A New Scheme for Network Congestion Control Based on Modified Adaptive Smith Predictor

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***Abstract* -- In this paper, a simplified network model based on fluid flow theory and stochastic differential equations is derived. Based on the linearized TCP/AQM model, the modified adaptive strategy is applied to adjust the traditional Smith predictor for reducing the dependency on the mathematical model. Then, an Adaptive Modified Smith-PI controller (AMS-PI) is introduced as a new AQM scheme. According to historical data, this algorithm can dynamically modify the output, compensate for the influence of time delay, and reduce effectively the sensitivity to the actual model. The simulation results demonstrate that the performance of the proposed AMS-PI scheme are clearly superior to those of the PI scheme under both cases involving long delay and burst data flow.**

Keywords -- Network congestion control; adaptive modified; Smith predictor; time-delay system

I. INTRODUCTION

Network congestion is an unavoidable problem to users. With the explosive growth of network users, the network congestion phenomenon is increasingly serious. Therefore, it is very important to establish the mechanism to regulate the queue length in the link. Recently, the Internet research community has paid much attention to the issue. Active queue management (AQM) mechanism is the scheme implemented in the router nodes to prevent network congestion, which regulates the queue length before the buffer is filled completely. A perfect AQM scheme should aim to guarantee higher throughput and smaller packet loss rates in routers. Meanwhile, the system is of preferable robustness.

Random Early Detection (RED) algorithm, as a representative of AQM algorithm, plays an important role in improving the throughput of TCP flow and reducing packet loss rates, however tuning RED parameters under different network scenarios is a difficult task. The deficiency in RED algorithm has attracted much attention from the scholars. For example, by use of the simplified TCP/AQM model, a PI controller is designed to realize the AQM algorithm in [1], where it has been illustrated that the designed PI controller could stabilize the queue length better than the RED algorithm. On the basis of PI controller, a PID control algorithm is introduced in [2], which results in a preferable control performance. It should be pointed out that both RED algorithm and PI, PID algorithm are lack of the adaptive mechanism [3]. In [4], an improved expert intelligent PID algorithm (IEI-PID) is proposed which combined expert knowledge with PID to adjust the parameters. In [5], an intelligent adaptive PI active queue management scheme is introduced which adaptively tune the PI controller parameters according to queue length dynamics. In [6], an adaptive proportional integral-velocity (API-V) is presented to improve the slow response of PI control. In [7], a novel adaptive REM (AREM) algorithm is introduced, which adjust the drop probability according to their difference between a preset threshold and queue length error.

From the viewpoint of control theory, network congestion control can be regarded as a complex dynamic, non-linear, time delay feedback system. Many of the existing algorithms are based on certain linear TCP model which is only effective around the operating point [3, 8-9]. Due to the inherent nonlinear and dynamic nature of the Internet, the algorithms mentioned above cannot be easily applied in a dynamic environment. Meanwhile, these algorithms do not fully take the influence of network delay on the algorithm performance into account. Consequently, system performance cannot satisfy what we expect under the time-delay circumstance.

Smith prediction control is a kind of method that is used widely to compensate the influence of the time-delay on the system. Many scholars studied the network congestion control algorithm based on Smith predictor

[10, 11]. However, Smith prediction control depends heavily on the accurate system model, if we can't identified precisely the delay time and the dynamic parameters, the result of Smith predictor will deviate from the object's output, resulting in that the closed-loop system is unstable. Because of the dynamic and inherent nonlinear nature of the Internet, it is impossible to obtain exact model of controlled object, so the traditional Smith prediction control has certain limitations.

In this paper, the simplified model of the network based on fluid flow theory and stochastic differential equations is derived firstly. The adaptive modified strategy is applied to modify traditional Smith predictor parameters online. The Smith prediction compensation model based on adaptive modified is proposed, which reduces the dependence of the prediction method for the mathematical model. The adaptive modified Smith predictor combined with PI controller is applied to active queue management, subsequently the adaptive modified Smith-PI scheme (AMS-PI) is presented. The performance of the proposed scheme is evaluated in the both cases involving the long delay and burst data flow via NS2 network simulator. The simulation results confirm that the proposed schemes obviously outperform PI.

The remainder of the paper is organized as follows. Section 2 derives the TCP/AQM simplified model. Section 3 describes traditional Smith prediction scheme. Section 4 presents the adaptive modified Smith-PI algorithm. Section 5 provides a description of the AQM scheme selected for comparison under the both cases involving the long delay and burst data flow. Finally, Section 6 gives a brief conclusion.

