - 1)S_1^2 - (c_2 - 0.5)S_2^2 - \sum_{k=1}^{2}\left[\frac{e_k^2}{\tau_k} - \frac{\hat{M}_k^2 e_k^2}{\sqrt{\left(\hat{M}_k e_k\right)^2 + \sigma^2(t)}} + M_k|e_k| - \frac{\tilde{M}_k\dot{\hat{M}}_k}{\beta_k}\right] \tag{30}$$

According to Lemma 2.2, it is straightforward to compute

$$M_k|e_k| = \hat{M}_k|e_k| + \tilde{M}_k|e_k| \le \frac{\hat{M}_k^2 e_k^2}{\sqrt{\left(\hat{M}_k e_k\right)^2 + \sigma^2(t)}} + \sigma(t) + \tilde{M}_k|e_k| \tag{31}$$

Subsequently, one obtains

$$\dot{V} \le -\sum_{i=0}^{2}\bar{c}_i S_i^2 - \sum_{k=1}^{2}\frac{e_k^2}{\tau_k} - \sum_{k=1}^{2}\frac{1}{\beta_k}\tilde{M}_k\left(\dot{\hat{M}}_k - \beta_k|e_k|\right) + 2\sigma(t) \tag{32}$$

After designing the update laws for $\hat{M}_k$ as $\dot{\hat{M}}_k = \beta_k|e_k|$, we get

$$\dot{V} \le -\sum_{i=0}^{2}\bar{c}_i S_i^2 - \sum_{k=1}^{2}\frac{e_k^2}{\tau_k} + 2\sigma(t) \tag{33}$$

By integrating the expression above over $[0, t]$, we have

$$\begin{aligned} V(t) &\le V(0) - \int_0^t\left(\sum_{i=0}^{2}\bar{c}_i S_i^2 + \sum_{k=1}^{2}\frac{e_k^2}{\tau_k}\right) + 2\int_0^t \sigma(\tau)d\tau \\ &\le V(0) + 2\sigma_1 \end{aligned} \tag{34}$$

From (34), it implies that S_i, e_k and $\hat{M}_k$ are bounded. This means that by definition x_i, α_i, and u are all bounded. This completes the proof.

Remark 3.1. *From the presented design, the following are the primary differences between the proposed control design and the literature: (i) the proposed scheme is directly derived from nonlinear control theory regardless of the system operating points, (ii) the control law given here can address the explosion of complexity issues that arise in backstepping and backstepping-like methods, and (iii) the developed control is designed step by step, while the sliding mode is determined by selecting the appropriate sliding surface.*

Remark 3.2. *Theorem 3.1 is significant since under Assumption 2.1, it provides a conclusion on how to construct the proposed control law to ensure that all signals in the overall closed-loop dynamics are semi-globally bounded and that the tracking errors x_0, x_1 and x_2 are zero. Theorem 3.1 can be implemented directly by utilizing a set of appropriate design parameters c_i and τ_k $(i = 0, 1, 2,\ k = 1, 2)$ that satisfy Equation (26) in the revised manuscript. The open source network simulator (NS-3) may, however, be used to practically apply Theorem 3.1, which will be taken into consideration in the future.*

4. **Simulation Results.** In this section, the effectiveness of the proposed controller is evaluated and verified in MATLAB environment under the following parameters of the networks.

$$C = 1750 \text{ packets/s}, \quad T_p = 0.1 \text{ s}, \quad q_r = 100 \text{ packets}$$

The tuning parameters of the proposed controller are $\beta_1 = \beta_2 = 20$, $\tau_1 = \tau_2 = 0.01$, $c_0 = c_1 = c_2 = 10$ and $\sigma(t) = 0.1e^{-0.1t}$. The initial parameters used in the simulations are $q_0 = 99$, $W_0 = 4$, $x_0 = 1$.

The time domain simulations are carried out via MATLAB environment. To investigate the system dynamic performance of the designed controller, as given in (23), in the system under study, the performance of the proposed controller is compared with that of the following controllers:

- Backstepping-Like Controller (BSLC) [12]

$$u = p = -\frac{1}{g_2(x_0, x_1, x_2)}\left[\frac{c_2 Q + P + x_1 + c_1 x_2 + c_1 \dot{P} + \dot{f}_1(x_0, x_1) + \dot{g}_1(x_0, x_1) x_2}{g_1(x_0, x_1)} + f_2(x_0, x_1, x_2)\right] \tag{35}$$

where

$$P = c_0 x_0 + x_1, \quad \dot{P} = c_0 x_1 + x_2, \quad Q = x_0 + c_0 x_1 + c_1 P + f_1(x_0, x_1) + g_1(x_0, x_1) x_2.$$

The controller parameters of the backstepping-like control law are chosen as follows: $c_i = 0.5$, $i = 0, 1, 2$.

