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# Network Congestion Algorithm based on Smith Predictor Fuzzy AQM

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**Abstract:** Since there are many problems of the traditional network congestion algorithm like the lack of robustness and low steady-state, this paper proposes network congestion algorithm based on Smith predictor fuzzy AQM. This algorithm first analyzes the TCP congestion control mathematical model and the Smith predictive control theory, and then by using the fuzzy control in control theory and Smith Predictor compensation designs a new AQM algorithm to eliminate the negative effects of jitter and delay on the network router and queue-to-end delay jitter, thus this thesis achieves the purpose of achieving the desired stability and transient performance in the delay network. Finally, simulation experiment of network congestion algorithm based on Smith predictor fuzzy AQM are conducted. The results show that: the proposed algorithm improves the performance of the system, and it has good robustness and steady-state.

**Keywords:** Feature Words; Clustering; Vector; Relational Table

## 1. Introduction

With the rapid development of computer and communication technology, network congestion control has become a hot research field. From the perspective of control theory, congestion control is a very complex issue, because it has the complex features like multi-dimensional, nonlinear, and dynamic and so on [1]. Recently, from control theory some mathematical models of congestion control research make detailed study and discussion on recent studies and the stability, robustness and fairness of congestion control protocol carried out recently. Although the window-based end-to-end congestion control mechanism ensures the robustness of the Internet, the traditional tail eliminating algorithm has high latency jitter. So in order to achieve the control of network congestion in the network side, this thesis proposes the AQM technology [2-6].

Cohort method was first used by Luck and Ray, which is proposed in the literature [5]. This method is based on deterministic state estimation and linear state feedback, and it can be seen as delay compensation method based on deterministic predictor, in which its sending end of sensors and control are separately set in queue buffer, so it can ensure that the sensor information and control information can be generated arrive at the receiving end in chronological order. Using the FIFO characteristics of queue buffer, the random time delay is changed into deterministic delay, and then the randomly delay system is changed into deterministic system, which make the system is easier to control. But because the performance of the observer and forecasting largely depend on the accuracy of the model, and the use of all delay queues will change all the delay into a maximum delay, which is artificially expanded delay, the obtained control performance is conservative [5-7].

Chan proposes an alternative method to the network control system with random delay. It uses the queues and a probabilistic predictor for delay compensation. The used probabilistic forecast is the best linear combination of predictors of two mean squares, and its weight matrix is calculated according to the probability of the known delay data. Compared to the queues proposed by Luck and Ray, the method proposed by Chan improves the performance of system prediction, but the queue is still introduces additional extension, and the method is just a delay compensation method, in which its stability need to combine specific control law to analyze. Additionally, the method only considers the delay between the sensors to the controller, and only makes compensation on it. Due to the introduction of additional uncertainty queue delay, the queue is not applicable to control system adopting rotation systems in the network control system. Since the existence of communication networks, information transmission will occupy the network communication lines and the carrying capacity of the network and the communication bandwidth is limited, these will inevitably result in the collision information and the phenomena of retransmission. Also due to the adoption of sampling, quantization, coding and decoding, the time awaiting delivery makes the information in control system generates conduct delay when the network transmission. This delay is called network-induced delay. Presence of delay will reduce control performance of system latency and even cause system instability, which makes complex analysis of the system. Although the analysis and modeling of delay system made great progress in recent years, there are many different types of delay in the network control system, so the existing methods generally can not be applied directly. Direct results caused by network congestion are increasing packet loss rate, increasing end to end data transmission delay and even serious paralysis of the entire system.