II. TCP/AQM SIMPLIFIED MODEL

In [12], the dynamic model of TCP flow has been established on the basis of fluid flow theory and stochastic differential equations. Ignored the TCP timeout mechanism, the model is depicted as the following set of nonlinear differential equation:

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

where $W(t)$ is the average TCP window size in packets, $q(t)$ is the instantaneous queue length in packets, $R(t)$ is the round-trip time (RTT) in second, T_p is the propagation delay in second, $C(t)$ is link capacity in packets per second, $N(t)$ is the number of TCP sessions, $p(t)$ is the packet-dropping probability, $p(t) \in [0,1]$. $q(t)$ and $W(t)$ satisfy $q \in [0, \overline{q}]$, $W \in [0, \overline{W}]$, Where $\overline{q}$, $\overline{W}$ denote buffer capacity and maximum window size, respectively [10].

In order to resolve the operating point, we assume $N(t)$ and $C(t)$ is a constant, that is to say, $N(t) \equiv N$, $C(t) \equiv C$. R_0 is the RTT for the operating point. Take (W, q) as the state, p as input. The operating point W_0, q_0, p_0 can be obtained by setting $\dot{W}(t) = 0$ and $\dot{q}(t) = 0$, which satisfy $p_0 = 2N^2 / R_0{}^2 C^2$ and $W_0 = R_0 C / N$.

Then, the system (1) can be linearized at the operating point by small signal analysis theory as follows:

$$\begin{cases} \delta \dot{W}(t) = -\dfrac{N}{R_0^2 C}(\delta W(t) + \delta W(t-R_0)) \\ \quad -\dfrac{1}{R_0^2 C}(\delta q(t) - \delta q(t-R_0)) - \dfrac{R_0 C}{2N^2} \delta p(t-R_0) \\ \delta \dot{q}(t) = \dfrac{N}{R_0} \delta W(t) - \dfrac{1}{R_0} \delta q(t) \end{cases} \tag{2}$$

where $\delta W = W - W_0$, $\delta q = q - q_0$, $\delta p = p - p_0$ denote the variations around nominal values, respectively. The linearized TCP dynamics (2) is described as shown in Fig.1.

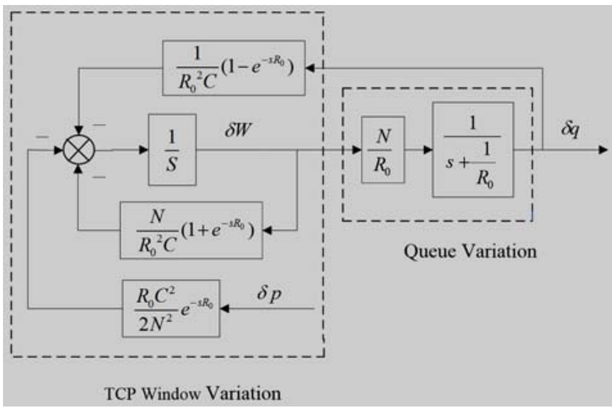


Fig.1. The block diagram of the linearized TCP dynamics

Ignoring the correlation between $t - R(t)$ and q, the research focus on low frequency performance. When the system is stable, it is apparent that $W \gg 1$ and $e^{-sR_0} \approx 1$.

Then, the simplified version of the linearized TCP dynamics is describes as shown in Fig.2.

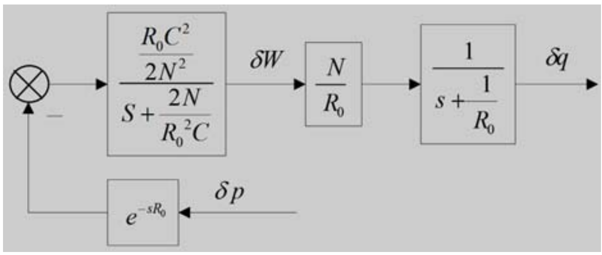


Fig.2. Simplified block diagram of the linearized TCP dynamics

Let

$$K = \frac{(R_0 C)^3}{4N^2},\ T_1 = R_0,\ T_2 = \frac{R_0^{\ 2} C}{2N}$$

The simplified TCP flow model, depicted by the transfer function $G_P(s)$, can be written as:

$$G_P(s) = \frac{Ke^{-R_0 s}}{(T_1 s + 1)(T_2 s + 1)} \qquad (3)$$

From equation (3), we can see that the controlled object is a linear second-order plant with time delay. Furthermore, the linearized TCP/AQM system is obviously described as a closed-loop control system shown in Fig.3. The measured queue length deviation $\delta q(k)$ and the packet-dropping probability $p(t)$ are the input and output of the AQM controller respectively. q_0 is the expected queue length.

