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Research article

Congestion tracking control for uncertain TCP/AQM network based on integral backstepping ☆

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ABSTRACT

An H_∞ congestion tracking control problem for nonlinear transmission control protocol/active queue management (TCP/AQM) network is proposed in this paper. Inspired by the existing network models, a modified TCP/AQM network model with external disturbance and modelling uncertainty is first introduced. And then, a novel function for the desired queue length is defined for the first time, which can simulate the changes in the queue length during a day. Next, a novel AQM scheme is presented to control network congestion by combining H_∞ theory and integral backstepping technique. The proposed method guarantees that the better tracking performance of the queue is achieved, and all the signals are asymptotically stable in the closed-loop system in probability. Finally, the effectiveness of the presented algorithm is tested by simulation results.

1. Introduction

Nowadays, communication networks play an important *role* in contemporary society, however, the traffic congestion has become a main problem in current network control. During the past three decades, the attention on network congestion control has been increasing [1–3], and a major method is called active queue management (AQM) algorithm. Among them, an earliest AQM method, called random early detection (RED), was proposed by [4]. Afterwards, a great deal of the modified algorithms were presented based on RED [5–7]. But, in order to obtain the proper performance, the choice of the design parameters became a main problem in [8]. Fortunately, Misra et al. [9] provided an analytical model for TCP/AQM by using the stochastic differential equation and fluid-flow theory in 2000. After that, several congestion schemes were designed based on control theory, such as P and PI [10], PD [11], PID [12]. Due to the disadvantages and limitations of these controllers, a fuzzy proportional integral (FPI) controller was adopted in [13], and its parameters can be adjusted by employing the genetic algorithm. In [14], a new technique, called straightforward AQM (SFAQM), was developed, which had only three relatively insensitive parameters and was easy to implement. A state feedback controller was proposed in [15] where the control parameters can be flexibly chosen.

In order to handle uncertainties in the TCP/AQM network, some advanced control approaches were adopted. [16–18] designed adaptive controllers, which are able to adapt to unknown or slowly varying parameters. Several advanced control methods, such as sliding mode, fuzzy and neural network control, were combined to deal with uncertain network in [19] and [20]. Because the upper bound of system uncertainty is hard to be obtained, an adaptive controller was adopted to estimate it in [21]. However, its disadvantage is that the chattering cannot be eliminated, because the sign function is used. Therefore, [21] proposed an adaptive control scheme to directly estimate system uncertainties. In practical networks, due to the existence of time-varying systematic parameters, [22] designed a sliding surface to compensate the effect of uncertainties in the network by linear matrix inequality (LMI).

Although a large number of the congestion control results have been achieved, there still exist some problems, which need to be solved. A main problem is the performance of the disturbance rejection among these control algorithms. [23] designed a time-domain H_∞ controller to deal with the external disturbance where the change of link bandwidth was regraded as a disturbance. Based on H_∞ control theory, an on-line estimation algorithm of TCP window size was investigated in [24], by which the computation burden was reduced. A robust H_∞ controller was designed for the TCP/AQM system with input saturation in [25]. [26–29] proposed

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several H_∞ controllers for discrete-time TCP/AQM systems. But, all the above-mentioned results are obtained based on the linearized model by using LMI approach.

Alternatively, it is well known that the backstepping is a main control technique of nonlinear systems [30–32]. Moreover, it has also been applied to regulate the nonlinear TCP/AQM network. [33] studied an output feedback controller by applying backstepping approach. [34] gave a novel window size observer based on the round-trip time (RTT) by using comparison lemma and backstepping technique. In 2015, Elham et al. [35] obtained an integral backstepping controller, which ensured that the control signal fell between zero and one. In the various types of TCP protocols, Elham et al. [36] chose TCP Vegas to design a controller to adjust dynamically queue levels based on backstepping. However, the study on congestion controller design for the nonlinear TCP/AQM network by making use of the backstepping technique is limited. So far, to the authors' best knowledge, there is no results on the tracking congestion control based on H_∞ theory and integral backstepping technique.

The main contributions of this paper are given as follows.

(1) Inspired by our previous result [37], a novel model of TCP behaviour is proposed. The position of the exogenous disturbance $\omega(t)$ in the new model can be described more accurately, which implies that the disturbance can be suppressed better by employing H_∞ method. In addition, a new function of the desired queue length q_{ref} is defined, which varies with time during one day, however, the existing q_{ref} in [20,21,38,39] and [40] is a constant.

(2) This paper is first to investigate the congestion control problem for the new TCP/AQM model with external disturbance and modelling uncertainties by combining H_∞ control theory and integral backstepping technique. Furthermore, the presented scheme guarantees that the queue $q(t)$ can follow the desired queue $q_{ref}(t)$. Besides, by comparing the simulation results between the PI control method, the minimax control scheme and the proposed approach, the superiority and effectiveness of the proposed approach can be verified.

(3) It should be highlighted that Assumptions 3 and 4 on the nonlinear function $g_i(\bar{x}_i)$ and the saturation function $g(v)$ in [41] are removed in this paper, which makes the presented controller less conservative.

The rest of this paper is structured as follows. A new TCP/AQM network model is presented in Section 2. Section 3 is concentrated on the design of AQM algorithm to achieve a satisfactory tracking performance. Section 4 gives a simulation example. After that, a conclusion is obtained in Section 5.

