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Research article

Adaptive backstepping H_∞ tracking control with prescribed performance for internet congestion ☆

Yang Liu [a,c,*], Xiaoping Liu [b,c], Yuanwei Jing [a], Shaowei Zhou [d]

[a] College of Information Science and Engineering, Northeastern University, Shenyang 110819, Liaoning, PR China
[b] Shandong Jianzhu University, Jinan 250101, Shandong, PR China
[c] Department of Electrical Engineering, Lakehead University, Thunder Bay, Ontario, Canada P7B 5E1
[d] College of Mathematics and Systems Science, Shandong University of Science and Technology, Qingdao 266590, PR China

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ABSTRACT

This paper extends the well-known control method, prescribed performance control (PPC), to network congestion control problems. An adaptive H_∞ tracking problem for Transmission Control Protocol/Active Queue Management (TCP/AQM) system with external disturbance is studied. Firstly, a modified network model is given. And then, the model is changed to an equivalent error model by using error transformation. Next, to solve the network congestion problem, prescribed performance, backstepping technique, adaptive control and H_∞ control are combined to design a congestion controller. Due to the use of prescribed performance, the controller can guarantee both the transient and steady state performance of the system. Meanwhile, the output of the system can track the desired queue, and unknown link capacity can be estimated. Finally, a simulation result is shown to clarify the feasibility and effectiveness of proposed approach.

1. Introduction

Internet congestion will occur if the total demand for a resource (e.g., link bandwidth) exceeds the available capacity of the resource. In the past three decades, lots of methods have been proposed to deal with internet congestion [1–5]. Among them, there exists a main class of methods called AQM algorithms, which are used to eliminate or relieve internet congestion. The first proposed AQM algorithm was named Random Early Detection (RED) [6]. But RED and its variant algorithms [7–9] are too sensitive to parameter configuration. In order to design and understand the behaviour of internet systems better, a TCP/AQM model was built by using fluid-flow theory in [10]. Afterwards, extensive schemes were applied to the congestion control based on the model [11–16]. In [11], a new control strategy, called Novel Autonomous Proportional and Differential RED (NPD-RED), was proposed. It can be applied to both wired and wired-wireless network routers based on TCP/RED model. Bigdeli et al. [12] gave a modified TCP Vegas/AQM internet and presented a novel indirect pole placement method, which was named Coefficient Diagram Method (CDM). It is known that Model Predictive Control (MPC) has become a mature and advanced control technique. It can predict the system dynamics, and then determine the optimal control signal during each sampling time [13]. Hence, [14] developed a so-called MPAQM congestion control algorithm. In addition, [15] and [16] designed the corresponding robust PID controller and LQ-Servo controller based on Linear Quadratic (LQ) method. And the two controllers were used to solve congestion situation of wired and wireless networks, respectively.

In 2008, a novel control strategy, called Prescribed Performance Control (PPC), was proposed firstly in [17]. Afterwards, excessive research results were obtained [18–22]. Meanwhile, this technique has also been applied to some practical systems [23–27]. Prescribed performance was used to process the tracking problem of robot force/position, and a neural network adaptive controller was designed in [23]. Wherein the robot dynamic model was known, and unknown force deformation model was estimated by using neural network. In contrast, [24] has no information for the robot dynamic model and force deformation model was demanded, and no approximator was used. In [25], PPC was utilized to solve some key technical problems of aircrafts by analyzing certain characteristics. In [26], an adaptive prescribed performance controller, which can improve driving comfort, was developed for vehicle active suspension systems with nonlinear spring and linear damper. Robustness and transient performance of the integrated

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* Corresponding author at: College of Information Science and Engineering, Northeastern University, Shenyang 110819, Liaoning, PR China.
E-mail addresses: liuyang0595@163.com (Y. Liu), xliu2@lakeheadu.ca (X. Liu), ywjjing@mail.neu.edu.cn (Y. Jing), zsw9675@163.com (S. Zhou).

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interceptor have been guaranteed comprehensively based on the dynamic surface control and prescribed performance control in [27]. In 2017, some new results were obtained in [28–33]. However, PPC has not been applied to TCP/AQM system until now.

It is well known that the adaptive technique is a powerful method to uncertain system [34]. Therefore, in order to handle unknown network situations, some researchers adopt adaptive control methods. [35] designed a controller which can adapt to unknown or slowly varying parameters by using feedback linearization and backstepping technique. A self-tuning construction, which can be used to estimate link capacity and traffic load on-line, was proposed in [36]. Sun et al. [37] gave a stable adaptive proportional-integral (SAPI) controller, which was robust to non-responsive flows. In order to overcome the drawback of the Generalized Mimimum Variance (GMV) method, that is, the system performance will become degraded when network changes, [38] proposed an Adaptive Generalized Mimimum Variance (AGMV) strategy. A few references have also designed some adaptive congestion controllers to deal with network congestion for TCP/AQM system with unknown parameters [39–41].

For the internet, it is necessary to consider its performance of disturbance rejection. H_∞ control is an effective tool for deal with external disturbance [42–44]. Based on H_∞ optimal theory, novel PI [45] and PID [46] controllers were investigated. It is known that conventional PI and PID controllers have two, three or more tuning parameters. However, the PI and PID controllers in [45] and [46] have only one tuning parameter. In order to deal with uncertainty and flow disturbance, an H_∞ Fuzzy Variable Structure Controller (HFVSC) was proposed by combining sliding-mode control with H_∞ scheme [47]. In [48], a state-observer-based H_∞ controller was used to estimate window size as well as time-varying and input saturation were taken into consideration for TCP/AQM systems. An AQM design method was developed by using three techniques, Particle Swarm Optimization (PSO), H_∞ and PI control in [49]. For verifying the feasibility of the proposed algorithm, a comparison was made among PI, Fuzzy PI and H_∞ PSO-PI. A discrete-time H_∞ controller for time-varying TCP/IP network with uncertainty was presented to handle network congestion [50]. In 2016, Cui et al. [51] provided a new H_∞ control method, wherein the observer was employed to reconstruct the window size, and a memoryless H_∞ controller was utilized to make the system asymptotically stable. But, all the results mentioned previously are obtained based on the linearized model.