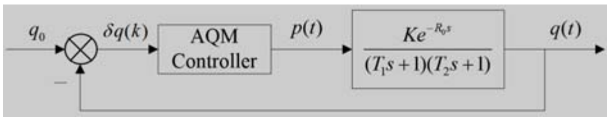


Fig.3. The block diagram of the linearized TCP/AQM system

Based on the linearized TCP/AQM model, Hollot [13] designed the classical PI controller as AQM control strategy. The controller can be written as

$$G_C(s) = K_{PI} \frac{(s/\omega_g) + 1}{s}$$

Because of the signal in the network is discrete, the PI controller should be discretized as the following form:

$$p(k) = a\delta q(k) + b\delta q(k-1) + p(k-1)$$

Where

$$\delta q(k) = q(k) - q_0,$$

$$a = K_{PI}\left(\frac{1}{\omega_g} + \frac{1}{f_s}\right),$$

$$b = K_{PI}\frac{1}{\omega_g},$$

f_s denotes the sampling frequency. As we all know, the classical PI algorithm is easy to implement, however, it can't guarantee its optimal performance for such a complicated plant with time-delay and disturbance.

III. TRADITIONAL SMITH PREDICTION ALGORITHM

In view of the controlled object with time delay, the traditional Smith predictor can compensate for the system time-delay via internal feedback, which makes that the denominator item of the closed-loop transfer function doesn't contain pure delay. The controlled variable gets feedback to the controller in advance, so as to offset the effects of the time-delay. The control schematic diagram with Smith predictor is shown in Fig.4.

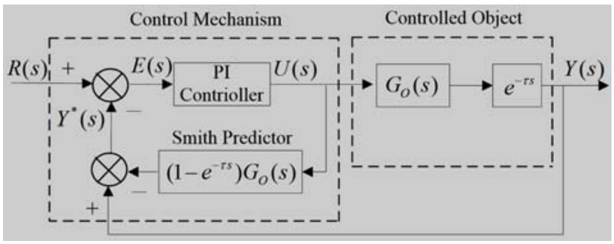


Fig.4. The control schematic diagram with Smith predictor

In Fig.4, $G_C(s)$, $(1-e^{-\tau s})G_0(s)$ is controller and Smith predictor respectively. $G_0(s)e^{-\tau s}$ represents the controlled object with the time-delay. After compensation, in the case of completely accurate prediction model, the closed-loop transfer function of the system is as follows:

$$\frac{Y(s)}{R(s)} = \frac{G_C(s)G_O(s)e^{-\tau s}}{1 + G_C(s)G_O(s)} \qquad (4)$$

According the equation (4), we can describe the TCP/AQM system with Smith predictor as Fig.5 that is equivalent to Fig.4.

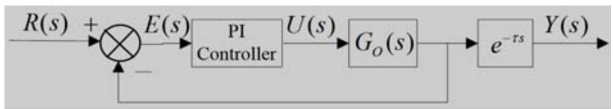


Fig.5. the equivalent system diagram with Smith predictor

As shown in Fig.5, due to the TCP/AQM system added Smith predictor, the feedback signal is transmitted directly to the input, and the control input is produced in time. Therefore, the performances of the system are improved significantly. In practice, if the controlled object has the accurate mathematical model the traditional Smith prediction algorithm is effective. Smith predictor can realize full compensation on the time-delay. If not, the control system may become unstable. Due to the inherent nonlinear and dynamic nature of the Internet, so the traditional Smith prediction is difficult to get satisfactory control performance in regulating the queue length.

IV. ADAPTIVE MODIFIED SMITH-PI ALGORITHM

In order to reduce the Smith prediction algorithm dependence on the controlled object model, we need take advantage of the historical data to modify the real-time prediction value, as far as possible to ensure that the prediction model can accurately predict the change trend of the controlled variables. From the point of view mentioned above, based on adaptive modified strategy, the adaptive modified Smith-PI algorithm (AMS-PI) is presented, which is applied to overcome the identification error influence on control system and realize that the Smith predictor can modify the parameters online adaptively. The adaptive modified Smith-PI control system schematic diagram is shown in Fig.6.