- Integral Sliding Mode controller (ISDM)

$$u = p = -\frac{(K\text{sign}(S) + c_2(f_1(x_0, x_1) + g_1(x_0, x_1)x_2) + c_2 f_2(x_0, x_1, x_2))}{c_2 g_2(x_0, x_1, x_2)} \tag{36}$$

where $S(x) = c_1 x_1 + c_2 x_2$. The controller parameters of the integral sliding mode control law are chosen as follows: $c_1 = 2$, $c_2 = 1$.

Based on the following issues, the simulation results are used to demonstrate the usefulness of the designed method: The tracking error between the queue length and the target queue length approaches zero; the window size is bounded, and the queue's packet loss ratio must be low and lies in the interval $[0, 1]$.

Below are the simulation findings, which are presented and discussed. Figures 1 and 2 illustrate time histories of the integral of error between queue length and desired queue length x_0, the queue length q, the window size W, the state variable x_2, and the packet loss ratio p, the surface errors S_0, S_1 and S_2, and the adaptive parameters $\hat{M}_1$ and $\hat{M}_2$ using the proposed technique. Figure 3 shows time histories of the integral of error between queue length and desired queue length x_0, the queue length q, the window size W, the state variable x_2, and the packet loss ratio p under the BSLC design. Figure 4 shows time responses of the integral of error between queue length and desired queue length x_0, the queue length q, the window size W, the state variable x_2, the packet loss ratio p, and the sliding surface $S(x)$ under the ISDM design.

From these figures, it is clear that the provided control law improves dynamic performance more than the other methods. It can be observed, for example, that the tracking error can fast converge to zero ($q \to q_r$) using the proposed method and the BSLC method except for the ISDM one. This indicates that the queue length follows the target queue length in a smooth manner. For the other time responses, also enhanced are dynamic (transient) performances, such as the reduction of oscillatory overshoot and the time it takes to rise and settle. It is observed from Figure 2 that the surface errors S_0, S_1 and S_2 settle down to zero while the adaptive parameters $\hat{M}_1$ and $\hat{M}_2$ eventually converge to unknown constant values. It is worth noting that, although the other controllers can meet the conditions outlined in the paper's objective, they have poor transient performance when compared to the proposed controller. It is seen from Figure 3 that even if

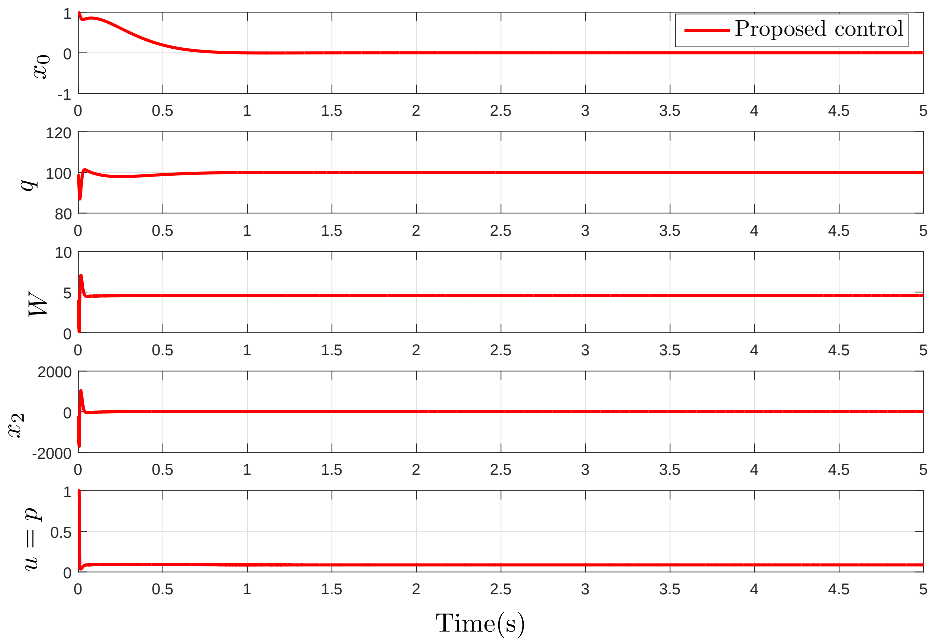


FIGURE 1. Controller performance – $x_0 = \int_0^t (q(\tau) - q_r)d\tau$, the queue length q, window size W, x_2, and packet loss ratio $(u = p)$ under the proposed controller