2. Modified TCP/AQM network model

Motivated by our previous achievement [37], a new TCP/AQM model is obtained, in which the time-delay is neglected and the external disturbances are considered.

$$\begin{cases} \dot{W}(t) = \dfrac{1}{R(t)} - \dfrac{W(t)}{2}\dfrac{W(t)}{R(t)}p(t) \\ \dot{q}(t) = \begin{cases} -C_0 + \dfrac{N(t)}{R(t)}W(t) + \omega(t) & q(t) > 0 \\ \max\left\{-C_0 + \dfrac{N(t)}{R(t)}W(t) + \omega(t), 0\right\} & q(t) = 0 \end{cases} \\ R(t) = \dfrac{q(t)}{C_0} + T_p \end{cases} \tag{1}$$

where $W(t) \in [W_{\min}, W_{\max}]$ is the TCP window size (in packets), $q(t) \in [q_{\min}, q_{\max}]$ is the queue length in the router (in packets), $R(t)$ is the round-trip time (in secs), C_0 is the available link capacity (in packets/s), T_p is the propagation delay (in secs), $N(t)$ is the number of TCP sessions, $p(t) \in [0, 1]$ is the probability of packet loss and $\omega(t)$ is the external disturbance, which can be regarded as UDP flows or short-lived TCP flows.

According to [39], the following rate model is considered in this paper.

$$\dot{r}(t) = \frac{\dot{W}(t) - r(t)\dot{R}(t)}{R(t)} \tag{2}$$

with $r(t) = \frac{W(t)}{R(t)}$. It follows from (1) and (2) that it has

$$\begin{aligned} \dot{r}(t) = {} & \frac{1}{R^2(t)} + \frac{r(t)}{R(t)} - \frac{r^2(t)}{2}p(t) \\ & - \frac{N(t)}{R(t)C_0}r^2(t) - \frac{r(t)}{R(t)C_0}\omega(t) \end{aligned} \tag{3}$$

$$\dot{q}(t) = N(t)r(t) + \omega(t) - C_0 \tag{4}$$

By setting $x_1 = q(t), x_2 = r(t), u(t) = p(t)$, the above model can be written as:

$$\begin{cases} \dot{x}_1(t) = N(t)x_2(t) + \omega(t) - C_0 \\ \dot{x}_2(t) = f(x) + g(x)u(t) + \varphi(x)\omega(t) \\ y(t) = x_1(t) \end{cases} \tag{5}$$

where $x(t) = [x_1(t)\ \ x_2(t)]^{\mathrm{T}} \in R^2, u(t) \in R, y(t) \in R. f(x), g(x)$ and $\varphi(x)$ are given as follows:

$$f(x) = \frac{1}{R^2(t)} + \frac{1}{R(t)}x_2(t) - \frac{N(t)}{R(t)C_0}x_2^2(t)$$

$$g(x) = -\frac{1}{2}x_2^2(t)$$

$$\varphi(x) = -\frac{1}{R(t)C_0}x_2(t)$$

In order to guarantee $u \in [0, 1]$, the system input is subject to nonlinear saturation defined by

$$u = \mathrm{sat}(v) = \begin{cases} 1 & v > 1 \\ v & 0 \le v \le 1 \\ 0 & v < 0 \end{cases} \tag{6}$$

According to [42–44], a smooth function $\phi(v)$, which is used to solve the sharp corner problem when $v = 1$ and $v = 0$, is defined by

$$\phi(v) = \begin{cases} \tanh(v) & v \ge 0 \\ 0 & v < 0 \end{cases} = \begin{cases} \dfrac{e^v - e^{-v}}{e^v + e^{-v}} & v \ge 0 \\ 0 & v < 0 \end{cases} \tag{7}$$

Then, u in (6) can be written as

$$u = \mathrm{sat}(v) = \phi(v) + d(v) \tag{8}$$

where $d(v) = \mathrm{sat}(v) - \phi(v)$ is a bounded function and $|d(v)| \le D$ due to [42–44]. With the aid of mean-value theory, there is a constant $0 < \sigma < 1$ such that

$$\phi(v) = \phi(v_0) + \phi_{v_\sigma}(v - v_0) \tag{9}$$

with $\phi_{v_\sigma} = \left.\frac{\partial\phi(v)}{\partial v}\right|_{v=v_\sigma}$ and $v_\sigma = \sigma v + (1-\sigma)v_0$. By selecting $v_0 = 0, \phi(v)$ can be expressed by

$$\phi(v) = \phi_{v_\sigma}v \tag{10}$$

Thus far, the control input u is transformed to

$$u = \phi_{v_\sigma}v + d(v) \tag{11}$$

Before obtaining the main result, some basic knowledge are first introduced.

Assumption 1 (*[45]*)**.** The external disturbance $\omega(t)$ is unknown and $\omega \in L_2[0, T)$ with $T > 0$.

Assumption 2 ([40]). $N(t)$ and $R(t)$ in (5) satisfy

$$0 < N_- \le N(t) \le N_+$$
$$T_p \le T_0 \le R(t) \le T_1 \le \frac{q_{\max}}{C_0} + T_p \tag{12}$$

where N_-, N_+, T_0 and T_1 are positive constants.

Assumption 3 ([35]). $L_1 < \int_0^t \left(q(\tau) - q_{ref}(\tau)\right) d\tau < L_2$, $\forall t \in [0, T]$, $T \in [0, \infty)$, where the desired queue length $q_{ref}(t)$ is given by

$$q_{ref}(t) = \begin{cases} -(t-10)^2 + 100, & 0 \le t \le 10 \\ 100, & 10 < t < 20 \\ -6.25(t-20)^2 + 100, & 20 \le t \le 24 \end{cases} \tag{13}$$

with the unit of time being hour.

