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Backstepping Based Variable Structure Controller Design for DiffServ Network

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Abstract—**In this paper, a nonlinear fluid flow model is used to analyze and control DiffServ Network. Backstepping design procedure is applied, which leads to a new adaptive sliding mode controller. In order to use backstepping design, the model is transformed into a parametric strict feedback form. And by using the adaptive backstepping sliding mode controller, buffer queue length regulation achieved against unknown system dynamics and uncertain disturbances. Under the ideal sliding mode, asymptotic stability is reached. The performance of the control scheme is verified by the simulation results.**

I. INTRODUCTION

THE DiffServ Network that is under consideration by IETF(Internet Engineering Task Force) can provide different services to users of the Internet [1]. It adheres to the basic Internet philosophy and can be seen as a kind of extending of the Internet. There are two important services of DiffServ Network, one is premium traffic service and the other is ordinary traffic service. Premium service is designed for applications with stringent delay and loss requirements on per packet basis that can specify upper bounds on their traffic needs and required quality of service [2], while ordinary traffic is intended for applications that have relaxed delay requirements and allow their rates into the network to be controlled [3].

For DiffServ Network, the fluid flow model is extensively used for network performance evaluation and control, especially for congestion control problems. Recently, in order to develop the network congestion controller, model-based schemes have been proposed to provide theoretic analysis for networking problems, but most of them are based on linear control theory. For example, analysis and control design tools are applied to control traffic in ATM networks [4] and analyze the stability of congestion control schemes in TCP/IP networks [5-8]. But due to the inaccurate and uncertain nature of network models, the design of congestion controllers whose performance can be analytically established and demonstrated in practice is still a challenging unresolved problem.

Sliding mode control (SMC), as a special class of nonlinear systems is widely accepted as a feasible robust control for dynamic systems [9]. The backstepping method is a breakthrough for adaptive nonlinear control. It provides a systematic procedure to construct a robust control Lyapunov function. So integrating backstepping algorithm into the design of SMC is an effective method for a kind of nonlinear system with uncertainties and disturbances [10], [11].

In this paper, our attention is focus on applying backstepping design with adaptive SMC to address the queue regulation of premium and ordinary buffers in DiffServ Network, especially when nonlinear uncertainties and disturbances are involved. An integrated idea is that the sliding surface as a linear combination of the control errors is constructed at the final step of the backstepping design. The SMC term ensures the convergence of the system states to the sliding surface, then the convergence of control errors are also ensured.

The rest of the paper is organized as follows: in section II, the problem statement is given by changing the fluid flow model into a nonlinear parametric strict feedback form as well as considering the unknown system dynamics and external disturbances. The backstepping design of adaptive SMC is described in section III, the stability analysis is integrated into the design procedure. In section IV simulations are performed in order to illustrate the feasibility of the control scheme and the conclusion is given in the last section.

II. PROBLEM STATEMENT

Based on fluid flow theory, a validated nonlinear DiffServ Network buffer dynamic is given as follows [3].

$$\dot{x}(t) = -C(t)(\frac{x(t)}{1+x(t)}) + \lambda(t) \tag{1}$$

where $x(t)$ denotes the queue length of the buffer, and it is taken as the state variable; $C(t)$ represents the to-be-assigned capacity, and it is chosen as the control input for premium buffer; while a nonlinear function $\lambda(t)$ is used to denote the

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average incoming traffic rate, and it is chosen as the control input for ordinary buffer.

For control purpose, the model might be represented as a system of coupled state and output equations

$$\begin{cases} \dot{x}_i(t) = -C_i(t)(\dfrac{x_i(t)}{x_i(t)+1}) + \lambda_i(t) \\ y_i(t) = x_i(t) \end{cases}. \quad (2)$$

Notice that the index $i=(p,r)$ represents premium and ordinary buffers dynamic respectively [12] here and all over this paper.

For the purpose of backstepping design, the given model in (2) is transformed into a new nonlinear parametric strict feedback form (NPSF) [13], with the following changes of coordinates, $x_{1p} = x_p$, $x_{2p} = -x_p/(x_p+1)$ for the premium buffer and $x_{1r} = x_r$, $x_{2r} = -x_r/(x_r+1)$ for the ordinary buffer.