Therefore, a large number of researchers start to concern on the nonlinear TCP/AQM model. [52] considered two different processing methods for network uncertainty by using adaptive sliding mode control. Because of the burstiness and time-varying nature of network parameters, it is very hard to implement a sliding mode controller on practical network. Hence, [53] adopted RBF neural network to approximate systematic uncertain parameters. In [54], the authors proposed an AQM algorithm to achieve the desired performance with finite-time. Here, a finite-time congestion controller was obtained by employing terminal sliding mode control to improve the convergent speed of the system. A recursive design method, called backstepping technique, was proposed, which has become a major control approach in nonlinear system control field. In recent years, backstepping technique was also applied to the network congestion control. Elham et al. [55] proposed a novel AQM algorithm based on integral backstepping, and gave a theorem which can make the control input $u \in [0, 1]$. The author in [56] introduced a modified fluid flow model that considered all delays in the topology and the AQM design was formulated as a structured form by the quadratic separation framework. And some research results have been obtained for congestion control by using backstepping, for details see [57–61] and references therein. However, the results are very limited for nonlinear TCP/AQM network by using backstepping. So far, to the best of the authors' knowledge, there is no results on adaptive tracking congestion control based on prescribed performance, H_∞ theory and backstepping technique.

The following five points are the main contributions of this paper.

(1) A new network model is proposed by combining the two existing models.
(2) PPC technique is extended to TCP/AQM network congestion problem, and a novel congestion control algorithm is presented to solve a tracking problem by using PPC, backstepping, adaptive control and H_∞ control.
(3) Both steady state tracking error and transient error of the closed-loop system satisfy the design requirements by using PPC.
(4) The output of system tracks the desired trajectory with proposed controller.
(5) Unknown parameter can be estimated well.

The remainders of this paper is structured as follows. A network model and certain necessary definitions and preliminaries are presented in Section 2. The controller design and main results are formulated in Section 3. Section 4 gives a simulation study to verify the proposed method. Finally, a conclusion is provided in Section 5.

Notations: Throughout the paper, R^i represents the $i-$ dimensional Euclidean space. If A denotes a given vector or matrix, then A^T indicates its transpose, $\|A\|$ stands for its Euclidean norm. $|x|$ is the absolute value of the real number x. $S^{-1}(a(t))$ is the inverse of the function $a(t)$.

2. System model and preliminaries

2.1. TCP/AQM system model

Inspired by [55] and [62], we can depict the behavior of the window size of senders and the queue length at the router by using the following TCP/AQM model, wherein the time-delay is ignored and unresponsive flows are considered.

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

where $W(t) \in [0, W_{\max}]$ is the TCP window size, $q(t) \in (0, q_{\max}]$ is the queue length in the router, $R(t)$ is the round-trip time, $C(t)$ is the available link capacity, T_p is the propagation delay, $N(t)$ is the number of TCP sessions, and $p \in [0, 1]$ is the probability of packet loss, $\omega(t)$ is unresponsive flows, which can be regarded as the external disturbance. Here, we suppose that $N(t)$, $R(t)$ are the constants, and $C(t)$ is an unknown constant, which needs to be estimated. Therefore, $N(t)$, $R(t)$ and $C(t)$ can be re-written as N, R and C.

According to [56], the following rate model is considered in this paper.

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

with $r(t) = \frac{W(t)}{R}$. It follows from (1) and (2) that a new model based on $r(t)$ and $q(t)$ is derived as follows.

$$\begin{cases} \dot{r}(t) = \dfrac{1}{R^2} - \left(\dfrac{1}{R^2} + \dfrac{r^2(t)}{2}\right)p(t) \\ \dot{q}(t) = Nr(t) + \omega(t) - C \end{cases} \tag{3}$$

Set $x_1(t) = q(t)$, $x_2(t) = r(t)$, $u(t) = p(t)$, then (3) can be rewritten as

$$\begin{cases} \dot{x}_1(t) = Nx_2(t) + \omega(t) - C \\ \dot{x}_2(t) = f(x) + g(x)u(t) \\ y(t) = x_1(t) \end{cases} \tag{4}$$

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

$$f(x) = \frac{1}{R^2}$$

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

Remark 1. The model (4) is different from the existing TCP/AQM network models with disturbances, such as [64]. In [64], the model is built by the following two steps: the state $W(t)$ is transformed to $r(t)$ based on $r(t) = (W(t))/R$ firstly, and then the disturbance is directly added to the second state of the system. However, the proposed new model is constructed by inverse steps: the disturbance is added to the model (1) firstly, and then the model with the external disturbance is transformed to the model of rate $r(t)$. By comparison, the merit of the proposed model is that the position of the exogenous disturbance $\omega(t)$ in system can be described more accurately. Therefore, the disturbance can be suppressed better by employing H_∞ method.

The objectives for this paper are described in details as follows.

(i) The output of system $q(t)$ tracks the desired queue length $q_{ref}(t)$.
(ii) All signals in the closed-loop are bounded.
(iii) The tracking error $e_1(t) = q(t) - q_{ref}(t)$ satisfies the prescribed transient and steady state performances.
(iv) The unknown link capacity C can be estimated.
(v) The system has the performance of disturbance rejection.

2.2. Performance function

Definition 1 ([63]). A smooth function $\rho: R_+ \to R_+$ will be called a performance function if it satisfies the following two conditions:

(1) $\rho(t)$ is positive and decreasing.
(2) $\lim_{t\to\infty}\rho(t) = \rho_\infty > 0$.