Assumption 4. q_{ref} and its first-order are piecewise continuous and bounded. Their bounds are as follows

$$0 \le q_{ref} \le L_3$$
$$L_{41} \le \dot{q}_{ref} \le L_{42}$$

Assumption 5 ([46]). There exist three design parameters $\vartheta > 0$, $\varsigma > 0$ and $\beta > 0$ such that

$$|\Delta| \le \vartheta \left(\|x\|_2 - \varsigma\right)$$

where Δ will be specified later and

$$\varsigma = L_3 + \frac{1}{\bar{N}} \times \max\left\{|C_0 + L_{41} - \beta L_2|, |C_0 + L_{42} - \beta L_1|\right\}.$$

Based on Assumption 2, the reference values of $N(t)$ and $R(t)$ can be defined to $\bar{N} = \frac{N_- + N_+}{2}$ and $\bar{R} = \frac{T_0 + T_1}{2}$, which together with (11), (5) can be rewritten as follows:

$$\begin{cases} \dot{x}_1(t) = \bar{N} x_2(t) + \omega(t) - C_0 \\ \dot{x}_2(t) = f_0(x) + g_0(x)\left(\phi_{v_\sigma} v + d(v)\right) + \varphi_0(x)\omega(t) \\ \qquad + \Delta(x, N, R, \omega, t) \\ y(t) = x_1(t) \end{cases} \tag{14}$$

with

$$\begin{aligned} f_0(x) &= \frac{1}{\bar{R}^2} + \frac{1}{\bar{R}} x_2(t) - \frac{\bar{N}}{\bar{R} C_0} x_2^2(t) \\ g_0(x) &= -\frac{1}{2} x_2^2(t) \\ \varphi_0(x) &= -\frac{1}{\bar{R} C_0} x_2(t) \\ \Delta(x, N, R, \omega, t) &= (f(x) - f_0(x)) \\ &\quad + (\varphi(x) - \varphi_0(x))\omega(t) \\ &= \Delta f(x) + \Delta\varphi(x)\omega(t) \end{aligned}$$

where $\Delta(x, N, R, \omega, t)$ represents the uncertainty.

Remark 1. Assumption 1 implies that the external disturbance is both bounded and square-integrable. UDP flow is regarded as the external disturbance. UDP flow will suddenly turns into the data channel and it will disappear with time increase, hence, using the function $\omega(t) = 0.2e^{-0.5t}$ to simulate the changes of UDP flow is reasonable. Moreover, it is a common assumption in H_∞ control design, which is also made in [45,47–49]. It follows from (1) that $R(t) = \frac{q(t)}{C_0} + T_p$, which implies $R(t) \in \left[T_p, \frac{q_{\max}}{C_0} + T_p\right]$ due to $q(t) \in [0, q_{\max}]$ for a specific network. Meanwhile, the number of TCP sessions N is known and bounded in a given TCP/AQM network. Hence, Assumption 2 is reasonable. The desired queue q_{ref} in (13) satisfies Assumption 4 as shown in Fig. 1, which models a typical change of queue length in one day. The queue length increases as t changes from 0 to 10, reaches the maximum at $t = 10$, then decreases as t goes from 20 to 24, and arrives at zero at $t = 24$. It repeats the same pattern everyday. Therefore, the q_{ref} is bounded due to (13), which means that Assumptions 3 and 4 are reasonable. However, in the existing results (see [33,35,37,38,50] and references therein), q_{ref} is usually set to a constant, the model of q_{ref} in this paper may be more suitable and rational to some extent. Unfortunately, the specific value L_1 and L_2 cannot be explicitly expressed. Besides, according to Remark 1 of [46], it is worth noting that Assumption 5 is less restrictive than that in [51,52] and [53].

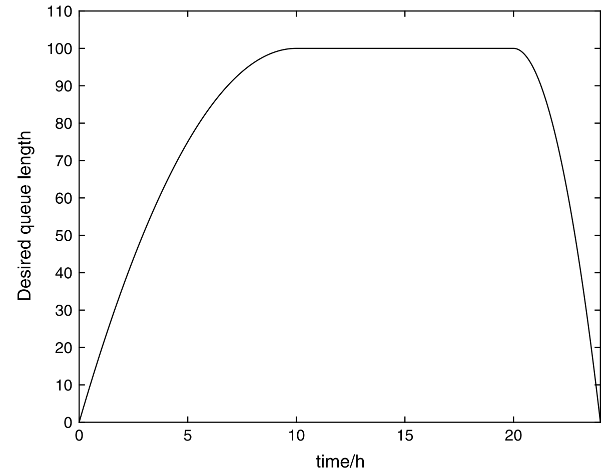

Fig. 1. Desired queue length.

Remark 2. Based on the above analysis and [42–44], it is a fact that

$$g_m = -\frac{W_{\max}^2}{2\bar{R}^2} \le g_0 = -\frac{W^2}{2\bar{R}^2} \le -\frac{W_{\min}^2}{2\bar{R}^2} = g_M$$
$$0 < \phi_{v_\sigma} \le 1$$

which means that $0 < -g_M \le -g_0 \le -g_m$, so $0 < -g_0\phi_{v_\sigma} \le -g_m$. As a result, $0 > g_0\phi_{v_\sigma} \ge g_m$.

In the following, the H_∞ tracking control problem is defined.

Definition 1. The H_∞ tracking problem for (14) is said to be solvable if there exists a state feedback control law $u = u(x)$ so that the closed-loop system has the following properties:

(i) The tracking error $(q - q_{ref})$ is globally asymptotically approaches zero when $\omega \equiv 0$;

(ii) It is L_2-stable, namely, there exists $\delta(x_0) > 0$ such that

$$\int_0^T \left\|q - q_{ref}\right\|^2 dt \le \gamma^2 \int_0^T \|\omega\|^2 dt + \delta(x_0) \tag{15}$$

for any x_0, $T > 0$, $\gamma > 0$ and $\omega \in L_2[0, T)$, where q_{ref} is the desired queue length, which varies with time.