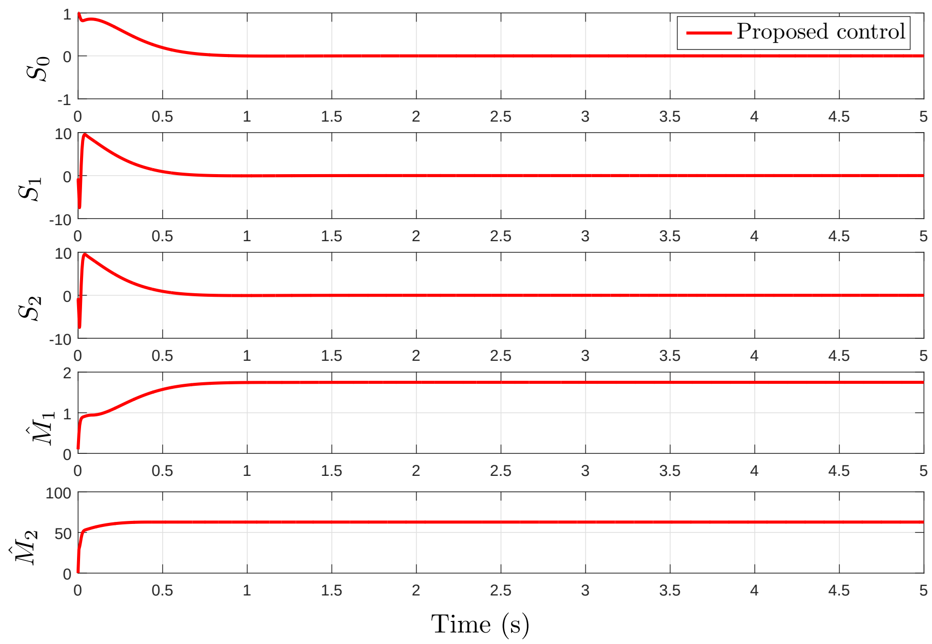


FIGURE 2. Controller performance – The surface errors S_0, S_1, S_2 and adaptive parameters $\hat{M}_1$ and $\hat{M}_2$ under the proposed controller

time responses of the BSLC scheme are faster than those of the ISDM one, they are slower than those of the proposed controller. Figure 4 shows that due to chattering effects, the tracking error between the queue length and the desired queue length cannot converge to zero. Aside from that, the ISDM method's sliding surface does not reach zero but oscillates around zero instead. This, however, is because of the undesired chattering effects