## 2. Mathematical Model

Currently, TCP uses a congestion control mechanism of sliding window proposed by Van Jacobson; when congestion occurs, in order to decrease the data transfer rate, typically the size of congestion window is reduced. In the mechanism, there parameters are usually required as follows: announce window, congestion window and slow start threshold. In the "Mathematical modeling of the Internet", the nonlinear dynamic model of TCP congestion control is given. Assuming the network topology made up of the same M TCP source nodes, which share a single bottleneck router, it has substantially the same RTT, but not necessarily along the same path transmission, M TCP flows through a congested router, which can be expressed as follows:

$$s(t)=\frac{r(t)}{s^2(t)}-\left(\frac{r(t)}{s^2(t)}+\frac{s^2(t)}{2r(t)}\right)o(t)=s(t)-p(t) \quad (1)$$

And

Wherein, $0\le s(t)\le 1$ is a block tag / loss probability; $s(t)$ is the loop of the RTT; $o(t)$ is the instantaneous queue length in the buffer; $s(t)$ is the unit time input flow rate; $r(t)$ is the number of active TCP packet; $y_p$ is the transmission delay; (t) is the link capacity; formula (1) is only a simplified model, which do not consider the delay of $s(t)$ and $o(t)$.

For existing TCP congestion control, it can be divided into slow start slow start, congestion avoidance fast retransmission and fast recovery. Without considering the transmission timeout factors, its mathematical model can be coupled to the non-linear differential equations:

$$\begin{aligned}R(t)&=\frac{1}{e(t)}-\frac{r(t)r(t-e(t))}{2e(t-e(t))}s(t-e(t))q(t)\\&=\frac{R(t)}{e(t)}l(t)-b\end{aligned} \quad (2)$$

$R(t)$ the size of TCP congestion window; $q(t)$ the length of buffer queue; R: round-trip delay; B link capacity; $l$ the number of TCP connection; $p(t)$ packet drop rate. In the formula (2-3), the first formula describes the changes of the TCP congestion window, and it can be divided into two parts: the first part $\frac{1}{e(t)}$, which is the linear increase at the congestion avoidance phase for TCP, and the second part is the window after half part for receiving the signal. It is shown as the following:

$$\frac{r(t)r(t-e(t))}{2e(t-e(t))}s(t-e(t))q(t) \quad (3)$$

In the second equation, $\frac{r(t)}{e(t)}s(t)$ represents the sending capability of the sending end. Figure 1 is used to indicate the differential equations (3), which can be more intuitive to show the dynamic characteristics of TCP window:

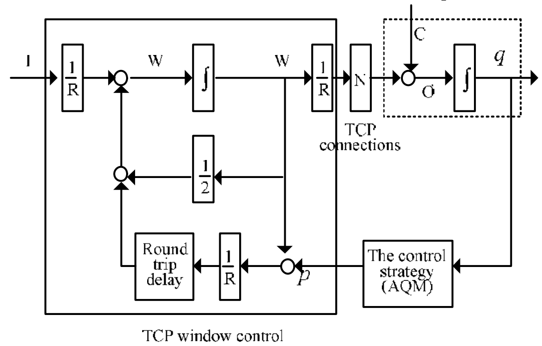



**Figure 1. Control charts of TCP congestion avoidance**

## 3. Smith Predictor

System block diagram of Smith predictor control is shown in Figure 2. D (s) represents the transfer function of the regulator, in which the compensator connected to D (s) and is called predictor; its transfer function is GP(s) $(1-e^{-ts})$; $t$ is the lag time; GP(s) $e^{-ts}$ indicates transfer function of the actual object with the pure delay, which can be you can obtained by the model identification methods; GP (s) for the transfer function of the controlled object without pure delay parts; $e^{-ts}$ is the transfer function of the controlled abject with pure delay parts.

The compensated transfer function of the system is shown as following:

$$\phi(s)=\frac{D(s)G_p(s)}{1+D(s)G_p(s)}e^{-ts} \quad (4)$$

It can be seen that Visible $e^{-ts}$ in out of a closed control loop, which does not affect the stability of the system, and only make the control action move at a time lapse in time coordinate. The transition process of the control system and other performance indicators are the same with the object properties as GP(s), that is, the system eliminates the influence of the system control quality caused by time delay.