Remark 3. For convenience, time variable t is ignored. Then, $x_1(t)$, $x_2(t)$, $f_0(x)$, $g_0(x)$, $\varphi_0(x)$, $u(t)$, $\omega(t)$, $q(t)$ and $\Delta(x, N, R, \omega, t)$ can be modified as $x_1, x_2, f_0, g_0, \varphi_0, u, \omega, q$ and Δ.

3. Main results

In this section, it will be shown that the H_∞ tracking problem is solvable for the uncertain nonlinear system (14) with Assumptions 1–5. To solve this problem, an integral backstepping method is employed. In what follows, the following coordinate transformation will be considered to design the controller step by step.

$$z_1 = q - q_{ref} = x_1 - q_{ref} \tag{16}$$

$$z_2 = \bar{N}x_2 - \alpha \tag{17}$$

where α is a virtual controller.

Step 1. Differentiating z_1 gives

$$\dot{z}_1 = \dot{x}_1 - \dot{q}_{ref} = \bar{N}x_2 + \omega - C_0 - \dot{q}_{ref} \tag{18}$$

Choose a Lyapunov function as follows

$$V_1 = \frac{1}{2}z_1^2 + \frac{1}{2}\beta\chi^2 \tag{19}$$

with $\chi = \int_0^t z_1(\tau)d\tau$. Then, differentiating V_1 with respect to time yields

$$\begin{aligned}\dot{V}_1 &= z_1\dot{z}_1 + \beta\chi\dot{\chi}\\ &= z_1(\bar{N}x_2 + \omega - C_0 - \dot{q}_{ref}) + \beta\chi z_1\end{aligned} \tag{20}$$

It follows from (17) that $\bar{N}x_2 = z_2 + \alpha$. Therefore, (20) can be expressed as

$$\begin{aligned}\dot{V}_1 &= z_1(z_2 + \alpha + \omega - C_0 - \dot{q}_{ref}) + \beta\chi z_1\\ &= z_1(z_2 + \alpha - C_0 - \dot{q}_{ref} + \beta\chi) + z_1\omega\\ &\le z_1(z_2 + \alpha - C_0 - \dot{q}_{ref} + \beta\chi)\\ &\quad - \left\|\frac{z_1}{2\gamma_1} - \gamma_1\omega\right\|^2 + \frac{z_1^2}{4\gamma_1^2} + \gamma_1^2\|\omega\|^2\\ &\le z_1(z_2 + \alpha - C_0 - \dot{q}_{ref} + \beta\chi + \frac{z_1}{4\gamma_1^2})\\ &\quad + \gamma_1^2\|\omega\|^2\end{aligned} \tag{21}$$

Choose the virtual controller α as

$$\alpha = -c_1z_1 + C_0 + \dot{q}_{ref} - \beta\chi - \frac{z_1}{4\gamma_1^2} \tag{22}$$

where c_1 is a positive design parameter. Substituting (22) into (21) gives

$$\dot{V}_1 \le -c_1z_1^2 + z_1z_2 + \gamma_1^2\|\omega\|^2 \tag{23}$$

Step 2. It is clear that

$$\begin{aligned}\dot{z}_2 &= \bar{N}\dot{x}_2 - \dot{\alpha}\\ &= \bar{N}\left(f_0 + g_0\phi_{v_\sigma}v + g_0d + \varphi_0\omega + \varDelta\right) - \dot{\alpha}\end{aligned} \tag{24}$$

Differentiating α gives

$$\begin{aligned}\dot{\alpha} &= \frac{\partial\alpha}{\partial z_1}\dot{z}_1 + \frac{\partial\alpha}{\partial\chi}\dot{\chi} + \ddot{q}_{ref}\\ &= -\left(c_1 + \frac{1}{4\gamma_1^2}\right)\left(\bar{N}x_2 + \omega - C_0 - \dot{q}_{ref}\right)\\ &\quad - \beta z_1 + \ddot{q}_{ref}\\ &= -\left(c_1 + \frac{1}{4\gamma_1^2}\right)\left(z_2 + \alpha + \omega - C_0 - \dot{q}_{ref}\right)\\ &\quad - \beta z_1 + \ddot{q}_{ref}\\ &= -\left(c_1 + \frac{1}{4\gamma_1^2}\right)z_2 - \left(c_1 + \frac{1}{4\gamma_1^2}\right)\alpha - \left(c_1 + \frac{1}{4\gamma_1^2}\right)\omega\\ &\quad + \left(c_1 + \frac{1}{4\gamma_1^2}\right)C_0 + \left(c_1 + \frac{1}{4\gamma_1^2}\right)\dot{q}_{ref} - \beta z_1 + \ddot{q}_{ref}\\ &= -\left(c_1 + \frac{1}{4\gamma_1^2}\right)z_2 - \left(c_1 + \frac{1}{4\gamma_1^2}\right)\\ &\quad \times\left(-c_1z_1 + C_0 + \dot{q}_{ref} - \beta\chi - \frac{z_1}{4\gamma_1^2}\right) - \left(c_1 + \frac{1}{4\gamma_1^2}\right)\omega\\ &\quad + \left(c_1 + \frac{1}{4\gamma_1^2}\right)C_0 + \left(c_1 + \frac{1}{4\gamma_1^2}\right)\dot{q}_{ref} - \beta z_1 + \ddot{q}_{ref}\\ &= \left(c_1^2 + \frac{c_1}{2\gamma_1^2} + \frac{1}{16\gamma_1^4} - \beta\right)z_1\\ &\quad - \left(c_1 + \frac{1}{4\gamma_1^2}\right)z_2\\ &\quad - \left(c_1 + \frac{1}{4\gamma_1^2}\right)(\omega - \beta\chi) + \ddot{q}_{ref}\end{aligned} \tag{25}$$