We can have

$$\begin{cases} \dot{x}_{1i} = -C_i x_{2i} + \lambda_i \\ \dot{x}_{2i} = C_i \dfrac{-x_{2i} + \lambda_i}{\left(x_{1i}+1\right)^2} \\ y_i = x_{1i} \end{cases}. \quad (3)$$

With the same index $i=(p,r)$, we introduce new state variables $w_{1i} = x_{1i}, w_{2i} = \dot{w}_{1i}$, which after substitution into equation (3), will lead to the following NPSF representation:

$$\begin{cases} \dot{w}_{1i} = w_{2i} \\ \dot{w}_{2i} = -C_i \dfrac{w_{2i}}{(w_{1i}+1)^2} + \dot{\lambda}_i \\ y_i = w_{1i} \end{cases}. \quad (4)$$

Considering the unknown dynamics and external disturbances in DiffServ network [14], the system is reformulated as follows:

$$\dot{w}_{2i} = -C_i(\frac{w_{2i}}{(w_{1i}+1)^2} + \Delta_{1i}) + \dot{\lambda}_i + \Delta_{2i} \quad (5)$$

where Δ_{1i} denotes the unknown system dynamics and Δ_{2i} is the uncertain external disturbances.

That is

$$\begin{cases} \dot{w}_{1i} = w_{2i} \\ \dot{w}_{2i} = -C_i(\dfrac{w_{2i}}{(w_{1i}+1)^2}) + \dot{\lambda}_i + F_i \\ y_i = w_{1i} \end{cases} \quad (6)$$

where F is the lumped uncertainty defined by

$$F_i = \Delta_{2i} - C_i \Delta_{1i}. \quad (7)$$

III. PROPOSED ADAPTIVE SMC BACKSTEPPING CONTROLLER

A. The Control Strategy

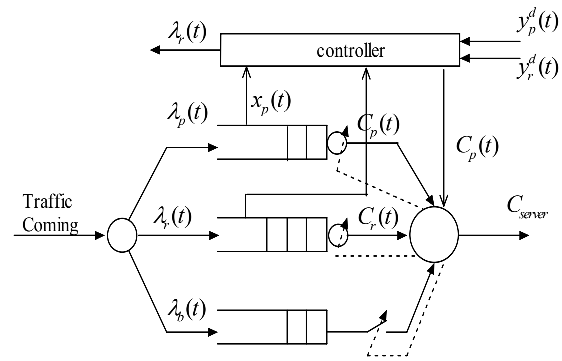

Fig. 1. Schematic diagram of the control strategy

For system (6), the state variables are w_{1i} w_{2i}, the control strategy is shown in Fig.1. For premium buffer the control signal is link capacity $C_p(t)$ and the data coming rate $\lambda_p(t)$ can be treated as disturbance of the system, so the control purpose is that thru accommodating link capacity let the system output signal w_{1p} trace the desired reference queue length y_p^d ; For ordinary buffer the link capacity $C_r(t)$ is the left over capacity calculated from $C_r(t) = C(t) - C_p(t)$ which is uncontrolled, so the control signal is $\dot{\lambda}_r(t)$, the control purpose of ordinary buffer is that thru adjusting the arriving rate of data $\lambda_r(t)$ let the output signal w_{1r} trace the desired reference queue length y_r^d .

B. Backstepping Design Procedure

The control objective is to design an adaptive backstepping sliding mode control system for the output of the system shown in (6) to track the reference trajectory, which is asymptotically. The proposed adaptive backstepping sliding mode control system is designed to achieve the position tracking objective and is described step by step as follows:

Step 1): For the tracking objective, define the tracking error as

$$z_{1i} = w_{1i} - y_i^d \quad (8)$$

and its first derivative is

$$\dot{z}_{1i} = \dot{w}_{1i} - \dot{y}_i^d = w_{2i} - \dot{y}_i^d . \quad (9)$$

Treating w_{2i} as a control signal for (9), the control law w_{2i}^d for w_{2i} which stabilizes w_{1i} would be

$$w_{2i}^d = -c_{1i} z_{1i} + \dot{y}_i^d . \quad (10)$$

where c_{1i} is a positive constant.