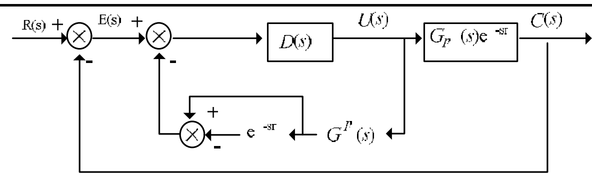



**Figure 2. System diagram of Smith predictive control**

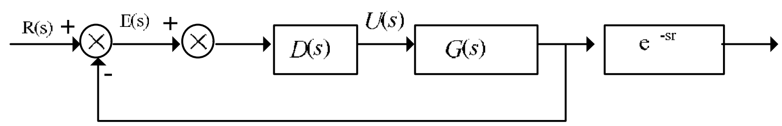



**Figure 3. Equivalent block diagram of Smith predictor control system**

## 4. Design of Smith-fuzzy Controller

For TCP congestion control model, the purpose of queue management is to design the corresponding data packet drop probability, which utilizes the network resource and makes the queue length small and stable. "AQM Algorithm based on Fuzzy Control" designs a fuzzy algorithm based on fuzzy logic for the model (3) and uses parameter self-tuning technology, which makes this algorithm has a better ability to adapt the changes of the network, but it does not consider the impact of large delay, so this thesis takes Smith predictor to compensate the delay. Figure 4 shows the system block diagram of Smith predictor based fuzzy controller:

In Figure 4, $d_p$ represents the length of queue; $p(t)$ is the dynamic marking probability; $q(t)$ represents the length of target queue; F(s) is on behalf of the fuzzy controller; $e^{-sro}$ represents the pure time delay; $Gw(s)$ represents the transfer function of sending window; $Gq(s)$ is the transfer function of the buffer queue length; $(1-e^{-sro})$ $Gw(s)$ $Gq(s)$ are on behalf of compensation function of Smith. With appropriate changes in the system, the system shown in Figure 4 can be equivalent to the system shown in Figure 5. It can be seen from Figure 4, the biggest advantage of Smith predictor system is that the delay unit is moved outside of the closed loop system, so the control quality is greatly improved.

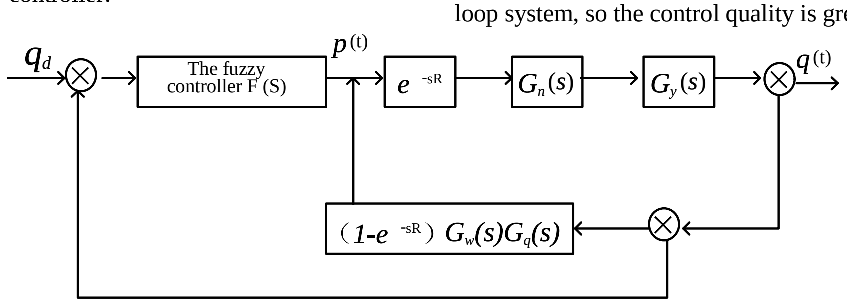



**Figure 4. System structure of Fuzzy Smith**

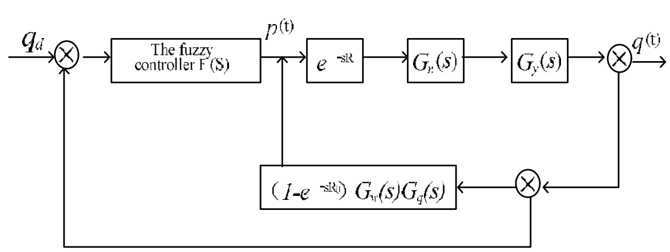



**Figure 5. Equivalent image of Fuzzy Smith system**

System transfer function in Figure 4 is shown as the following:

$$H(s)=\frac{F(s)G(s)e^{-sro}}{1+G(s)(1-e^{-sro})F(s)+F(s)G(s)e^{-sro}}$$
$$=\frac{F(s)G(s)e^{-sro}}{1+F(s)G(s)} \tag{5}$$

From Formula (5) can be seen that Figure 4 is equivalent to Figure 5. From Figure 5, it can be seen that the parts out of the delay are moved outside of the closed -loop delay. Since the feedback signal is not delayed and the response if controlled amount is advanced, system performance is greatly improved.