Substituting (25) into (24) produces

$$\begin{aligned}\dot{z}_2 &= \bar{N}\left(f_0 + g_0\phi_{v_\sigma}v + g_0d + \varphi_0\omega + \varDelta\right)\\ &\quad - \left(c_1^2 + \frac{c_1}{2\gamma_1^2} + \frac{1}{16\gamma_1^4} - \beta\right)z_1\\ &\quad + \left(c_1 + \frac{1}{4\gamma_1^2}\right)z_2\\ &\quad + \left(c_1 + \frac{1}{4\gamma_1^2}\right)(\omega - \beta\chi) - \ddot{q}_{ref}\end{aligned} \tag{26}$$

The Lyapunov function is taken to be

$$V = \frac{1}{2}z_1^2 + \frac{1}{2}\beta\chi^2 + \frac{1}{2\bar{N}}z_2^2 \tag{27}$$

The time derivative of (27) is

$$\begin{aligned}\dot{V} &= \dot{V}_1 + \frac{1}{\bar{N}}z_2\dot{z}_2\\ &\le -c_1z_1^2 + z_1z_2 + \gamma_1^2\|\omega\|^2\\ &\quad + z_2(f_0 + g_0\phi_{v_\sigma}v + \frac{1}{2}z_2g_0^2\\ &\quad - \frac{1}{\bar{N}}\left(c_1^2 + \frac{c_1}{2\gamma_1^2} + \frac{1}{16\gamma_1^4} - \beta\right)z_1\\ &\quad + \frac{1}{\bar{N}}\left(c_1 + \frac{1}{4\gamma_1^2}\right)z_2\\ &\quad - \frac{1}{\bar{N}}\left(c_1 + \frac{1}{4\gamma_1^2}\right)\beta\chi\\ &\quad - \frac{1}{\bar{N}}\ddot{q}_{ref}) + z_2\varDelta + \frac{1}{2}D^2\\ &\quad + z_2\left(\frac{1}{\bar{N}}\left(c_1 + \frac{1}{4\gamma_1^2}\right) + \varphi_0\right)\omega\end{aligned}$$

According to Assumption 5, it can be verified that

$$\begin{aligned}\dot{V} &\le -c_1z_1^2 + z_1z_2 + \gamma_1^2\|\omega\|^2\\ &\quad + z_2(f_0 + g_0\phi_{v_\sigma}v + \frac{1}{2}z_2g_0^2\\ &\quad - \frac{1}{\bar{N}}\left(c_1^2 + \frac{c_1}{2\gamma_1^2} + \frac{1}{16\gamma_1^4} - \beta\right)z_1\\ &\quad + \frac{1}{\bar{N}}\left(c_1 + \frac{1}{4\gamma_1^2}\right)z_2\\ &\quad - \frac{1}{\bar{N}}\left(c_1 + \frac{1}{4\gamma_1^2}\right)\beta\chi\\ &\quad - \frac{1}{\bar{N}}\ddot{q}_{ref}) + |z_2|\,\vartheta\left(\|x\|_2 - \varsigma\right) + \frac{1}{2}D^2\\ &\quad - \left\|\frac{z_2\psi}{2\gamma_2} - \gamma_2\omega\right\| + \frac{z_2^2\psi^2}{4\gamma_2^2} + \gamma_2^2\|\omega\|^2\\ &\le -c_1z_1^2 + z_2\left(g_0\phi_{v_\sigma}v + Q\right) + \frac{1}{2}D^2\\ &\quad + \gamma_1^2\|\omega\|^2 + \gamma_2^2\|\omega\|^2 + e_{11}\vartheta^2\left(\|x\|_2 - \varsigma\right)^2\end{aligned} \tag{28}$$

with $\psi = \frac{1}{\bar{N}}\left(c_1 + \frac{1}{4\gamma_1^2}\right) + \varphi_0$, $e_{11} > 0$ and

$$Q = \left(f_0 - \frac{1}{\bar{N}}\ddot{q}_{ref} + \frac{1}{2}z_2g_0^2\right.$$

$$-\frac{1}{\bar{N}}\left(c_1^2+\frac{c_1}{2\gamma_1^2}+\frac{1}{16\gamma_1^4}-\beta-\bar{N}\right)z_1 +\frac{1}{\bar{N}}\left(c_1+\frac{1}{4\gamma_1^2}+\frac{\psi^2\bar{N}}{4\gamma_2^2}+\frac{\bar{N}}{4e_{11}}\right)z_2 -\frac{1}{\bar{N}}\left(c_1+\frac{1}{4\gamma_1^2}\right)\beta\chi\Bigg)$$

As a result, the control law υ is selected as

$$\upsilon=-\frac{1}{g_m}\left(c_2z_2+Q\right) \tag{29}$$

where c_2 is also a positive design parameter. It is a fact from (29) and Remark 2 that $z_2\left(g_0\phi_{\upsilon_\sigma}\upsilon+Q\right)$ can be expressed as

$$z_2\left(g_0\phi_{\upsilon_\sigma}\upsilon+Q\right)=-\frac{1}{g_m}c_2z_2^2g_0\phi_{\upsilon_\sigma}+\left(1-\frac{1}{g_m}g_0\phi_{\upsilon_\sigma}\right)z_2Q \le -c_2z_2^2 \tag{30}$$

(30) is substituted into (28), which gives

$$\dot{V}\le -c_1\|z_1\|^2-c_2\|z_2\|^2+\left(\gamma_1^2+\gamma_2^2\right)\|\omega\|^2+ e_{11}\vartheta^2\left(\|x\|_2-\varsigma\right)^2+\frac{1}{2}D^2 \tag{31}$$

It follows from (16), (17) and (22) that one has

$$z_1=x_1-q_{ref}$$
$$z_2=\bar{N}x_2+\left(c_1+\frac{1}{4\gamma_1^2}\right)z_1-C_0-\dot{q}_{ref}+\beta\chi \tag{32}$$

Its compact form is expressed mathematically as

$$x=\Omega_1z+\Omega_2 \tag{33}$$

where $z=[z_1,z_2]^{\mathrm{T}}$, $\Omega_1=\begin{bmatrix}1 & 0\\ -\frac{1}{\bar{N}}\left(c_1+\frac{1}{4\gamma_1^2}\right) & \frac{1}{\bar{N}}\end{bmatrix}$, $\Omega_2=\begin{bmatrix}q_{ref}\\ \frac{1}{\bar{N}}\left(C_0+\dot{q}_{ref}-\beta\chi\right)\end{bmatrix}$.