Define z_{2i} as the difference between w_{2i} and w_{2i}^d, we get

$$z_{2i} = w_{2i} - w_{2i}^d = w_{2i} + c_{1i} z_{1i} - \dot{y}_i^d . \quad (11)$$

Substituting (10) into (11)

$$\dot{z}_{1i} = w_{2i} - \dot{y}_i^d = z_{2i} - c_{1i} z_{1i} . \quad (12)$$

Then let

$$\alpha_{1i} = c_{1i} z_{1i} , \quad (13)$$

z_{2i} is written as

$$z_{2i} = w_{2i} + \alpha_{1i} - \dot{y}_i^d . \quad (14)$$

The first Lyapunov function is chosen as

$$V_{1i} = \frac{1}{2} z_{1i}^2, \quad (15)$$

and the derivative of V_{1i} is

$$\dot{V}_{1i} = z_{1i}\dot{z}_{1i} = z_{1i}(-c_{1i}z_{1i} + z_{2i}) = -c_{1i}z_{1i}^2 + z_{1i}z_{2i}. \quad (16)$$

Step 2): The derivative of z_{2i} is expressed as

$$\dot{z}_{2i} = \dot{w}_{2i} + \dot{\alpha}_{1i} - \ddot{y}_i^d = -C_i \frac{w_{2i}}{(w_{1i}+1)^2} + \dot{\lambda}_i + F_i + \dot{\alpha}_{1i} - \dot{y}_i^d . \quad (17)$$

Here, to design the backstepping controller, the uncertainty is assumed to be bounded, $|F_i| \le \bar{F}_i$, and define the sliding surface as

$$s_i = g_{1i} z_{1i} + z_{2i} \quad (18)$$

where g_{1i} is a positive constants.

Choose the second Laypunov function as:

$$V_{2i} = V_{1i} + \frac{1}{2} s_i^2. \quad (19)$$

The derivative of V_{2i} can be derived as follows:

$$\begin{aligned}
\dot{V}_{2i} &= \dot{V}_{1i} + s_i\dot{s}_i \\
&= -c_{1i}z_{1i}^2 + z_{1i}z_{2i} + s_i\dot{s}_i \\
&= -c_{1i}z_{1i}^2 + z_{1i}z_{2i} + s_i(g_{1i}\dot{z}_{1i} + \dot{z}_{2i}) \\
&= -c_{1i}z_{1i}^2 + z_{1i}z_{2i} + s_i[g_{1i}(-c_{1i}z_{1i} + z_{2i}) - C_i \frac{w_{2i}}{(w_{1i}+1)^2} \\
&\qquad + \dot{\lambda}_i + F_i + \dot{\alpha}_1 - \dot{y}_i^d].
\end{aligned} \quad (20)$$

According to (20), a backstepping sliding mode controller is designed as

$$\begin{aligned}
C_P = -\frac{(w_{1p}+1)^2}{w_{2p}} &[-\dot{\lambda}_p - g_{1p}(-c_{1p}z_{1p} + z_{2p}) - \bar{F}_p \operatorname{sgn}(s_p) \\
&- K_p s_p - \varepsilon_p \operatorname{sgn}(s_p) - \dot{\alpha}_{1p} + \ddot{y}_p^d],
\end{aligned} \quad (21)$$

$$\begin{aligned}
\dot{\lambda}_r = -g_{1r}(-c_{1r}z_{1r} + z_{2r}) + C_r \frac{w_{2r}}{(w_{1r}+1)^2} - \bar{F}_r \operatorname{sgn}(s_r) \\
- K_r s_r - \varepsilon_r \operatorname{sgn}(s_r) - \dot{\alpha}_{1r} + \ddot{y}_r^d.
\end{aligned} \quad (22)$$

where K_i and ε_i are positive constant.