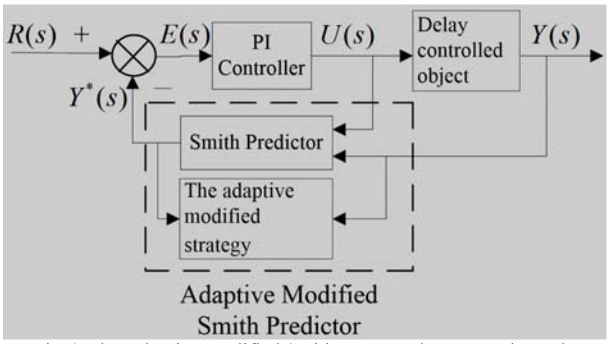


Fig.6. The adaptive modified Smith-PI control system schematic diagram

Because the adaptive predict output $Y^*(s)$ reflect the system output ahead of τ, we should compare the actual output $Y(s)$ with the predict output $Y^*(k-\beta)$ which is the β step before. Smith predictor adopts n order adaptive modified strategy. The algorithm is described as:

$$Y^*(k) = Y^*(k) + \sum_{i=1}^{n} \lambda[Y(k-i+1) - Y^*(k-i+1-\beta)]$$

Where λ is the modified parameter, its value can be calculated using the following formula:

$$\lambda = \lambda_0 + (Counter - 1)\cdot\Delta\lambda$$

where λ_0 is the modified parameter value by default, $\Delta\lambda$ is the parameter increment, $Counter$ is continuous inaccurate response times.

In network congestion control, the system is of bounded disturbances around the operating point. In this paper, λ is set as constant, we take a first order adaptive modified method to compensate the influence from identification error on the system. The algorithm is described as:

$$Y^*(k) = Y^*(k) + \lambda[Y(k) - Y^*(k-\beta)]$$

That is to say that we modify the current predict output according to the previous predict effect. It makes modification more simply so as to obtain perfect control performance.

V. SIMULATIONS AND PERFORMANCE EVALUATION

In this section, simulation experiments are implemented to validate the performance of the proposed AMS-PI controller using NS2 network simulator. A dumb-bell network topology is used as shown in Fig.7. The only bottleneck link with a link capacity of 15 Mbps exists between router A and router B. The link capacity is 10Mbps from senders to router A and from router B to receiver with the propagation delay of 10ms for each link. The buffer size and the expected queue length are set to 500 and 200 packets respectively for all AQM schemes. The packet size is 1000 bytes. AQM algorithms are implemented at router A, and other nodes are drop tail mechanism.

The parameters of PI controller are set to the default parameters in NS2: a= 0.00001822, b= 0.00001816 and the sample frequency is 170Hz, which are often used in studies of AQM schemes [14-16]. In the adaptive modified Smith-PI controller, the values of other parameters can be set according to the expected steady state, in this paper, we let =0.4, =0.1.

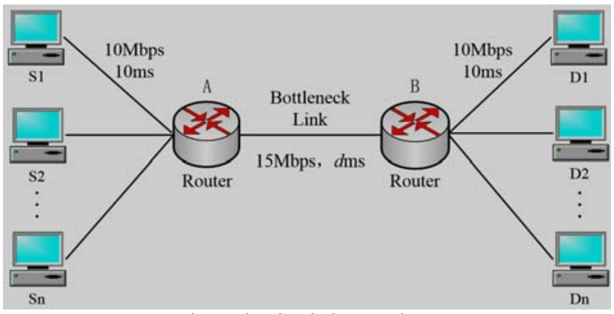
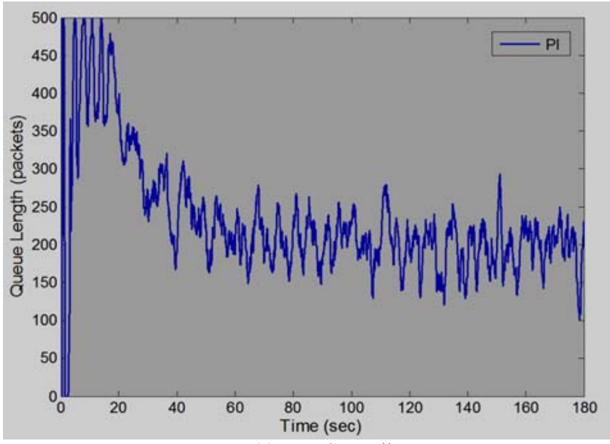