In this paper, we choose the following function as prescribed performance function

$$\rho(t) = (\rho_0 - \rho_\infty)e^{-\lambda t} + \rho_\infty \tag{5}$$

where ρ_0, ρ_∞ and λ are positive and can be chosen according to design requirements. And the proposed control objective (iii) can be achieved by using the following inequality

$$-\rho(t) < e_1(t) < \rho(t) \tag{6}$$

Remark 2. The constant ρ_∞ represents the maximum allowable size of the tracking error $e_1(t)$ at the steady state. Meanwhile, the maximum overshoot of the tracking error is not more than ρ_0. Then, the steady-state error of the system can converge to a prescribed area by selecting appropriate parameters.

2.3. Error transformation

If there exists a function $S(\varepsilon)$ which satisfies the following properties:

1) $S(\varepsilon)$ is smooth and strictly increasing;
2) $-1 < S(\varepsilon) < 1$ (7)
3) $\lim_{\varepsilon\to+\infty} S(\varepsilon) = 1$, and $\lim_{\varepsilon\to-\infty} S(\varepsilon) = -1$ (8)

with ε being the transformed error and the error $e_1(t)$ being related to ε by

$$e_1(t) = \rho(t)S(\varepsilon) \tag{9}$$

then the inequality (6) will be satisfied automatically.

Based on the above description, the function $S(\varepsilon)$ can be chosen as the following hyperbolic tangent function

$$S(\varepsilon) = \frac{\exp(\varepsilon) - \exp(-\varepsilon)}{\exp(\varepsilon) + \exp(-\varepsilon)} \tag{10}$$

2.4. Model transformation

Firstly, the following errors are defined

$$\begin{cases} e_1(t) = x_1(t) - q_{ref}(t) \\ e_2(t) = x_2(t) - \dot{q}_{ref}(t) \end{cases} \tag{11}$$

According to (11), the TCP/AQM system (4) is changed to the following error model.

$$\begin{cases} \dot{e}_1(t) = Ne_2(t) + (N-1)\dot{q}_{ref}(t) + \omega(t) - C \\ \dot{e}_2(t) = \bar{f}(e) + \bar{g}(e)u(t) \end{cases} \tag{12}$$

where $e(t) = \left[e_1(t)\ e_2(t)\right]^{\mathrm{T}}$, $\bar{f}(e)$ and $\bar{g}(e)$ are defined as follows

$$\bar{f}(e) = \frac{1}{R^2} - \ddot{q}_{ref}(t)$$

$$\bar{g}(e) = -\frac{1}{R^2} - \frac{\left(e_2(t) + \dot{q}_{ref}(t)\right)^2}{2}$$

The next, differentiating (9) with respect to time gives

$$\dot{e}_1(t) = \dot{\rho}(t)S(\varepsilon) + \rho(t)\frac{\partial S}{\partial \varepsilon}\dot{\varepsilon}(t) \tag{13}$$

It follows from (12) and (13) that

$$\begin{aligned} \dot{\varepsilon}(t) &= \frac{\dot{e}_1(t) - \dot{\rho}(t)S(\varepsilon)}{\rho(t)\frac{\partial S}{\partial \varepsilon}} \\ &= \frac{Ne_2(t) + (N-1)\dot{q}_{ref}(t) + \omega(t) - C - \dot{\rho}(t)S(\varepsilon)}{\rho(t)\frac{\partial S}{\partial \varepsilon}} \\ &= -\frac{\dot{\rho}(t)S(\varepsilon)}{\rho(t)\frac{\partial S}{\partial \varepsilon}} + \frac{1}{\rho(t)\frac{\partial S}{\partial \varepsilon}}\Big(Ne_2(t) + (N-1)\dot{q}_{ref}(t) + \omega(t) - C\Big) \\ &= F(\varepsilon, \rho) + G(\varepsilon, \rho)\Big(Ne_2(t) + (N-1)\dot{q}_{ref}(t) + \omega(t) - C\Big) \end{aligned} \tag{14}$$

where

$$F(\varepsilon,\rho) = -\frac{\dot\rho(t)S(\varepsilon)}{\rho(t)\frac{\partial S}{\partial\varepsilon}}$$

$$G(\varepsilon,\rho) = \frac{1}{\rho(t)\frac{\partial S}{\partial\varepsilon}}$$

Therefore, substituting (14) into (12) produces the following system.

$$\begin{cases}\dot\varepsilon(t) = F(\varepsilon,\rho) + G(\varepsilon,\rho)\Big(Ne_2(t) + (N-1)\dot q_{ref}(t) + \omega(t) - C\Big)\\ \dot e_2(t) = \bar f(e) + \bar g(e)u(t)\end{cases} \tag{15}$$

Remark 3. For convenience, time variable t is omitted, so $\varepsilon(t)$, $F(\varepsilon,\rho)$, $G(\varepsilon,\rho)$, $e_2(t)$, $\omega(t)$, $\bar f(e)$, $\bar g(e)$ and $u(t)$ are denoted as ε, F, G, e_2, ω, $\bar f$, $\bar g$ and u.

H_∞ tracking control problem is defined as follows.

Definition 2. The H_∞ tracking problem for (15) is said to be solvable if there exists a state feedback control law $u = u(x)$ so that the closed-loop system satisfies the following properties:

(1) The tracking error $e_1(t)$ of the resulting closed-loop system (16) is asymptotically stable with ω 0;
(2) The closed-loop system is L_2-stable, namely, there exists a nonnegative constant $\tilde\delta(x_0)$ such that

$$\int_0^T \|e_1\|^2 dt \le \tilde\gamma^2\int_0^T \|\omega\|^2 dt + \tilde\delta(x_0)$$

for any initial condition, $T>0$, $\tilde\gamma>0$ and $\omega\in L_2[0,T)$.