In the real network, the instantaneous queue length in the router can be obtained in real time, the desired queue length $e_{ref}$ is selected, and the of the error e (t) and the change rate o deviation $\mathrm{V}e(t)$ of instantaneous queue length can be expressed as:

$$e(t)=e_{ref}-e_n$$
$$\Delta e(t)=de(t)/d_t \tag{6}$$

$e(t)$ and $\mathrm{V}e(t)$ are chosen as the input of the fuzzy controller, because these two inputs can be more stringently reflect the dynamic characteristics of the changes of router queue length. In the fuzzy control system, E and $E_c$ are used to represent their corresponding linguistic variables; as for the output amount the increasing amount of the drop probability is as $\mathrm{V}p(t)$; in fuzzy system linguistic variables is $D_p$. In the fuzzy set, the more the elements in the collection are, the more sophisticated the control is, and the amount of computation will have increased exponentially. but in order to better respond to the processing speed, based on expert knowledge and experience of the designer, weighing control accuracy and computing volume, here the fuzzy sets of E and $E_c$ are defined as {NB (negative big), NS (negative small), ZE (zero), PS (positive small), PB (CP)}; the fuzzy set of $D_p$ is defined as {-3, -2, -1, 0, 1, 2, 3}; in order to facilitate the calculation, the selected membership function of the fuzzy set is triangular function, and each variable fuzzy sets and membership functions are shown in Figure 6 to Figure 8.

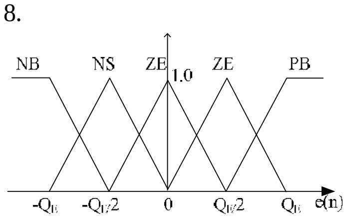



**Figure 6. Fuzzy sets of variable E and membership functions**

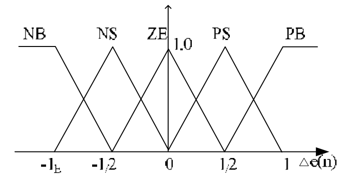



**Figure 7. Fuzzy sets of variable $E_c$ and membership functions**

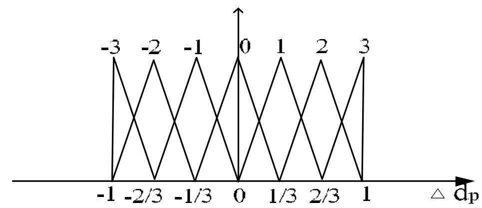



**Figure 8. Fuzzy sets of variable $D_p$ and membership functions**

The control rules in the fuzzy programming library are the following "if-then" statement:
If $E$ is NB and $E_c$ is ZF, then $D_p$ is 2 or expressed as (NB, ZF) = 2 with the function form, shown as Table 1.

**Table 1. Control rules of the fuzzy controller**

| $D_p$ | | E | | | | |
|---|---|---|---|---|---|---|
| | | ZF | NS | PS | PB | NB |
| $E_c$ | ZF | 2 | 1 | 0 | -1 | -2 |
| | NS | 3 | 2 | 1 | 0 | -1 |
| | PS | 1 | 0 | -1 | -2 | -3 |
| | PB | 2 | 1 | 0 | -2 | -1 |
| | NB | 3 | 3 | 2 | 1 | 0 |

According to the above fuzzy rules, the weighted average method is used, it can be seen that the relationship of the input and output in fuzzy system can be expressed as:

$$\Delta p(n)=\frac{\sum_{i=1}^{k}\left(y_i u_i(e)u_i\Delta(e)\right)}{\sum_{i=1}^{k}\left(u_i(e)u_i\mathrm{V}(e)\right)} \tag{8}$$

$y_i$ denotes the fuzzy center value of "then" part of the $i_{th}$ fuzzy rule; $ul(x)$ represents the membership function of fuzzy set $i$.