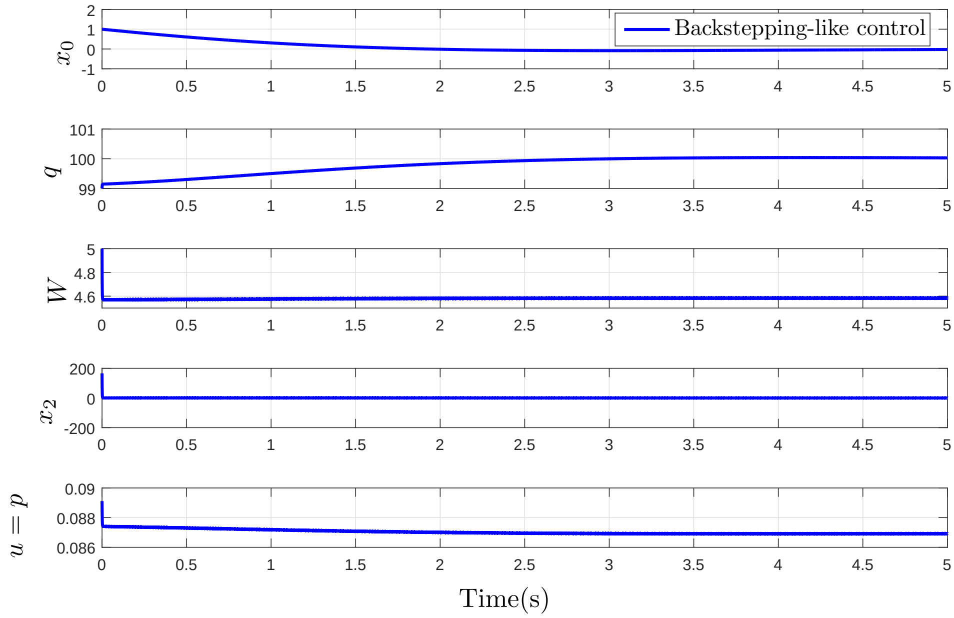


FIGURE 3. Controller performance – $x_0 = \int_0^t (q(\tau) - q_r)d\tau$, the queue length q, window size W, x_2, and packet loss ratio ($u = p$) under the backstepping-like controller

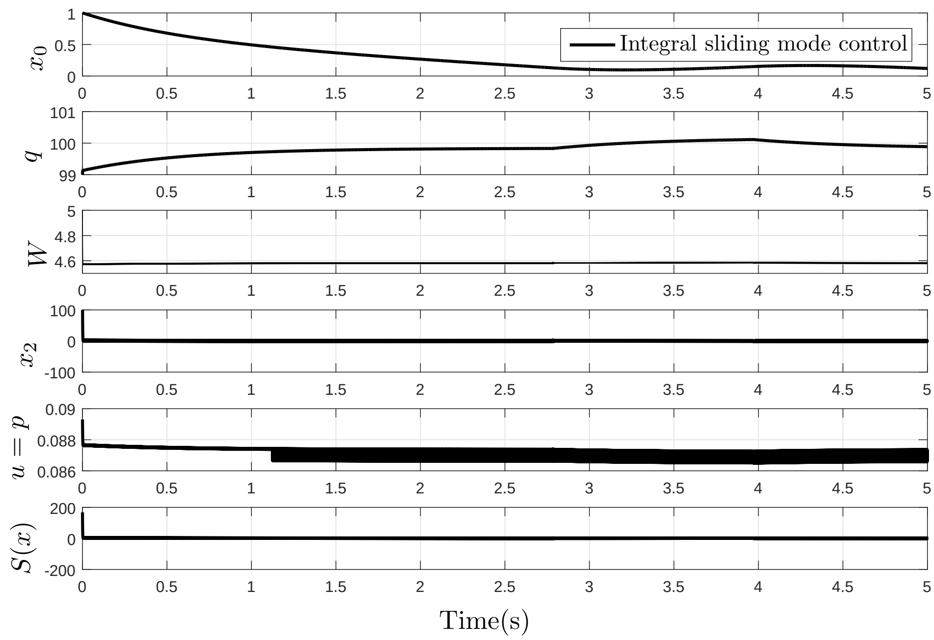


FIGURE 4. Controller performance – $x_0 = \int_0^t (q(\tau) - q_r)d\tau$, the queue length q, window size W, x_2, packet loss ratio ($u = p$) and the sliding surface $S(x)$ under the integral sliding mode controller

arising in the control input (packet loss ratio). Moreover, it can be seen from Figures 2-4 that under the proposed controller, the BSLC controller, the ISDM controller, the packet loss ratio $u = p(t)$ belongs to the interval $[0, 1]$, as required.

In practice, it is well-known that a perfect dynamic model of the system considered is unavailable. As a result, it needs to investigate the robustness of the proposed controller with system parameter variations. The system parameter variations need to be considered for robustness investigation of the developed controller. Especially, the parameter of the system can be uncertain, i.e., the link capacity C; moreover, it is difficult to find precisely this value. It is, therefore, necessary to assess the robustness of the resulting controller over this variation.

A robustness test has been carried out by introducing a changing of the parameter from its nominal value, i.e., the link capacity C. In particular, a $\pm 30\%$ of variation in the value of C is considered for this study. In comparison with the system responses under normal conditions, it can be seen in Figure 5 that in spite of the system parameter variation the proposed scheme can still give consistent control performance. In particular, the state variables x_0, x_1 and x_2 converge to zero, and the window size W and the packet loss ratio p are stable. Therefore, the developed controller is not sensitive to the parameter variation.