3. Main results

In this section, it will be shown that the adaptive H_∞ tracking problem is solvable for nonlinear system (15). First, the main result of this work can be summarized in the following theorem.

Theorem 1. *The adaptive H_∞ tracking control problem for (15) is solvable with the feedback control law $u(t)$ in (23) and the adaptive law $\dot{\hat C}$ in (24).*

Remark 4. The proposed method not only can make the queue tracking error satisfy the predefined transient and steady state performances, but also make the TCP/AQM network have the superior performance of disturbance rejection. Besides, the unknown link capacity C can be estimated better.

Proof. To solve this problem, the backstepping method is employed, and the following change of coordinates will be used to design a controller step by step.

$$z_2 = e_2 - \alpha$$

where α is a virtual controller.

Step 1. Choose a Lyapunov function as follows

$$V_1 = \frac{1}{2}\varepsilon^2 + \frac{1}{2}\tilde C^{\mathrm T}\Gamma_C^{-1}\tilde C \tag{16}$$

where Γ_C is an arbitrary positive definite matrix, and $\tilde C = C - \hat C$ with $\hat C$ the estimation of C. Then, differentiating V_1 with respect to time yields

$$\begin{aligned}\dot V_1 =&\ \varepsilon\dot\varepsilon - \tilde C^{\mathrm T}\Gamma_C^{-1}\dot{\hat C}\\ =&\ \varepsilon\Big(F + GNe_2 + G(N-1)\dot q_{ref} + G\omega - GC\Big) - \tilde C^{\mathrm T}\Gamma_C^{-1}\dot{\hat C}\\ =&\ \varepsilon\Big(F + GNz_2 + GN\alpha + G(N-1)\dot q_{ref} - GC\Big) + \varepsilon G\omega - \tilde C^{\mathrm T}\Gamma_C^{-1}\dot{\hat C}\\ =&\ \varepsilon\Big(F + GNz_2 + GN\alpha + G(N-1)\dot q_{ref} - GC\Big) - \tilde C^{\mathrm T}\Gamma_C^{-1}\dot{\hat C}\\ &-\left\|\frac{\varepsilon G}{2\gamma_1} - \gamma_1\omega\right\|^2 + \frac{\varepsilon^2G^2}{4\gamma_1^2} + \gamma_1^2\|\omega\|^2\\ \le&\ \varepsilon\left(F + GNz_2 + GN\alpha + G(N-1)\dot q_{ref} - GC + \frac{\varepsilon G^2}{4\gamma_1^2}\right)\\ &+\gamma_1^2\|\omega\|^2 - \tilde C^{\mathrm T}\Gamma_C^{-1}\dot{\hat C}\end{aligned} \tag{17}$$

Choose the virtual controller α as

$$\alpha = \frac{1}{GN}\left(-c_1\varepsilon - F - G(N-1)\dot q_{ref} - \frac{\varepsilon G^2}{4\gamma_1^2} + G\hat C\right) \tag{18}$$

where $c_1 > 1$ is a positive constant. If (18) is plugged into (17), $\dot V_1$ becomes

$$\dot V_1 \le -c_1\varepsilon^2 + \varepsilon GNz_2 + \gamma_1^2\|\omega\|^2 - \tilde C^{\mathrm T}\Gamma_C^{-1}\left(\dot{\hat C} + \Gamma_C G^{\mathrm T}\varepsilon\right) \tag{19}$$

Step 2. It is clear that

$$\dot z_2 = \dot e_2 - \dot\alpha = \bar f + \bar g u - \dot\alpha \tag{20}$$

Differentiating α gives

$$\begin{aligned}\dot\alpha =&\ \frac{\partial\alpha}{\partial G}\left(\frac{\partial G}{\partial\varepsilon}\dot\varepsilon + \frac{\partial G}{\partial\rho}\dot\rho\right) + \frac{\partial\alpha}{\partial\varepsilon}\dot\varepsilon + \frac{\partial\alpha}{\partial F}\left(\frac{\partial F}{\partial\varepsilon}\dot\varepsilon + \frac{\partial F}{\partial\rho}\dot\rho + \frac{\partial F}{\partial\dot\rho}\ddot\rho\right) + \frac{\partial\alpha}{\partial\dot q_{ref}}\ddot q_{ref} + \frac{\partial\alpha}{\partial\hat C}\dot{\hat C}\\ =&\ \left(\frac{\partial\alpha}{\partial G}\frac{\partial G}{\partial\varepsilon} + \frac{\partial\alpha}{\partial\varepsilon} + \frac{\partial\alpha}{\partial F}\frac{\partial F}{\partial\varepsilon}\right)\Big(F + G\Big(Ne_2 + (N-1)\dot q_{ref} + \omega - C\Big)\Big)\\ &+\frac{\partial\alpha}{\partial\dot q_{ref}}\ddot q_{ref} + \frac{\partial\alpha}{\partial\hat C}\dot{\hat C} + \frac{\partial\alpha}{\partial G}\frac{\partial G}{\partial\rho}\dot\rho + \frac{\partial\alpha}{\partial F}\frac{\partial F}{\partial\rho}\dot\rho + \frac{\partial\alpha}{\partial F}\frac{\partial F}{\partial\dot\rho}\ddot\rho\\ =&\ \left(\frac{\partial\alpha}{\partial G}\frac{\partial G}{\partial\varepsilon} + \frac{\partial\alpha}{\partial\varepsilon} + \frac{\partial\alpha}{\partial F}\frac{\partial F}{\partial\varepsilon}\right)\Big(F + G\Big(Ne_2 + (N-1)\dot q_{ref}\Big)\Big)\\ &+\frac{\partial\alpha}{\partial\dot q_{ref}}\ddot q_{ref} + \frac{\partial\alpha}{\partial\hat C}\dot{\hat C} + \frac{\partial\alpha}{\partial G}\frac{\partial G}{\partial\rho}\dot\rho + \frac{\partial\alpha}{\partial F}\frac{\partial F}{\partial\rho}\dot\rho + \frac{\partial\alpha}{\partial F}\frac{\partial F}{\partial\dot\rho}\ddot\rho\\ &+\left(\frac{\partial\alpha}{\partial G}\frac{\partial G}{\partial\varepsilon} + \frac{\partial\alpha}{\partial\varepsilon} + \frac{\partial\alpha}{\partial F}\frac{\partial F}{\partial\varepsilon}\right)(G\omega - GC)\\ =&\ \Lambda_1 + \Lambda_2(G\omega - GC)\end{aligned} \tag{21}$$