## 5. Fuzzy Self-tuning Controls

As for the two-dimensional fuzzy controller, its control parameters are quantization factor $k_e, k_c$ and the scale factor $k_u$, a two-dimensional theory of fuzzy control system is shown in Figure 9. The parts in the dashed box are a two-dimensional fuzzy controller; in addition there are four links as number system storage unit, evaluation (performance), rule amendment and parameters correction. Wherein, the data storage unit is used for storing the various data of the evaluation control system performance. Performance evaluates the controlling effect according to the information provided by the system. The results are sent into the rule amendments and parameter correction links, which are respectively as basis of the rule amendments and parameter correction.

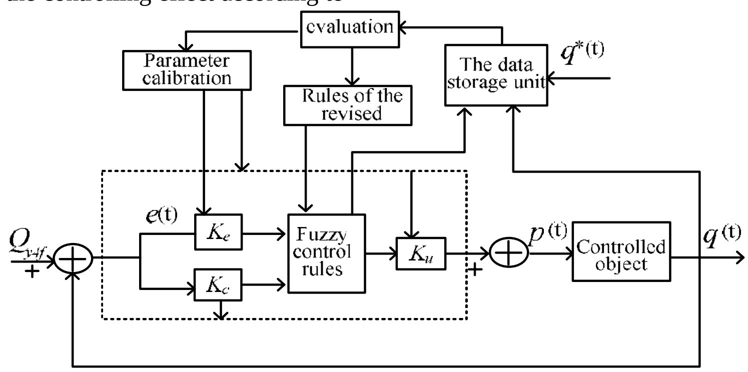



**Figure 9. AQM system model of the self-tuning fuzzy logic control**

When the network parameters change great, the fuzzy logic controller gain can be adjusted to offset the impact of changes. It can be seen that when the number of network connection $N$ is increasing, the $p(t)$ should be increased; when the link capacity $c$ is increased, $p(t)$ should be decreases; when the delay it is required to increase $p(t)$. Thus, the control behavior of logic controller is corresponding increased or decreased to improve the performance of fuzzy systems.

In order to control the parameters correction and control rule amendments, the performance of the control should be evaluated, so the fuzzy performance indicators FP of the quality of evaluation system are defined as the following:

$$RP = \min\{u_{ol}(e_{ok}), u_{er}(e_{er})\}$$

Wherein, OV and $RP$ are respectively the overshoot and rise time of the system response, and the deviation of their target values are as $ol^*$ and $er^*$

$$\begin{aligned} u_{ol} &= ol - ol* \\ e_{ol} &= er - er* \end{aligned} \quad (9)$$

According to the fuzzy indicators of system, if the parameters of the system need to be modified? When the number of network connections increases, the positive overshoot increases, and at this time, the control behavior should be increased, otherwise, the control behavior should be decreased; when link capacity is increased, the overshoot is decreased, and at this time the control behavior should be decreased. The correction rules of the specific parameters are as shown in Table 2, and the variation ranges of these rules are as following:

$[-c_i, c_i](i=1,2)$ and $[d,-d]$, wherein, $\Delta c_i$ and $\Delta_d$ respectively represent the increase or decrease.

**Table 2. Regulation rules of proportional system**

| Input/Output Characteristics | | $\Delta c_1$ | $\Delta c_2$ | $d$ |
|---|---|---|---|---|
| $e_{ol}$ | N | NB | PS | PB |
| | P | PB | NS | NB |
| $e_{er}$ | N | PB | NB | NB |
| | P | NB | PB | PB |

## 6. Simulations and Analysis

This paper uses NS-2 simulation software to make simulation research for algorithm performance of fuzzy control, and experiments adopt dumbbell-shaped network topology shown in Figure 10 and compare the simulation results with the PI control.