Due to

$$\begin{aligned}\|x\|_2&=\|\Omega_1z+\Omega_2\|_2\\ &\le\|\Omega_1z\|_2+\|\Omega_2\|_2\\ &\le\|\Omega_1\|_F\cdot\|z\|_2+\|\Omega_2\|_2\\ &=\sqrt{1+\frac{1}{\bar{N}^2}+\frac{1}{\bar{N}^2}\left(c_1+\frac{1}{4\gamma_1^2}\right)^2}\|z\|_2 +\sqrt{q_{ref}^2+\frac{1}{\bar{N}^2}\left(C_0+\dot{q}_{ref}-\beta\chi\right)^2}\\ &\le\sqrt{1+\frac{1}{\bar{N}^2}+\frac{1}{\bar{N}^2}\left(c_1+\frac{1}{4\gamma_1^2}\right)^2}\|z\|_2 +\left|q_{ref}\right|+\left|\frac{1}{\bar{N}}\left(C_0+\dot{q}_{ref}-\beta\chi\right)\right|\\ &\le\sqrt{1+\frac{1}{\bar{N}^2}+\frac{1}{\bar{N}^2}\left(c_1+\frac{1}{4\gamma_1^2}\right)^2}\|z\|_2+L_3 +\frac{1}{\bar{N}}\times\max\left\{\left|C_0+L_{41}-\beta L_2\right|,\left|C_0+L_{42}-\beta L_1\right|\right\}\\ &=\sqrt{1+\frac{1}{\bar{N}^2}+\frac{1}{\bar{N}^2}\left(c_1+\frac{1}{4\gamma_1^2}\right)^2}\|z\|_2+\varsigma\end{aligned}$$

(31) is turned into

$$\begin{aligned}\dot{V}&\le -c_1\|z_1\|^2-c_2\|z_2\|^2+\left(\gamma_1^2+\gamma_2^2\right)\|\omega\|^2 +e_{11}\vartheta^2\left(\|x\|_2-\varsigma\right)^2\\ &=-c_1\|z_1\|^2-c_2\|z_2\|^2+\left(\gamma_1^2+\gamma_2^2\right)\|\omega\|^2 +e_{11}\vartheta^2\left(1+\frac{1}{\bar{N}^2}+\frac{1}{\bar{N}^2}\left(c_1+\frac{1}{4\gamma_1^2}\right)^2\right)\|z\|^2\\ &=-\sum_{i=1}^{2}\left[c_i-e_{11}\vartheta^2 \times\left(1+\frac{1}{\bar{N}^2}+\frac{1}{\bar{N}^2}\left(c_1+\frac{1}{4\gamma_1^2}\right)^2\right)\right] \times\|z_i\|^2+\left(\gamma_1^2+\gamma_2^2\right)\|\omega\|^2\end{aligned} \tag{34}$$

If the designed parameters c_1, c_2 and e_{11} are chosen so that

$$c_i>e_{11}\vartheta^2\left(1+\frac{1}{\bar{N}^2}+\frac{1}{\bar{N}^2}\left(c_1+\frac{1}{4\gamma_1^2}\right)^2\right),\ i=1,2 \tag{35}$$

then it follows from (34) that

$$\dot{V}\le-\sum_{i=1}^{2}\left[c_i-e_{11}\vartheta^2 \times\left(1+\frac{1}{\bar{N}^2}\left(1+\left(c_1+\frac{1}{4\gamma_1^2}\right)^2\right)\right)\right]\|z_i\|^2$$

with $\omega=0$, which implies that the tracking error z_1 approaches zero.

It is clear that c_2 can be easily selected when c_1 is determined based on (35). c_1 is selected based on the following inequality

$$0>\frac{e_{11}\vartheta^2}{\bar{N}^2}c_1^2+\left(\frac{e_{11}\vartheta^2}{2\bar{N}^2\gamma_1^2}-1\right)c_1 +e_{11}\vartheta^2\left(1+\frac{1}{\bar{N}^2}+\frac{1}{16\bar{N}^2\gamma_1^4}\right) \tag{36}$$

(36) is a quadratic inequality of c_1. According to Vieta theorem, inequality (36) must have a positive solution, if parameters e_{11} and ϑ satisfy one of the following three situations:

(a) $\nabla>0$ and $\Pi_p<0$.
(b) $\nabla>0$, $\Sigma_s>0$ and $\Pi_p>0$.
(c) $\nabla=0$ and $\Sigma_s>0$.

where ∇ is the discriminant of roots of unary quadric equation, Σ_s and Π_p represent the sum and product of two solutions, respectively. Due to $\Pi_p=\bar{N}^2+1+\frac{1}{16\gamma_1^4}>0$, the first case (a) is impossible. Then, c_1 has a positive solution if and only if $\Sigma_s>0$ and $\nabla\ge0$, namely,

$$0<\frac{2\bar{N}^2\gamma_1^2-e_{11}\vartheta^2}{2e_{11}\gamma_1^2\vartheta^2} \tag{37}$$

$$0\le\bar{N}^4\gamma_1^2-e_{11}\vartheta^2\bar{N}^2-4e_{11}^2\vartheta^4\bar{N}^2\gamma_1^2-4e_{11}^2\vartheta^4\gamma_1^2 \tag{38}$$