where

$$\begin{aligned}\Lambda_1 =&\ \left(\frac{\partial\alpha}{\partial G}\frac{\partial G}{\partial\varepsilon} + \frac{\partial\alpha}{\partial\varepsilon} + \frac{\partial\alpha}{\partial F}\frac{\partial F}{\partial\varepsilon}\right)\Big(F + G\Big(Ne_2 + (N-1)\dot q_{ref}\Big)\Big)\\ &+\frac{\partial\alpha}{\partial\dot q_{ref}}\ddot q_{ref} + \frac{\partial\alpha}{\partial\hat C}\dot{\hat C} + \frac{\partial\alpha}{\partial G}\frac{\partial G}{\partial\rho}\dot\rho + \frac{\partial\alpha}{\partial F}\frac{\partial F}{\partial\rho}\dot\rho + \frac{\partial\alpha}{\partial F}\frac{\partial F}{\partial\dot\rho}\ddot\rho\\ \Lambda_2 =&\ \frac{\partial\alpha}{\partial G}\frac{\partial G}{\partial\varepsilon} + \frac{\partial\alpha}{\partial\varepsilon} + \frac{\partial\alpha}{\partial F}\frac{\partial F}{\partial\varepsilon}\end{aligned}$$

The Lyapunov function is chosen as

$$V = V_1 + \frac{1}{2}z_2^2$$

Differentiating V with respect to time yields

$$\begin{aligned}\dot{V} =& \dot{V}_1 + z_2\dot{z}_2\\ \le& -c_1\varepsilon^2 + GN\varepsilon z_2 + \gamma_1^2\|\omega\|^2 - \tilde{C}^T\Gamma_C^{-1}\left(\dot{\hat{C}} + \Gamma_C G^T\varepsilon\right)\\ &+z_2\left(\bar{f} + \bar{g}u - \Lambda_1 + \Lambda_2 G\hat{C}\right)\\ &-z_2\Lambda_2 G\omega + z_2\Lambda_2 G\tilde{C}\\ =& -c_1\varepsilon^2 + GN\varepsilon z_2 + \gamma_1^2\|\omega\|^2 - \tilde{C}^T\Gamma_C^{-1}\left(\dot{\hat{C}} + \Gamma_C G^T\varepsilon - \Gamma_C G^T\Lambda_2^T z_2\right)\\ &+z_2\left(\bar{f} + \bar{g}u - \Lambda_1 + \Lambda_2 G\hat{C}\right)\\ &-\left\|\frac{z_2\Lambda_2 G}{2\gamma_2} + \gamma_2\omega\right\|^2 + \frac{z_2^2\Lambda_2^2G_2^2}{4\gamma_2^2} + \gamma_2^2\|\omega\|^2\\ \le& -c_1\varepsilon^2 - \tilde{C}^T\Gamma_C^{-1}\left(\dot{\hat{C}} + \Gamma_C G^T\varepsilon - \Gamma_C G^T\Lambda_2^T z_2\right)\\ &+z_2\left(GN\varepsilon + \bar{f} + \bar{g}u - \Lambda_1 + \Lambda_2 G\hat{C} + \frac{z_2\Lambda_2^2G_2^2}{4\gamma_2^2}\right)\\ &+\left(\gamma_1^2 + \gamma_2^2\right)\|\omega\|^2\\ =& -c_1\varepsilon^2 + z_2\left(GN\varepsilon + \bar{f} + \bar{g}u - \Lambda_1 + \Lambda_2 G\hat{C} + \frac{z_2\Lambda_2^2G_2^2}{4\gamma_2^2}\right)\\ &-\tilde{C}^T\Gamma_C^{-1}\left(\dot{\hat{C}} + \Gamma_C G^T\varepsilon - \Gamma_C G^T\Lambda_2^T z_2\right) + \gamma^2\|\omega\|^2\end{aligned} \tag{22}$$

with $\gamma^2 = \gamma_1^2 + \gamma_2^2$.

Choose the control law $u(t)$ and the adaptive law $\dot{\hat{C}}$ as

$$u = \bar{g}^{-1}\left(-c_2 z_2 - GN\varepsilon - \bar{f} + \Lambda_1 - \Lambda_2 G\hat{C} - \frac{z_2\Lambda_2^2G_2^2}{4\gamma_2^2}\right) \tag{23}$$

$$\dot{\hat{C}} = -\Gamma_C G^T\varepsilon + \Gamma_C G^T\Lambda_2^T z_2 \tag{24}$$

where $c_2 > 0$ is a design parameter. Substituting (23) and (24) into (22) produces

$$\dot{V} \le -c_1\|\varepsilon\|^2 - c_2\|z_2\|^2 + \gamma^2\|\omega\|^2 \tag{25}$$

with $\omega = 0$, which implies that ε approaches zero. It can be calculated from (9) and (10) that $\varepsilon = \frac{1}{2}\ln\frac{\rho(t)+e_1(t)}{\rho(t)-e_1(t)}$. Thus, the tracking error e_1 also goes to zero.