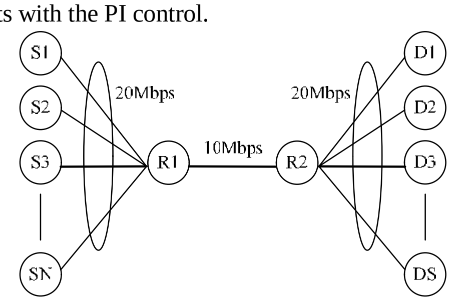
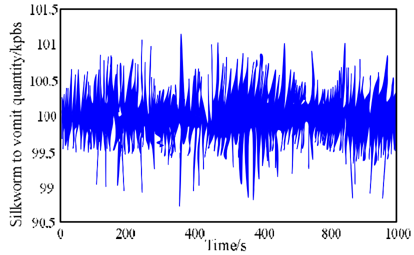


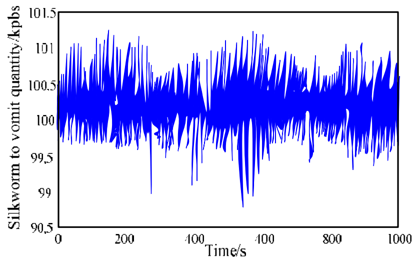

**Figure 10. Network emulation topology**

The bandwidth of the link between source node Si and the router R1 between the destination node and router R2 are 20Mbps; between routers R1 and R2, there is only one bottleneck link, and its bandwidth is as 10Mbps.

Simulation 1: The router's buffer capacity is 300packets; the link delay between source node Si and the router R1 is 2ms; the link delay between routers R1 and R2 routers is 20ms; the link delay between the destination node and the router 2 is 4ms; the network connection is as N = 50, and the results are shown in Figure 11.




(a)




(b)

**Figure 11. Comparison of the queue length of these two controllers**

Figure 11 (a) is the router queue length of the PI controller; Figure 11 (b) is the router queue length of the Adaptive Fuzzy Control Based on Smith. From the figure, it can be seen from that compared with PI controller the stability of Adaptive Fuzzy Control Based on Smith has been greatly improved, which reached our design requirements.

Simulation 2: Using the data in simulation 1, the utilization at the router buffer queue can be seen; from Figure 12 it can be seen that the utilization of SAFC controller is significantly higher than the PI controller, thus it solves the problem of low utilization of the buffer queue.

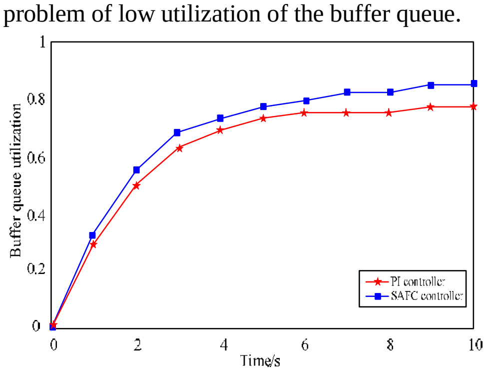



**Figure 12. Utilization of buffer queue**

Simulation 3: considering the large delay, the link delay between the source node Si and the router R1 is 10ms; the link delay between router R1 and router R2 is 0.2s; the link delay between the destination node and router 2 is 50ms. Network connections are unchanged, and the results are shown in Figure 13.

As can be seen from Figure 13, in a large delay environment, the utilization of SAFC significantly is much higher than the PI controller, and it is not changed too much with the delay.

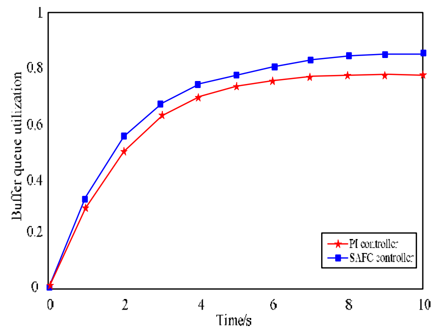



**Figure 13. Utilization of the buffer queue under large delay**

## 7. Conclusion

For the complexity of the network and sudden of data streams, this paper proposes a Smith adaptive fuzzy control strategy based on queue length deviation and the deviation rate of change. Simulation compared with the PI control algorithm, the SAFC control algorithm improves the system performance, compensate the impact of large delay on network performance, which make the queue length tends to certain stability and reduce the impact of delay jitter on length of the queue. It has good adaptation ability to the network status changes and good robustness with large delay network, which effectively avoid network congestion and improve the network quality of service.

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