(34) can be transformed into (39) for verifying H_∞ performance of the system,

$$\dot{V}\le-\left(c_1-e_{11}\vartheta^2\left(1+\frac{1}{\bar{N}^2}+\frac{1}{\bar{N}^2}\left(c_1+\frac{1}{4\gamma_1^2}\right)^2\right)\right) \times\|z_1\|^2+\left(\gamma_1^2+\gamma_2^2\right)\|\omega\|^2+\frac{1}{2}D^2 \tag{39}$$

Choose $c_1=c_{10}+1$ with $c_{10}>0$, then

$$\dot{V}\le-\left(c_{10}+1-e_{11}\vartheta^2\left(1+\frac{1}{\bar{N}^2}+\frac{1}{\bar{N}^2}\left(c_1+\frac{1}{4\gamma_1^2}\right)^2\right)\right) \times\|z_1\|^2+\gamma^2\|\omega\|^2+\frac{1}{2}D^2$$

$$\leq -\|z_1\|^2 + \gamma^2\|\omega\|^2 + \frac{1}{2}D^2 \tag{40}$$

where $c_{10} = e_{11}\vartheta^2\left(1 + \frac{1}{N^2} + \frac{1}{N^2}\left(c_1 + \frac{1}{4\gamma_1^2}\right)^2\right)$, $\gamma^2 = \gamma_1^2 + \gamma_2^2$.

Integrating (40) gets

$$V - V(0) \leq \int_0^T \left(\gamma^2\|\omega\|^2 - \|z_1\|^2 + \frac{1}{2}D^2\right) dt \tag{41}$$

which means that

$$\begin{aligned}\int_0^T \|z_1\|^2 dt &\leq \gamma^2\int_0^T \|\omega\|^2 dt - V + V(0) + \frac{1}{2}D^2 \\ &\leq \gamma^2\int_0^T \|\omega\|^2 dt + V(0) + \frac{1}{2}D^2 \\ &= \gamma^2\int_0^T \|\omega\|^2 dt + \delta(x_0)\end{aligned} \tag{42}$$

As a result, the L_2 gain from the disturbance input to the controlled output of the closed-loop system is not bigger than γ.

So far, the main result in this paper has been proved, which is summarized in Theorem 1.

Theorem 1. *With Assumptions 1–5, the H_∞ tracking control problem for (14) is solvable with the feedback control law v in (29), if there exist appropriate parameters c_1, c_2, ϑ and e_{11} so that (35) holds.*

4. Simulation results

In this section, a single bottleneck link is considered and its topology structure is dumbbell. The proposed approach is simulated by using Matlab. The systematic parameters, external disturbance, and uncertainty in system (14) are given as follows:

$$\begin{aligned}\bar{N} &= 60, \bar{R} = 0.246s, C_0 = 3750 \text{ packets/s}, \\ c_1 &= 15, c_2 = 2, \\ \beta &= 500, \gamma_1 = 1, \gamma_2 = 1, e_{11} = 1, \\ \Delta &= 0.1\sin(t)\left(\sqrt{x_1^2 + x_2^2} - 195\right), \\ \omega &= 0.2e^{-0.5t}\end{aligned}$$

Simulation results are collected and recorded in Figs. 2–4. Specifically, Fig. 2 shows the tracking error. It can be seen that the tracking error converges to zero within about 1 h and reaches 0.8 when the external disturbance is added to network at $t = 20$. However, the effect of disturbance is eliminated soon. The trajectory of u in Fig. 3 is always between 0 and 1. It shows that q tracks q_{ref} and the tracking result is satisfactory in Fig. 4. From above results, it is obvious that the proposed scheme is effective.

Besides, some comparisons between the PI control approach [20], the minimax control scheme [50], the integral backstepping technique [35] and the presented method are made to illustrate the effectiveness of the proposed method better. For one thing, the system parameters are $\bar{N} = 60$, $\bar{R} = 0.246$ s, $C_0 = 3750$ packets/s, the disturbance is set to zero, the initial condition is $x(0) = [0, 0]^T$ and the desired queue length is defined as $q_{ref} = 60$. The design parameters are given as follows:

Case 1 (*The proposed method*): $c_1 = 15, c_2 = 2, \beta = 500, \gamma_1 = 1, \gamma_2 = 1, e_{11} = 1$;

Case 2 (*PI controller*): $k_p = 1.822 \times 10^{-5}$ and $k_i = 1.816 \times 10^{-5}$ based on [20] and [33];

Case 3 (*Minimax scheme*): according to [50], $k_1 = -0.0032$ and $k_2 = -0.09$;

Case 4 (*Integral backstepping technique*): due to [35], $\alpha = 0.01$, $\beta = 1$ and $\lambda = 2$.

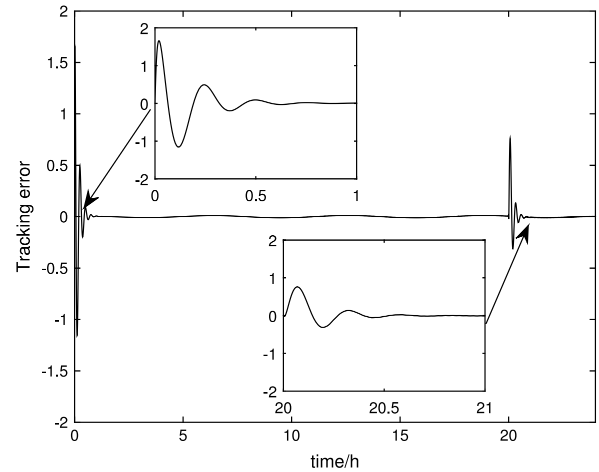

Fig. 2. Tracking error.