In order to verify H_∞ performance of the system, (25) is transformed into (26).

$$\dot{V} \le -c_1\|\varepsilon\|^2 + \gamma^2\|\omega\|^2 \tag{26}$$

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

$$\dot{V} \le -(c_{10} + 1)\|\varepsilon\|^2 + \gamma^2\|\omega\|^2 \le -\|\varepsilon\|^2 + \gamma^2\|\omega\|^2 \tag{27}$$

Integrating (27) gets

$$V - V(0) \le \int_0^T \left(\gamma^2\|\omega\|^2 - \|\varepsilon\|^2\right)dt \tag{28}$$

which means that

$$\begin{aligned}\int_0^T \|\varepsilon\|^2 dt \le& \gamma^2\int_0^T \|\omega\|^2 dt - V + V(0)\\ \le& \gamma^2\int_0^T \|\omega\|^2 dt + V(0)\\ =& \gamma^2\int_0^T \|\omega\|^2 dt + \delta(x_0)\end{aligned} \tag{29}$$

Because $S(\varepsilon)$ is selected as the hyperbolic tangent function in this work, that is, $tanh(\varepsilon)$, and $tanh^2(\varepsilon) \le \varepsilon^2$, the following inequality holds

$$\|e_1\|^2 = \|S(\varepsilon)\rho(t)\|^2 \le \|\varepsilon\|^2\rho_0^2 \tag{30}$$

It can be deduced from (29) and (30) that one has

$$\int_0^T \|e_1\|^2 dt \le \tilde{\gamma}^2\int_0^T \|\omega\|^2 dt + \tilde{\delta}(x_0) \tag{31}$$

with $\tilde{\gamma}^2 = \rho_0^2\gamma^2$ and $\tilde{\delta}(x_0) = \rho_0^2\delta(x_0)$. As a result, the L_2 gain from the disturbance input to the controlled output of the closed-loop system is not bigger than $\tilde{\gamma}$. □

4. Simulation results

In this section, a typical dumbbell topology, which is shown in Fig. 1, is considered. From Fig. 1, it can be observed that the bottleneck link locates between router 1 and router 2 and N sources send data flows to their respective receivers through the bottleneck. The proposed approach is performed by using Matlab. Firstly, the corresponding system parameters, design parameters, external disturbance, and unknown parameters in system (4) are given as follows.

$$\begin{aligned}N =& 60,\ C = 1750 packets/s,\ T_p = 0.1s,\\ c_1 =& 25,\ c_2 = 15,\ \gamma_1 = 4,\ \gamma_2 = 1,\ \Gamma_C = 10,\\ \omega =& 1,\ q_{ref} = 100,\ \rho_0 = 0.2,\ \rho_\infty = 0.01,\ \lambda = 1,\\ x(0) =& \left[100.1\ \ 0\ \ 0\right]^T\end{aligned} \tag{32}$$

And $S(\varepsilon)$ is selected as

$$S(\varepsilon) = \frac{e^\varepsilon - e^{-\varepsilon}}{e^\varepsilon + e^{-\varepsilon}} \tag{33}$$

Simulation results are collected and recorded in Figs. 2–3. The control law u is shown in the left figure of Fig. 2. It can be seen that its trajectory is always between 0.1 and 0.2, that is, the probability of packet loss is very small. The right figure in Fig. 2 shows the curve of the adaptive law. It can be observed that the adaptive controller can estimate link capacity C well with the proposed adaptive law. The result of the tracking error is provided in the left figure of Fig. 3, where the tracking error keeps in the prescribed range all the time. The situation that the queue tracks the desired

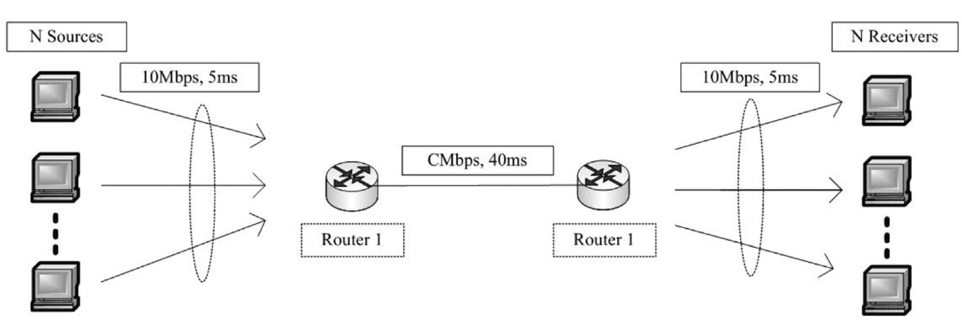

Fig. 1. Simulation topology.