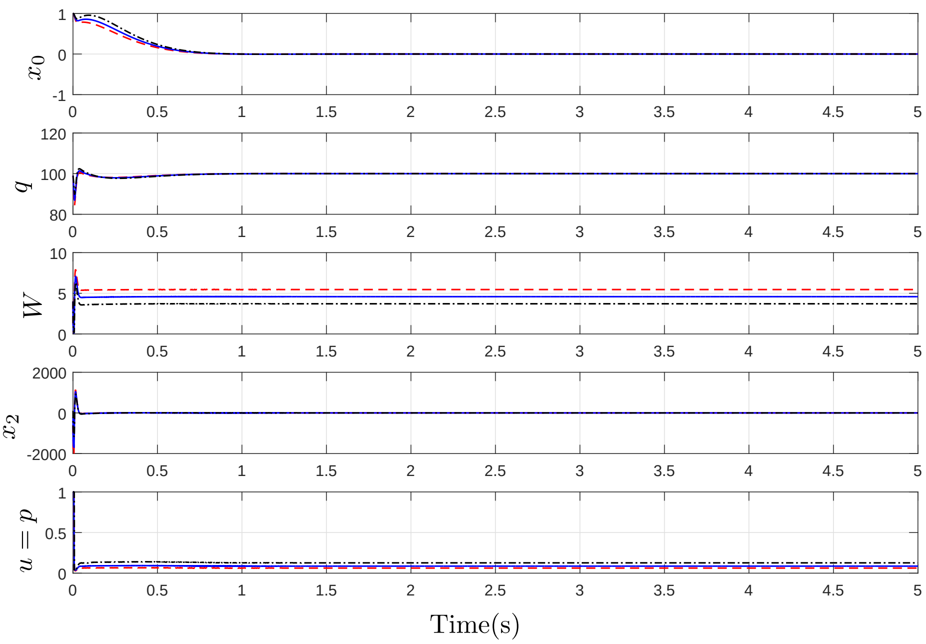


FIGURE 5. Controller performance – $x_0 = \int_0^t (q(\tau) - q_r) d\tau$, the queue length q, window size W, x_2, and packet loss ratio $(u = p)$ under parameter variation of the link capacity (Solid: nominal value, Dashed: $+30\%$, Dashdotted: -30%)

In summary, the simulation results show that the provided method outperforms the BSLC and the ISDM methods. It is evident that according to the desired requirements, it is evident that the queue length q rapidly tracks the desired queue length q_r and the window size W is stable with the suggested control strategy. Furthermore, the state variables x_0, x_1, and x_2 reach zero faster than the other controllers, and the packet loss ratio falls within the interval $[0, 1]$. Compared with the BSLC, the proposed design can deal with the explosion of complexity arising in both backstepping and backstepping-like methods. It can be observed that the developed controller is systematically designed while the integral sliding mode control depends on selecting the suitable sliding surface. It also has better dynamic properties, as evidenced by the quick dampening of oscillations across all time trajectories.

5. **Conclusion.** To solve the queue tracking problem for congestion tracking control, a nonlinear controller has been developed using the dynamic surface asymptotic control technique in this study. The simulation results indicate that the proposed control method performs well. It can also keep the window size and all closed-loop system trajectories stable and bounded, as well as make tracking errors between the queue and the reference queue lengths converge to zeros quickly. The presented design process performs better than the backstepping-like and the integral sliding mode methods in terms of transient control performance. Furthermore, the results show that the suggested controller is successful at alleviating the congestion tracking problem and enhancing transient performance in closed-loop system dynamics according to the desired objective. The extension of this approach to an adaptive control approach for TCP/AQM networks in the presence of unknown parameters and a model reference shape asymptotic tracking control [19] will be the focus of future research.

REFERENCES

[1] S. Floyd and V. Jacobson, Random early detection gateways for congestion avoidance, *IEEE/ACM Trans. Networking*, vol.1, no.4, pp.397-413, 1993.

[2] C. Zhou, J. He and Q. Chen, A robust active queue management scheme for network congestion, *Computer & Electrical Engineering*, vol.39, no.2, pp.285-294, 2013.

[3] S. Mohammadi, H. M. Pour, M. Jafari and A. Javadi, Fuzzy-based PID active queue manager for TCP/IP networks, *Proc. of the 10th International Conference on Information Science, Signal Processing and Their Applications (ISSPA2010)*, Kuala Lumpur, pp.434-439, 2010.

[4] C. Han, M. Li, Y. Jing, L. Lei, Z. Pang and D. Sun, Nonlinear model predictive congestion control for networks, *IFAC-PapersOnLine*, vol.50, no.1, pp.552-557, 2017.

[5] Z. H. Li, Y. Liu and Y.-W. Jing, Design of adaptive backstepping congestion controller for TCP networks with UDP flows based on minimax, *ISA Transactions*, vol.95, pp.27-34, 2019.