Step 3): Since the lumped uncertainty F is unknown in practical application, the upper bound $\bar{F}$ is difficult to determine; therefore, an adaptive law is proposed to adapt the value of the lumped uncertainty.

Then, the third Lyapunov function is chosen as

$$V_{3i} = V_{2i} + \frac{1}{2\gamma_i} \tilde{F}_i^2 \quad (23)$$

where $\tilde{F}_i = F_i - \hat{F}_i$, $\hat{F}_i$ is the prediction of system uncertainty and γ_i is a positive constant.

The derivative of V_{3i} is

$$\begin{aligned}
\dot{V}_{3i} &= \dot{V}_{2i} - \frac{1}{\gamma_i}\tilde{F}_i\dot{\hat{F}}_i \\
&= -c_{1i}z_{1i}^2 + z_{1i}z_{2i} + s_i[g_{1i}(-c_{1i}z_{1i} + z_{2i}) - C_i \frac{w_{2i}}{(w_{1i}+1)^2} \\
&\qquad + \dot{\lambda}_i + F_i + \dot{\alpha}_{1i} - \ddot{y}_i^d] - \frac{1}{\gamma_i}\tilde{F}_i\dot{\hat{F}}_i \quad (24) \\
&= -c_{1i}z_{1i}^2 + z_{1i}z_{2i} + s_i[g_{1i}(-c_1 z_1 + z_2) - C_i \frac{w_{2i}}{(w_{1i}+1)^2} \\
&\qquad + \dot{\lambda}_i + \hat{F}_i + \dot{\alpha}_{1i} - \ddot{y}_i^d] - \frac{1}{\gamma_i}\tilde{F}_i(\dot{\hat{F}}_i - \gamma_i s_i).
\end{aligned}$$

According to (24), an adaptive backstepping sliding mode control law is proposed as follows:

$$\begin{aligned}
C_P = -\frac{(w_{1p}+1)^2}{w_{2p}} &[-\dot{\lambda}_p - g_{1p}(-c_{1p}z_{1p} + z_{2p}) - \hat{F}_p \operatorname{sgn}(s_p) \\
&- K_p s_p - \varepsilon_p \operatorname{sgn}(s_p) - \dot{\alpha}_{1p} + \ddot{y}_p^d],
\end{aligned} \quad (25)$$

$$\begin{aligned}
\dot{\lambda}_r = -g_{1r}(-c_{1r}z_{1r} + z_{2r}) + C_r \frac{w_{2r}}{(w_{1r}+1)^2} - \hat{F}_r \operatorname{sgn}(s_r) \\
- K_r s_r - \varepsilon_r \operatorname{sgn}(s_r) - \dot{\alpha}_{1r} + \ddot{y}_r^d.
\end{aligned} \quad (26)$$

The adaptation law for $\dot{\hat{F}}_i$ is designed as

$$\dot{\hat{F}}_i = \gamma_i s_i . \quad (27)$$

C. *Stability Analysis*

Theorem 1: For the dynamic system in (6), the tracking error $x_{1i} - y_i^d$ converges to zero asymptotically with the control of premium buffer link capacity C_P in (25) and ordinary buffer arriving rate $\dot{\lambda}_r$ in (26) if the coefficients satisfy $K_i(c_{1i} + g_{1i}) > 1/4$.

Proof: Substitute (25) (27) and (26) (27) into (24) separately, for both premium and ordinary buffer the expressions are the same, here to be brief, omit the indices $i = (p, r)$, then we can get

$$\begin{aligned}
\dot{V}_3 &= -c_1 z_1^2 + z_1 z_2 + s(-Ks - \varepsilon \operatorname{sgn}(s)) \\
&= -c_1 z_1^2 + z_1 z_2 - Ks^2 - \varepsilon |s|.
\end{aligned} \quad (28)$$

where K and ε are the positive constant defined in equation (21) and (22).