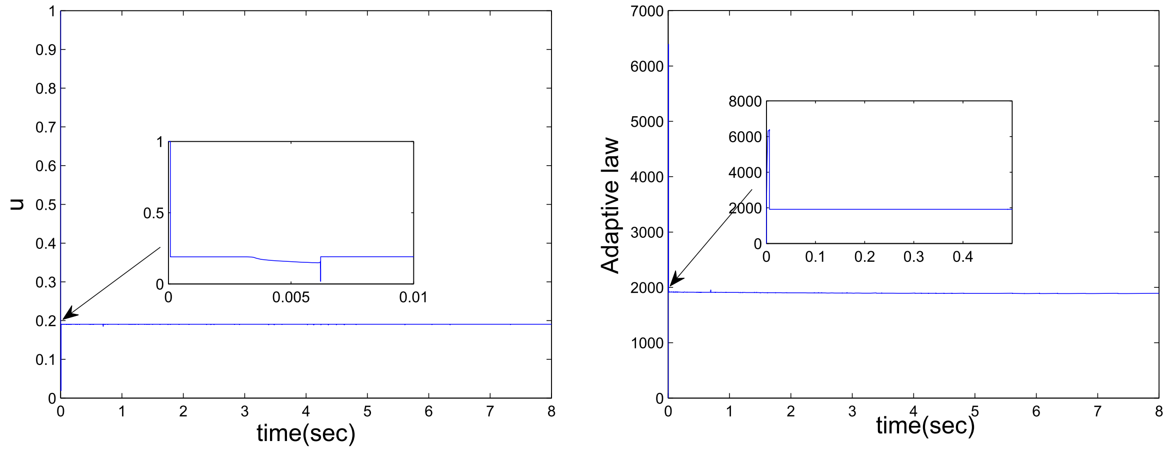

Fig. 2. Left is the control law and right is the adaptive law.

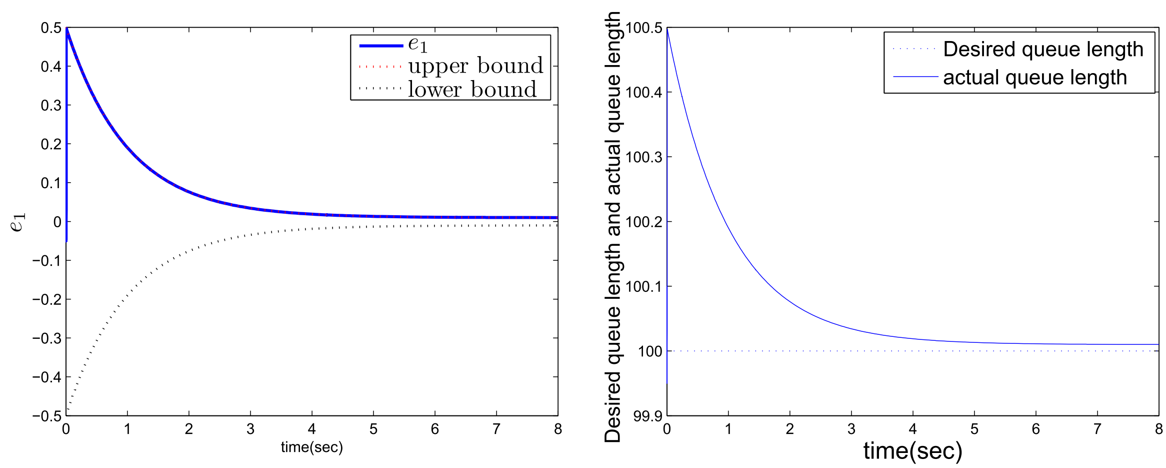

Fig. 3. Left is the tracking error and right is the queue and desired queue length.

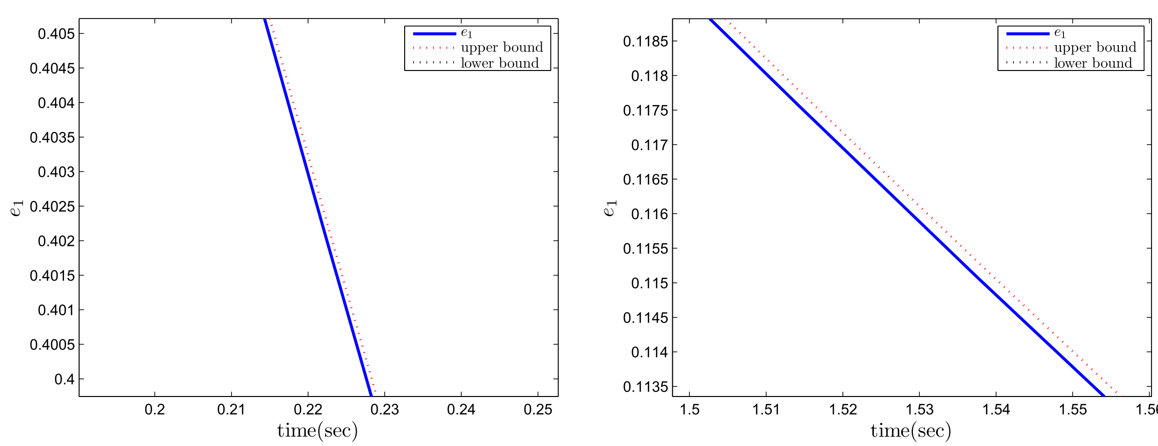

Fig. 4. Left is the e_1 from 0.2 s to 0.25 s and right is the e_1 from 1.5 s to 1.56 s.

queue is shown in the right figure of Fig. 3. The result shows that the queue can track the desired queue in the allowable error range. Figs.4 and 5 are part of the e_1 in different time scales. These two figures illustrate that the error curve is always under the upper bound. From above results, it is obvious that the proposed scheme is effective.

Besides, in order to explain the superiority of the presented approach better, the simulation comparison is made between the proposed method and the backstepping and integral backstepping techniques by considering three different initial errors. The parameters of the proposed controller are $c_1 = 15, c_2 = 10$. The parameters in the backstepping and integral backstepping methods are $c_1 = 10, c_2 = 20, \gamma_1 = 50, \gamma_2 = 0.1$, and $c_1 = 1, c_2 = 15, \gamma_1 = 3, \gamma_2 = 2, \beta = 1$, respectively. Other parameters are the same with (32). The initial conditions are set to $x(0) = [100.1\ 0\ 0]^T$, $x(0) = [110.1\ 0\ 0]^T$, and $x(0) = [180.1\ 0\ 0]^T$, that is, $e_1(0) = 0.1, 10.1$, and 80.1, and $\rho_0 = 0.2, 11$, and 81.