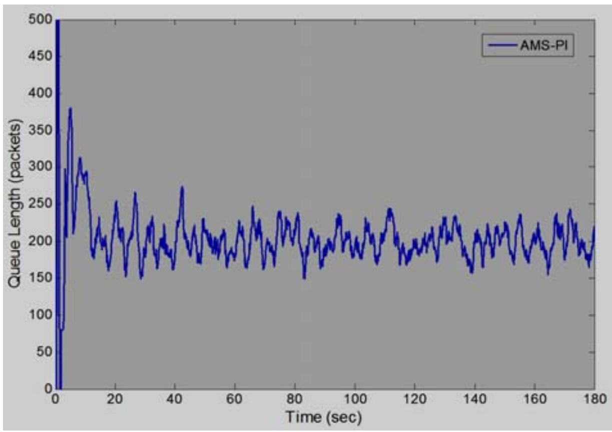
Fig.7. The simulation topology

Experiment 1

In this experiment, the performance of AMS-PI controller in the case of long time delay is evaluated. There are 100 TCP sessions, and the bottleneck link delay is for 200ms. The simulation time is 180s. Fig.8 denotes the control effectiveness of the algorithms on queue length. It is obvious that the AMS-PI controller show the more effective than PI algorithms. The queue length controlled by AMS-PI can converge more quickly and demonstrate less oscillation compared with PI controller.



(a) PI Controller

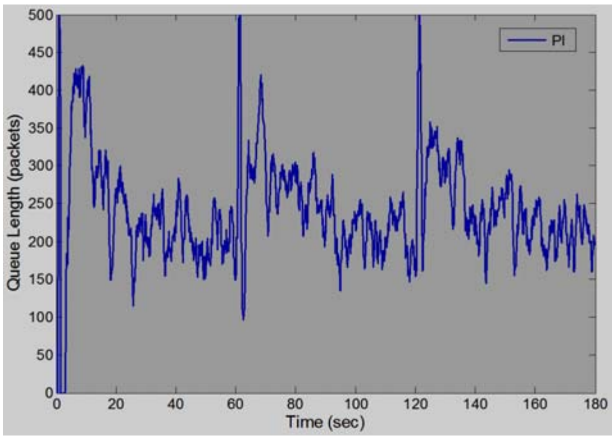


(b) AMS-PI Controller

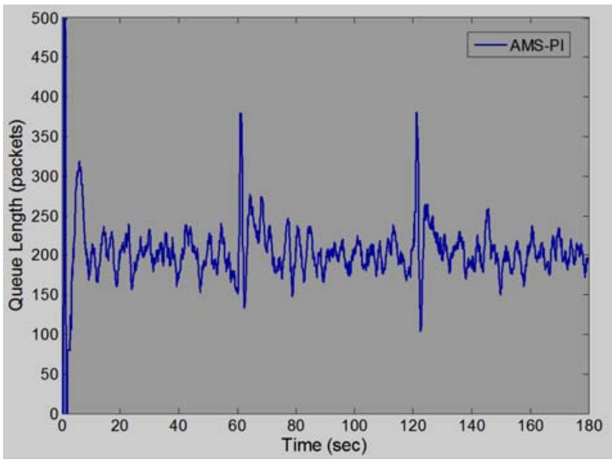
Fig.8. The algorithm simulation diagram for long delay

Experiment 2

We now validate the ability of AMS-PI controller to deal with sudden data flow. Firstly, setting N for 60 TCP sessions, subsequently at 30ms extra 30 TCP sessions added, the remainder 30 TCP sessions start when t=120s. The simulation time is 180s. The simulation results are plotted in Fig.9. It is apparent that the queue length controlled by PI controller deviates largely from the desired queue length encountering sudden data flow. Meanwhile, the steady-state error of the controlled system is larger. Furthermore, the settling time of PI controller is longer than AMS-PI. By contrast, the new AMS-PI controller can regulate the queue length easily when the network environment is changed. The system shows better robustness.



(a) PI Controller



(b) AMS-PI Controller

Fig.9. The algorithm simulation diagram for burst data flow

VI. CONCLUSIONS

In this paper, a novel AQM scheme called Adaptive Modified Smith-PI controller (AMS-PI) has been proposed. As is shown in the simulation experiments, AMS-PI controller has better performance than PI scheme under the both cases involving the long time delay and burst data flow.

Compared with PI, AMS-PI controller guarantee faster convergence to desired queue length, and adapt to the variations in TCP flow. These properties of AMS-PI mean that the system can obtain higher link utilization, better transient performances and stronger robustness.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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