Note that (28) can be written as

$$\dot{V}_3 = -\mathbf{z}^T \mathbf{P} \mathbf{z} - \varepsilon |s| \quad (29)$$

where $\mathbf{P}$ is a symmetric matrix with the following form

$$\mathbf{P} = \begin{bmatrix} c_1 + Kg_1^2 & Kg_1 - 1/2 \\ Kg_1 - 1/2 & K \end{bmatrix} \quad (30)$$

and $\mathbf{z}^T = [z_1 \;\; z_2]$.

Note that if $\mathbf{P}$ is positive then $\dot{V}_3$ is negative and a sufficient condition to guarantee that $\mathbf{P}$ is positive definite is

$$\begin{aligned} |\mathbf{P}| &= K(c_1 + Kg_1^2) - (Kg_1 - 1/2)^2 \\ &= K(c_1 + g_1) - 1/4 > 0. \end{aligned} \tag{31}$$

That is

$$K(c_1 + g_1) > 1/4, \tag{32}$$

then $\dot{V}_3 < 0$.

So, when $t \to \infty$, z_1 and z_2 converge to zero. As a result, the stability of the proposed adaptive backstepping sliding mode control system can be guaranteed, moreover, since the condition holds $s\dot{s} < 0$, sliding mode is guaranteed on the sliding surface $s = 0$. So it is true that $x_{1p} - y_p^d \to 0$ and $x_{1r} - y_r^d \to 0$, asymptotically.

IV. Simulation Results

Simulation results for premium buffer and ordinary buffer are showed separately. During the simulation, $x_p(0) = 90$ and $x_r(0) = 22$. The controller design parameters are set to c_{1i}=1, $g_{1i} = 1$ and $\gamma_i = 0.2$. While to avoid infinite frequency switching of the control signal, a boundary layer with $\psi = 0.02$ is used.

For premium buffer the desired reference queue length y_p^d is a constant 100, the desired (solid) and actual (dashed) trajectories are showed in Fig. 2. It is showed that $x_p(t)$ converges to $y_p^d = 100$ very quickly. The tracking errors z_{1p} and z_{2p} converges to zero and the control signal $C_p(t)$ are presented in Fig. 3 and Fig. 4.

For ordinary buffer the desired reference queue length y_r^d is a sine wave showed in Fig. 5 in solid and the actual trajectory is in dashed. It is showed that $x_r(t)$ converges to y_r^d very quickly. The tracking errors z_{1r} and z_{2r} converge to zero, and the control signal $\dot{\lambda}(t)$ are presented in Fig. 6 and Fig. 7.