The comparison results are shown in Figs. 6–7. It follows from the Figs. 6–7 that the presented method makes the output tracking

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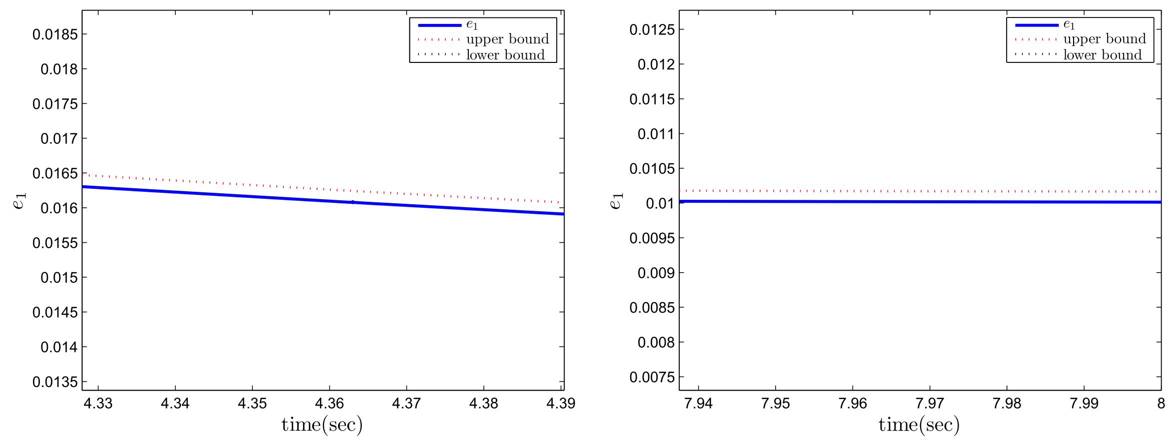

Fig. 5. Left is the e_1 from 4.33 s to 4.39 s and right is the e_1 from 7.94 s to 8 s.

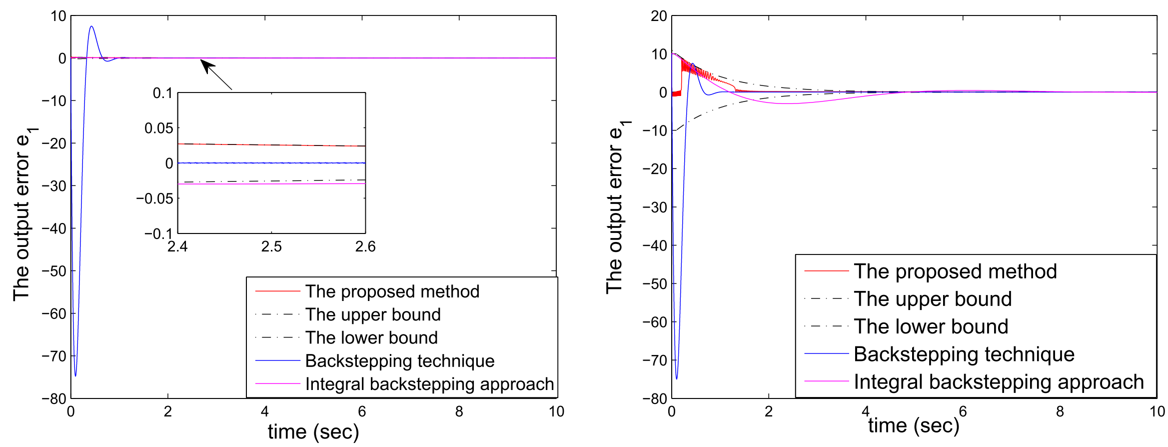

Fig. 6. Left is the comparison results with $e_1(0) = 0.1$ and right is the comparison results with $e_1(0) = 10.1$.

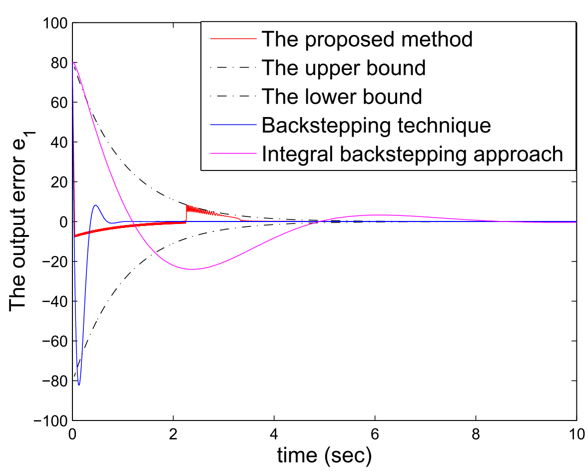

Fig. 7. The comparison results with $e_1(0) = 80.1$.

error $e_1(t)$ converge faster than another two techniques. Moreover, by using proposed controller, $e_1(t)$ converges to an arbitrarily small residual set, which was prescribed initially. It can also be observed that the proposed controller makes the maximum overshoot less than and the convergence rate faster than the predefined values by using proposed controller. However, the existing design methods cannot guarantee the above mentioned performance based on simulation results. Although the error $e_1(t)$ is close to the upper bound in the left Figure of the Fig. 6, it can be seen clearly from Figs. 4 and 5 that it is still between the upper bound and the lower bound.

5. Conclusions

In this paper, a modified TCP/AQM model has been proposed by combining the two existing models and a novel adaptive congestion controller has been designed based on prescribed performance, backstepping technique, adaptive control and H_∞ theory. The developed controller not only can guarantee that the queue length tracks the desired queue length, but also tracking error converges to the prescribed area. Meanwhile, the unknown parameter, namely, link capacity, can be estimated well with the proposed adaptive controller. Finally, it is pointed out that the effectiveness and superiority of the proposed approach have been verified via simulation results.

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