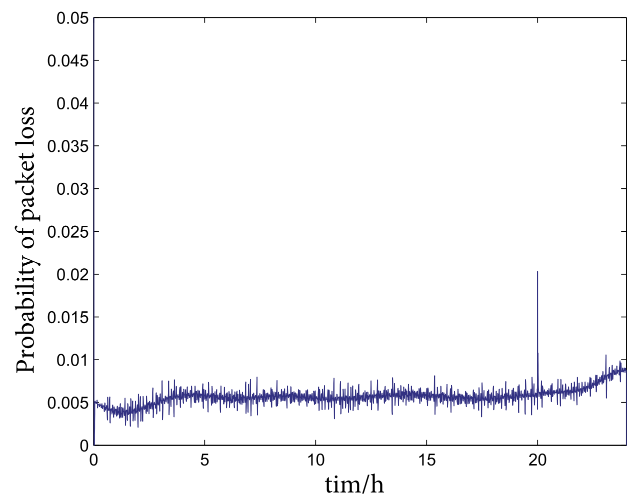

Fig. 3. Probability of packets loss.

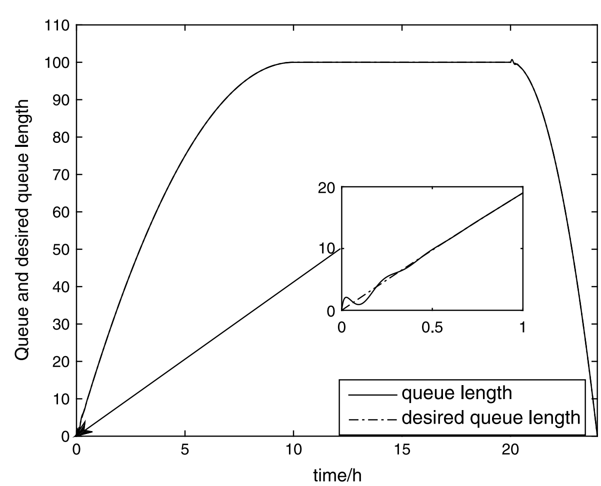

Fig. 4. Queue and desired queue length.

The simulation results are shown in Figs. 5–6. The compared results of the queue length and probability of packet loss are shown in Figs. 5 and 6. The maximum values of $q(t)$ in Fig. 5 are 350, 100.06, 81.13, 75.60 by using PI, integral backstepping, minimax and the proposed methods, respectively. Hence, on one hand, it can

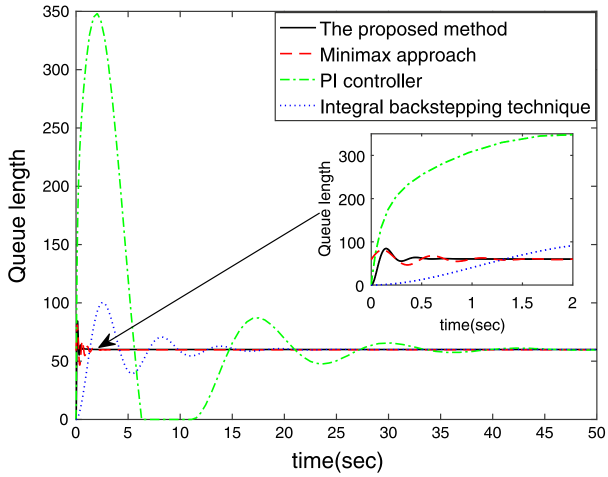

Fig. 5. Compared results of the queue length.

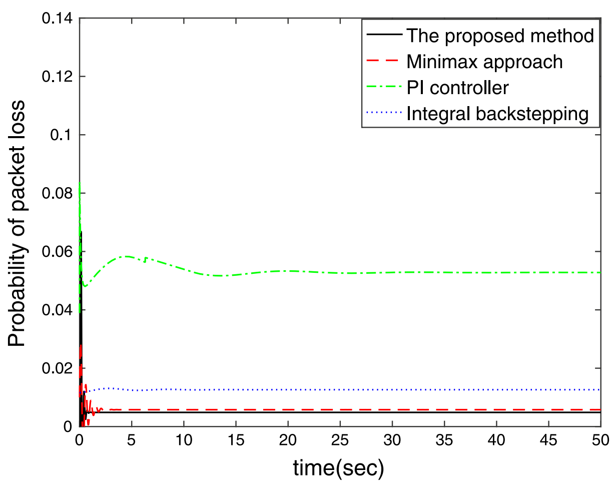

Fig. 6. Compared results of the probability of packets loss.

be easily seen from Fig. 5 that the proposed method has the smaller maximum overshoot and less chattering than the PI and integral backstepping control methods; on the other hand, from the sub-figure of Fig. 5, the fluctuation by using the minimax approach is more than the presented scheme. Meanwhile, it follows from Fig. 6 that a smaller control input signal is achieved by comparing four trajectories because the probability of packet loss in steady state is 0.4648, 0.0126, 0.0058 and 0.0049 by employing PI, integral backstepping, minimax and the proposed methods, respectively. Based on the above discussion and analysis, the proposed scheme possesses the better performances.

5. Conclusions

A new model has been proposed by combining the two existing model for TCP/AQM network and a novel congestion controller has been designed based on H_∞ theory and integral backstepping technique. The developed controller guarantees that the queue tracks the desired length and is able to attenuate the influence of the disturbance and uncertainty. Finally, two examples are provided to verify the effectiveness and superiority of the proposed design method.

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