[6] Z. H. Li, Y. Liu and Y.-W. Jing, Acitve queue management algorithm for TCP networks with integral backstepping and minimax, *International Journal of Control, Automation and Systems*, vol.17, no.4, pp.1059-1066, 2019.

[7] Y. Liu, X. Liu, Y. Jing, Z. Zhang and X. Chen, Congestion tracking control for uncertain TCP/AQM network based on integral backstepping, *ISA Transactions*, vol.89, pp.131-138, 2019.

[8] K. Wang, Y. Liu, X. Liu, Y. Jing and S. Zhang, Adaptive fuzzy funnel congestion control for TCP/AQM network, *ISA Transactions*, vol.95, pp.11-17, 2019.

[9] K. Wang, Y. Jing and S. Zhang, Minimax controller design based on backstepping sliding mode for TCP network systems, *Proc. of 2017 29th Chinese Control and Decision Conference (CCDC)*, Chongqing, pp.764-768, 2017.

[10] Y. Liu, Y. Jing and X. Chen, Adaptive neural practically finite-time congestion control for TCP/AQM network, *Neurocomputing*, vol.351, pp.26-32, 2019.

[11] M. Jalili-Kharaajoo, Sliding mode queue management in TCP/AQM networks, *Proc. of International Conference on Telecommunication (ICT2004)*, pp.638-643, 2004.

[12] K. Wongsurith, A. Kanchanaharuthai, S. Poonyanirun and P. Ngamsom, A backstepping-like congestion tracking control for TCP/AQM systems, *Kasem Bundit Engineering Journal*, vol.12, pp.18-33, 2022.

[13] Y.-H. Liu, Adaptive dynamic surface asymptotic tracking for a class of uncertain nonlinear systems, *International Journal of Robust, Nonlinear and Control*, vol.28, pp.1-13, 2017.

[14] V. Misra, W. B. Gong and D. Towsely, Fluid-based analysis of a network of AQM routers supporting TCP flows with an application to RED, *Proc. of ACM/SIGCOMM*, pp.151-160, 2000.

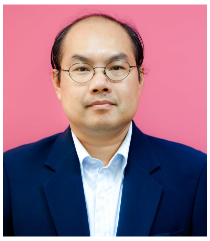
[15] C. V. Hollot, V. Misra, D. Towsley and W. B. Gong, Analysis and design of controllers for AQM routers supporting TCP flows, *IEEE Trans. Automation Control*, vol.47, pp.945-959, 2002.

[16] M. Krstic, I. Kanellakopoulos and P. Kokotivic, *Nonlinear and Adaptive Control Design*, John Wiley & Sons, New York, 1995.

[17] Z. Zuo and C. Wang, Adaptive trajectory tracking control of output constrained multi-rotors systems, *IET Control Theory Applications*, vol.8, pp.1163-1174, 2014.
[18] S. Poonyanirun and A. Kanchanaharuthai, Congestion tracking control for wireless TCP/AQM network via immersion and invariance, *Asian Journal of Control*, 2022.
[19] W. Chen, Y. Wang and X. Tang, Model reference shape asymptotic tracking control for linear systems, *ICIC Express Letters*, vol.14, no.11, pp.1049-1058, 2020.

Author Biography

Somchai Poonyanirun received B.Eng. degree in Telecommunication Engineering from King Mongkut's Institute of Technology Ladkrabang, Thailand, M.Eng. degree in Electrical Engineering from Chulalongkorn University in 1995 and 1998, respectively. Currently, he is a lecturer at the Department of Electrical Engineering at Rangsit University, Thailand. His research interests include communication system and control together with congestion tracking control for TCP/AQM network systems.



Adirak Kanchanaharuthai received the B.Eng. degree in Control Engineering from King Mongkut's Institute of Technology Ladkrabang, Thailand, the M.Eng. degree in Electrical Engineering from Chulalongkorn University, Thailand, and the Ph.D. degree in Systems and Control Engineering from Case Western Reserve University, Cleveland, OH, USA, in 1995, 1997, and 2012, respectively. Currently, he is an Associate Professor at the Department of Electrical Engineering at Rangsit University, Thailand. His main research interests include power system dynamics, stability and control, renewable energy systems, energy storage systems, and applications of nonlinear control theory to power systems, flexible alternating current transmission systems (FACTS) devices, and congestion tracking control for TCP/AQM network systems.