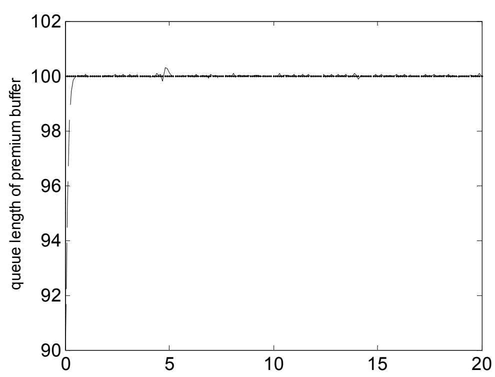

Fig. 2. Buffer length of premium traffic $x_p(t)$ and y_p^d

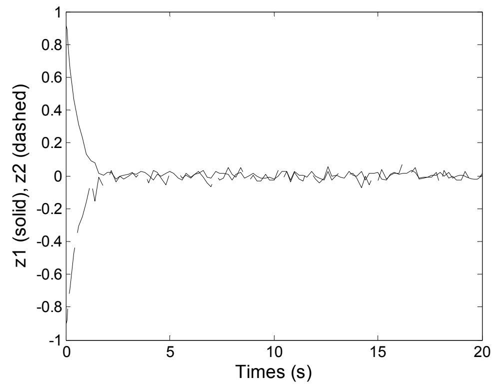

Fig. 3. Tracking error of premium traffic z_{1p} and z_{2p}

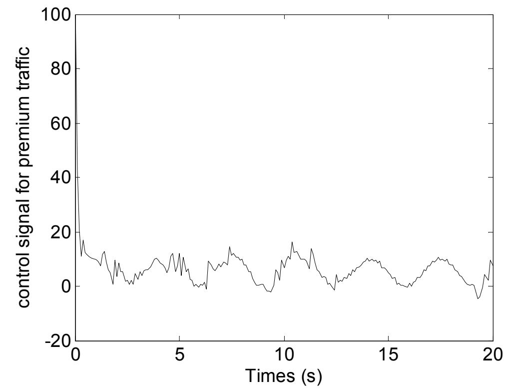

Fig. 4. Control signal for premium traffic

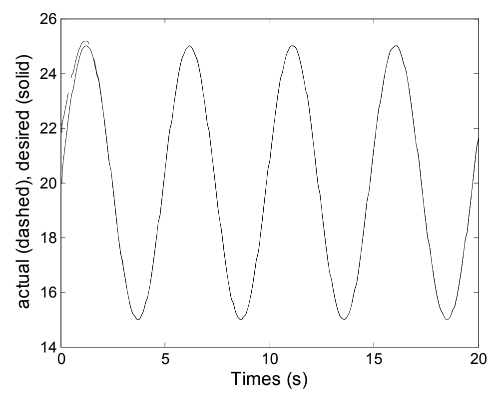

Fig. 5. Buffer length of ordinary traffic $x_r(t)$ and y_r^d

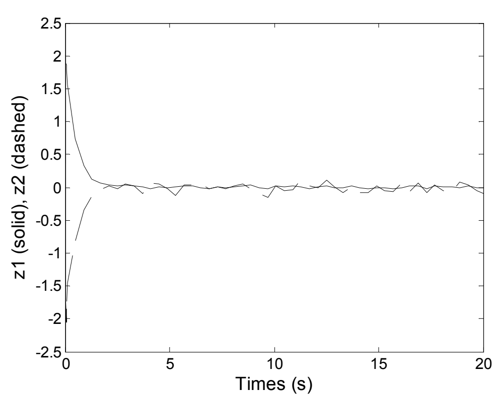

Fig. 6. Tracking error of ordinary traffic z_{1r} and z_{2r}

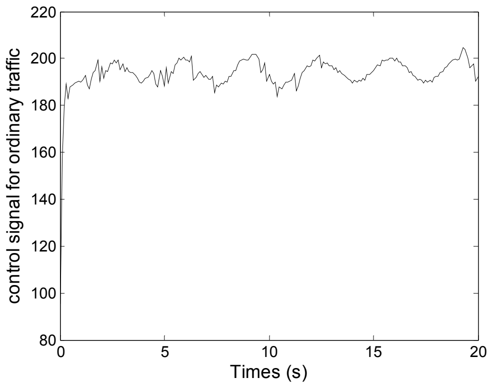

Fig. 7. Control signal for ordinary traffic

Remark: In ordinary traffic a step disturbance is added when $t = 10s$. Fig. 8 shows that the queue length has no difficulty to trace the reference length. The tracking error converges to zero as well. However, a classical backstepping controller will probably fail dealing with disturbances [15].

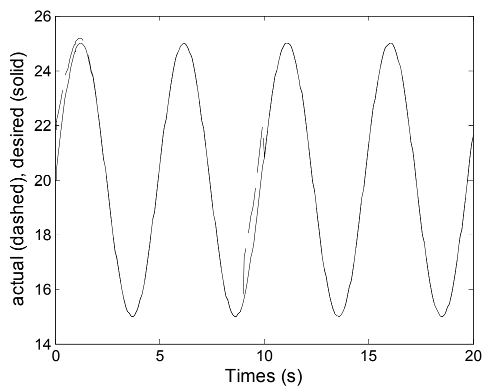

Fig. 8. Ordinary buffer length with a disturbance

V. Conclusion

This paper is concerned with the adaptive sliding mode control by using backstepping design for DiffServ Network. The robustness of the proposed controller guarantees the regulation of the queue length with unknown model dynamics and uncertain external disturbances. In effect, the simulation results demonstrate that in both premium and ordinary buffer the proposed method can obtain faster transients and less oscillatory responses under dynamic network conditions, which translates into higher link utilization, low packet loss rate and small queue fluctuations.

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